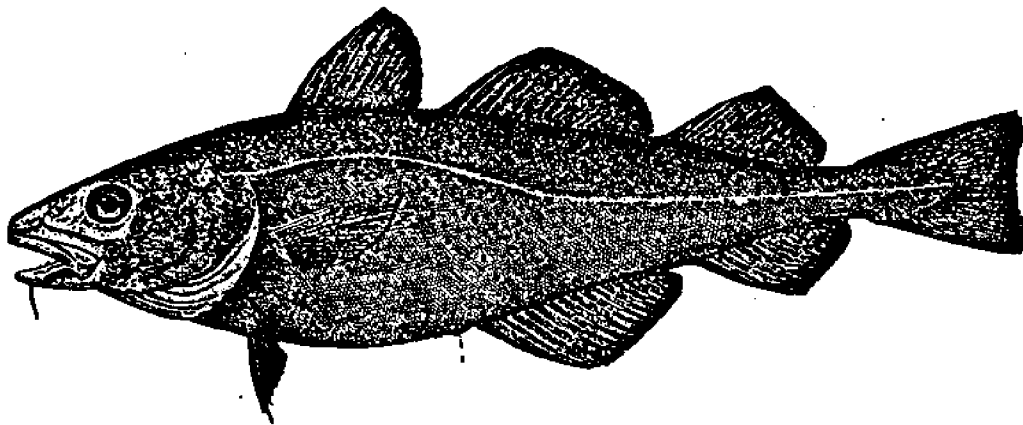


C-FARMS

Coastal Finfish Aquaculture-Rearing Model System



Project leader:

Sean Silva

Project team:

Evan Richardson

Mike Shaw

Chris Spaulding

Project advisors:

Dr. Jeff Savage

Dr. Barbaros Celikkol

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Abstract

The decline of commercial fish stocks coupled with the increased demand for fish has led to the need for aquacultural fish farming. Lack of inshore sites for fish farming and attendant visual alterations of the natural coastline have caused the farming movement to head offshore. Open ocean fish farming presents a far greater design challenge than traditional, protected coastal water fish farming. The volatile conditions require a design that takes into consideration dynamic forces as well as static forces. C-FARMS provides a unique solution to the open ocean fish farming problem. Rather than rely solely on the strength of the cage for surviving the higher sea state conditions, C-FARMS uses submersion in order to reduce the wave forces on the cage, and offers an ability for rapid withdrawal to a safe haven if necessary.

Design decisions were biologically based due to species specificity and physiology of codfish. C-FARMS final solution is a shallow submersible cage system which can be towed to a safe haven in emergency situations. Each system, consisting of two octagonal cages, which are capable of holding sixty-six thousand pounds of cod. The cages are constructed of two inch steel pipe and surrounded by a rectangular wooden frame which also acts as a walkway and towing frame. The system utilizes a ballast system consisting of eleven fifty-five gallon float drums as ballast tanks to submerge it to a depth of ten feet.

A 1/12.5 scale model has been built to specifically test the raising and lowering system. The model was tested in the university pool and the results from these tests indicate our design is a realistic approach. Based on the results, recommendations have been made for further research which include building a larger model and testing it in the open ocean with real fish. This future work will be carried out by U.N.H. ocean engineering graduate student, Langley Gace this summer.

Introduction

Purpose

The purpose of this project was to further the development of fish farming by offering a solution to the problems incurred offshore.

Background

The state of open ocean fisheries today is in turmoil due to the progressive decline of fish populations from overfishing of exploitable age classes, environmental effects and the loss of juvenile habitats. At the same time the demand for fish products is on the rapid incline. In 1988, the Food and Agricultural Organization (FAO) estimated an annual increase in fisheries production of 7% since 1975, with a total world production of 98 million metric tons (MMT) (Fridley, 1993). Only 14MMT of the world's salt water catch was due to aquacultural (stock enhancement and cage culture). In the United States, this demand for fish production is so great that fish products are the third greatest U.S. import (\$6.0 billion a year) exceeded only by drugs and oil (Bardach, Champ, Takahash, and Wilder, 1992). Fish consumption in the United States is estimated at about 17 pounds per person and is expected to double by the end of this century, with an annual increase of 2.1 percent (Bardach et. al., 1992). A high demand for fish products in the United States has caused the majority of mainstay fisheries to exceed their maximum biological limits and has forced the United States to begin importing less desirable species. These increasing and decreasing rates of consumption and production, respectively, suggest a need for management and technology to concentrate on marine aquaculture (mariculture) rather than traditional fish capture methods.

Whereas terrestrial agriculture has benefited from centuries of research, modern mariculture is only twenty years old and is succeeding with little or no research and development (Willinsky and Champ, 1993). The majority of any research and development has been centered in hatcheries which have benefited coastal and inland bodies of water. The need for offshore or "open" ocean fishery systems has already been established, and these may help to alleviate many

institutional, regulatory, and environmental problems associated with coastal marine and inland freshwater technology (Fridley, 1993). One of these technological areas has been the development of cage culture or "net pens" for fish. In the early 1970's, the Norwegians established a cage culture system that raised Atlantic salmon, *Salmo salar*, over a two year period, to marketable size of four to five pounds (Fridley, 1993). Soon after the Norwegians began net pen systems, the United States and Canada followed. Along the northern coast of Maine fish farming sites were developed, in which smolts, produced from freshwater hatcheries, could be placed in sea cages. The salmon remained in the pens for approximately 18 months and were then harvested for sale. Sites were limited to calm inshore estuaries and bays; so this approach was adaptable to the states of Maine, Washington, Alaska and some states bordering on the Gulf of Mexico. These near shore sites have now caused concerns about environmental contamination and aesthetics, which indicates a need to move net pens to offshore sites.

In 1991, the Marine Technological Society (MTS) met at the University of Hawaii to discuss a workshop on the "needs for offshore mariculture systems". The objective of the MTS proceedings was to "concentrate an emphasis on enclosure engineering and system stimulation for feeding and growth" of fish (Bardach et.al., 1992). The workshop took into consideration the specifics of cage shape, size, strength, and the construction of anchoring, to be adapted for various sea conditions as well as the establishment of culture methods. At a conference held by the National Science Foundation it was determined that only twenty companies are working on new offshore fish farming designs and only eighteen different systems are in the design stage or operation (McCoy, 1993). So far no deep water, open ocean system is in commercial operation.

The future of net pen aquaculture is directed mostly towards submerged cage systems, which will probably hold large quantities of cod, halibut, or tuna. The Coastal Finfish Aquacultural Rearing Model System project (C-FARMS), at the University of New Hampshire, has proposed a system that recognizes the trend towards offshore

cages and the need for alternative solutions in finfish mariculture.

Important Considerations For Offshore Net Pen System Design

The MTS '92 workshop proceedings defined the basic research needs for a good offshore net pen system. It established that 1) anchoring and design had to withstand oceanic forces and biological fouling, 2) providing technological and economical feasibility of submerging fish cages to a fixed water depth for protection from wind and wave action. In addition, certain priorities for cage design and operation need to be developed for landing and handling approaches, harvesting, on-site processing, and feeding. Offshore cage systems must also be capable of being raised, lowered and/or relocated away from pollutants when crop saving measures are needed (Fridley, 1993). Above all, the most important three aspects which contribute to a good net pen fishery are; site selection, material selection, and system operation (Riley).

Site Selection

Although experts say that U.S. net pen sites are limited to Puget Sound, northern Maine, and the Gulf of Mexico, the Norwegians have defined reasonable "open ocean" net pen sites as those outside the 12 mile territorial limits, in wave action below significant height of four meters (McCoy, 1993). This criteria establishes many prospective sites along the coastal waters of the United States. The advantages of such prospective sites are enormous compared to inshore sites now in operation. Offshore sites offer a lower transfer of parasites and disease from natural populations in water surrounding the cage-reared fish because of lower natural fish populations. Offshore cages sites also allow for greater stocking densities than inshore sites (2 to 4 times more per unit water volume) (Willinsky and Champ, 1993). The useful volume of partially submerged offshore cages also increases, reducing the stress on the fish by increasing their swimming space. Lastly, waste has a greater

tendency to be dispersed over the larger open area in offshore sites. In order to achieve the maximum benefit from these advantages, several factors that affect a particular site of interest must be considered. These include current, water depth, temperature, salinity, and aesthetics, in addition to expected sea states.

Current

In order to obtain maximum growth from caged fish, it is important to have a strong, constant supply of oxygen from clean water. Clean water is available through the constant mixing of water from natural current and tidal flow. Together, these velocity components help remove metabolic waste products and any uneaten feed. If water flow is too slow, then fouling from waste products and the settlement of sessile animals and algae can grow to plug the nets. This poses a continuous cleaning problem to maintain the nets or face an increase in fish mortality. If the current is too fast, an increased stress on the fish occurs in which the fish waste energy swimming just to maintain itself in the water column. Increased wave motion and current also causes folds in the nets which tend to trap the fish and shear the nets. It is necessary to use weights to keep the net open in heavy current. If such measures are not taken then the nets lose their volume as the current pushes up, which, in turn, crowds the fish causing them to become entangled and abraded (McCoy, 1993). It has been suggested that a minimum peak tidal current of 50 cm/sec and a maximum peak current of 200 cm/sec be present when selecting suitable sites for net pen fish cages (Riley). Laboratory studies done with cultured carp suggest that a flow through rate of one liter of water per minute per kilogram of fish be used in mariculture systems, but this can be as low as 0.3L/min/kg (Meske, 1985). C-FARMS has assumed a current speed of at least one half knot at its system location.

Depth

One of the major disadvantages of inshore net pen sites is the shallowness of the water. Again, fouling becomes evident when waste and uneaten food fall to the

the water. Again, fouling becomes evident when waste and uneaten food fall to the bottom of the sea floor and begin to build up. Such build-up causes an increase in unwanted organic matter resulting in a decrease in dissolved oxygen in the surrounding water. Extensive research on this subject indicates that the most logistical approach to solving this problem of anoxic fouling is to move the cage higher up in the water column. This is achieved by moving the sites offshore into deeper water.

It has been established that a minimum clearance of 2-3 meters should exist underneath the cage (Riley). The recommended C-FARM cage location has a minimum under-cage clearance of approximately 70 ft. (app. 23m). The designated site of the system will be off White I. Ledge as indicated on the map in Figure 1.

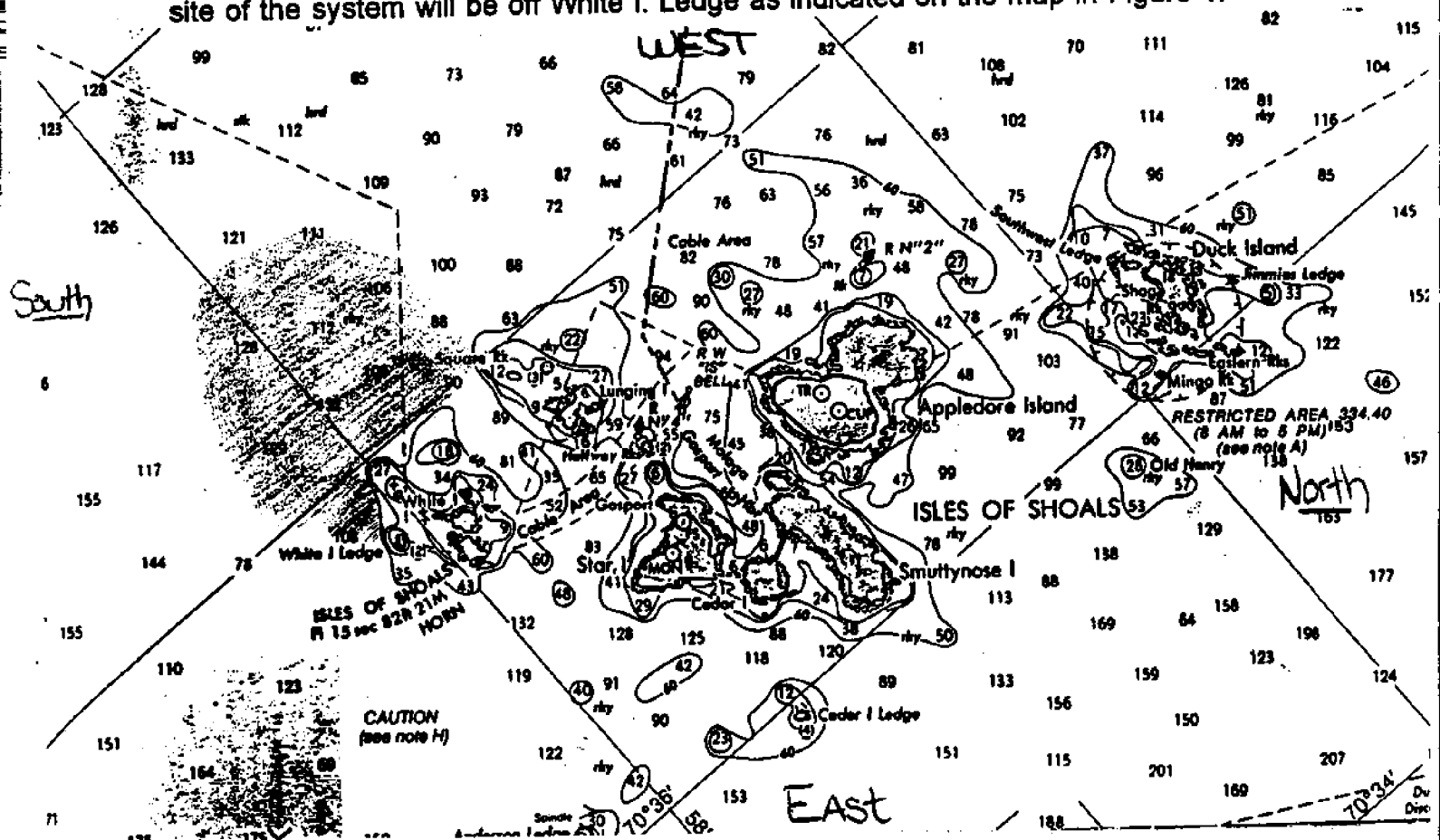


Figure 1. Site selected depth and area of C-FARMS net pen system off the Isles of Shoals, Gulf of Maine. Shaded area indicates potential sites of use. (Map from NOAA Nautical Chart 13274 - Portsmouth Harbor to Boston Harbor)

C-FARMS

Temperature

If the temperature of the area selected is too warm, then oxygen levels tend to be too low. However, if the temperature drops too low, such as 0° C (which can be the case off the northern coast of Maine) then the fish will experience what is known as "superchill". In the case of "superchill", fish will seek deeper water depths, away from the colder surface water, at which time they are under tremendous stress. It has also been determined that the growth of the fish tends to be much slower in colder water temperatures; therefore causing slower production to marketable size. Moving the net pens to offshore sites allows the fish to seek the greater depths during colder months due to the destratification of water layers offshore. There is also less of a tendency for ice to build up offshore. Furthermore, fish such as salmon tend to feed best in temperatures between 12-15°C, during the late summer and early fall (Riley). The C-FARMS system is designed for operation only in the months (May to September) when the water temperature is most beneficial for maximum growth rates of codfish in the Gulf of Maine.

Salinity

Although not much is known about the effects of salinity levels on cod, it is generally not a problem for anadromous species such as salmonids (trout, salmon). However, salinity levels that are too low can cause problems for cod and most marine fish. Low concentrations of ionocytes surrounding the fish can cause osmotic problems such as cell lysis. Therefore, sites selected for such species should avoid freshwater channels into the ocean. Offshore sites rarely experience this. Also, if salinity levels are too high, then the fish are hypoosmotic to their surroundings and will become dehydrated; sites selected should avoid salty runoff areas. This too can be assured by moving offshore where stronger current and wave activity cause ionic mixing.

Aesthetics

Net pen sites in the bays and estuaries of northern Maine's coastal waters have unleashed a fury of complaints as being "aesthetically objectionable" to tourists and landowners. This has become an increasingly important consideration in determining a fish farming site, whether it be company owned or privately operated. By moving the net pen cages offshore, it is hoped that most or all of this controversy can be avoided.

IMPORTANT OPERATIONAL CONSIDERATIONS

Feeding

Feeding is a very important aspect of the net pen system; it makes up approximately 40% of the production cost, but is controllable by the operator. Feeding can be done by various mechanical means but is most often done manually in order to observe the fishes' behavior first hand. In the Maine salmon pen systems, the fish are usually fed to satiation on an average of two to three times a day (Riley). Fish can generally withstand long periods of starvation; however, the quality in meat production goes down if it is prolonged. The caged fish are generally fed a dry feed that is high in protein and fats. Feed that is high in protein causes the fish to produce lower amounts of oil than foods high in carbohydrate (quick energy). Studies show that the protein efficiency ratio (PER), unit growth per unit protein input, should equal approximately 10% of the fish's total weight per day (Meske, 1985). This is also based on the feed concentration ratio (FCR), in which a certain amount of feed is required to achieve a unit weight of increase. Studies raising carp in a laboratory setting show that most fish achieved a 5:1 FCR (5kg of feed resulting in an increase of 1kg in weight) (Meske, 1985). It is thought that growth rates of cage cultured fish can be made to triple the fairly slow and constant growth rates seen in nature.

Stock Density

Fish growth is dependent on the space and volume of the cage per unit of fish volume which in turn depends on excretion and flow. It has already been established that waste from gill and/or anal excretion can be minimized by superior site selection. Also, growth is maximized by using proper methods of feeding to reduce the amounts of bacteria, fungi, and trypsin inhibitors from developing on the fishes' skin. If more fish are placed in a closed environment than that environment can handle, then the risk of waste, disease, and added stress to the fish increases. The C-FARMS project calls for a maximum of 0.4 lbs. of codfish per cubic foot of water. This is based on the suggestion of Dr. Ken Waiwood, a fish biologist at St. Andrews Biological Station.

Cleaning/Fouling

As mentioned extensively throughout this paper, sessile invertebrates such as mussels, tubularia, polychaetes, and barnacles along with sea vegetation (algae), inevitably grow on marine net pen structures. This in turn increases the weight and stress on the equipment. Various methods are used in to remove fouling organisms and wastes from pen materials. The nets are generally cleaned once a year by hand and/or by partial or total removal of the nets to shore in order to let the sun "dry" or "bake" the living material. Baking is a commonly used method in which the organisms that have fouled the nets, dry up, die, and lose their adhesion, thus freeing them from the mesh. Introducing other species such as crabs, winkles, or flatfish into the pens in order to naturally clean the nets has been tried but the results were not significant (Riley).

Another possibility for keeping the nets clean is the use of antifoulant paints on the mesh itself. The Fexabar Corporation has applied to the state of Maine for the registration of a waterbase antifoulant net coating called FlexGard XI. Fexabar Corporation presently has state and federal approval for its antifoulant as a bottom boat paint, and all countries selling salmon to the United States are using FlexGard XI on their net pens. The advantages of such an antifouling agent are numerous. It

offers a lower operation cost to the net pen systems due to less maintainance and cleaning. It also offers simple application, protection from sunlight, resistance to abrasion, flexibility, and long life (Flexabar Corp., 1993). However, FlexGard XI contains toxic chemicals which may cause irritation with prolonged use. The greatest disadvantage of FlexGard XI is that it is not available in the United States for legal use in aquaculture (special use permits pending).

The C-FARMS project plans to use the cleaning method based on total removal of the nets after harvest. This should be readily accomplished since the elapsed time for the total operation will be only four to six months of the year, leaving the remaining months for cage cleaning and maintainance.

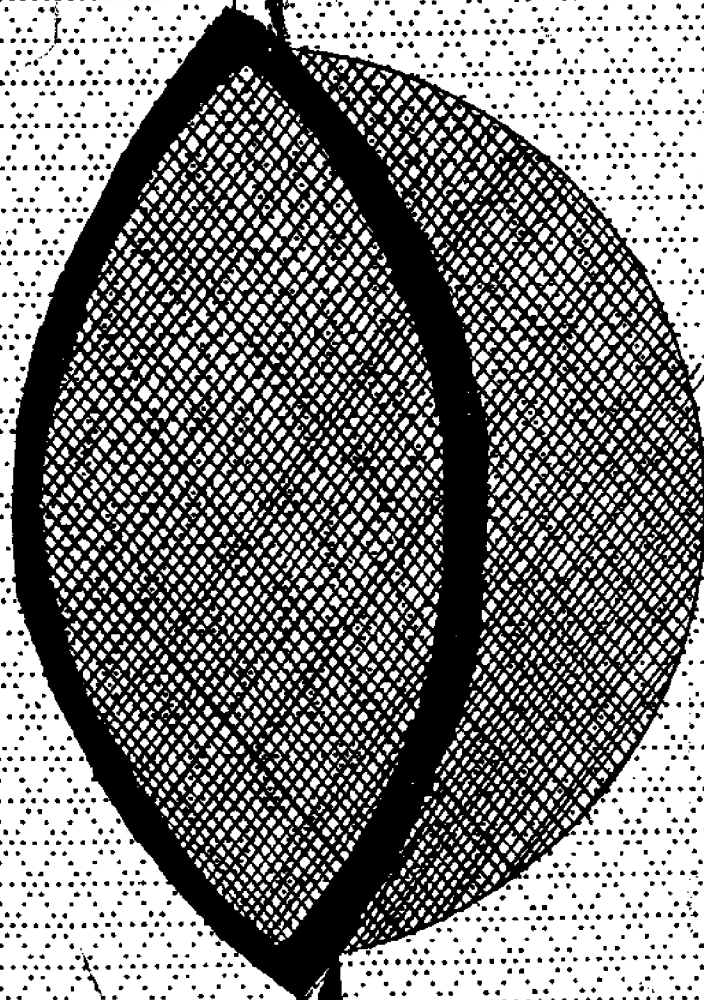
Harvesting

Harvesting is most commonly done by "fishing" the fish out by means of brailing nets or seine nets. Once the fish are removed from the pen they are usually placed in containers of sea water or brine in order to reduce their activity (Riley). The fish may also be tranquilized with a carbon dioxide solution. The harvested fish are then killed and "bled" on site, and may be packaged on site or sent away for packaging and delivery. The C-FARMS net pens will be totally harvested, i.e., all of the codfish will be taken from the pens after the four to six month grow out period. The system can be towed, therefore the fish can be transported to a desired location to be harvested and then packaged for delivery.

ALTERNATIVE DESIGNS

Five different systems were considered during the conceptual design phase therefore a final design was formulated. The first alternative considered was a ring type cage which was constructed from a continuous ring which would be moored at the surface and the netting would be weighted at the bottom to maintain its shape (see figure 2). From the information obtained from Dr. Larry Buckley, URI/NOAA Cooperative Marine Education and Research Program, Narragansett RI. it was

Bing Cage Design



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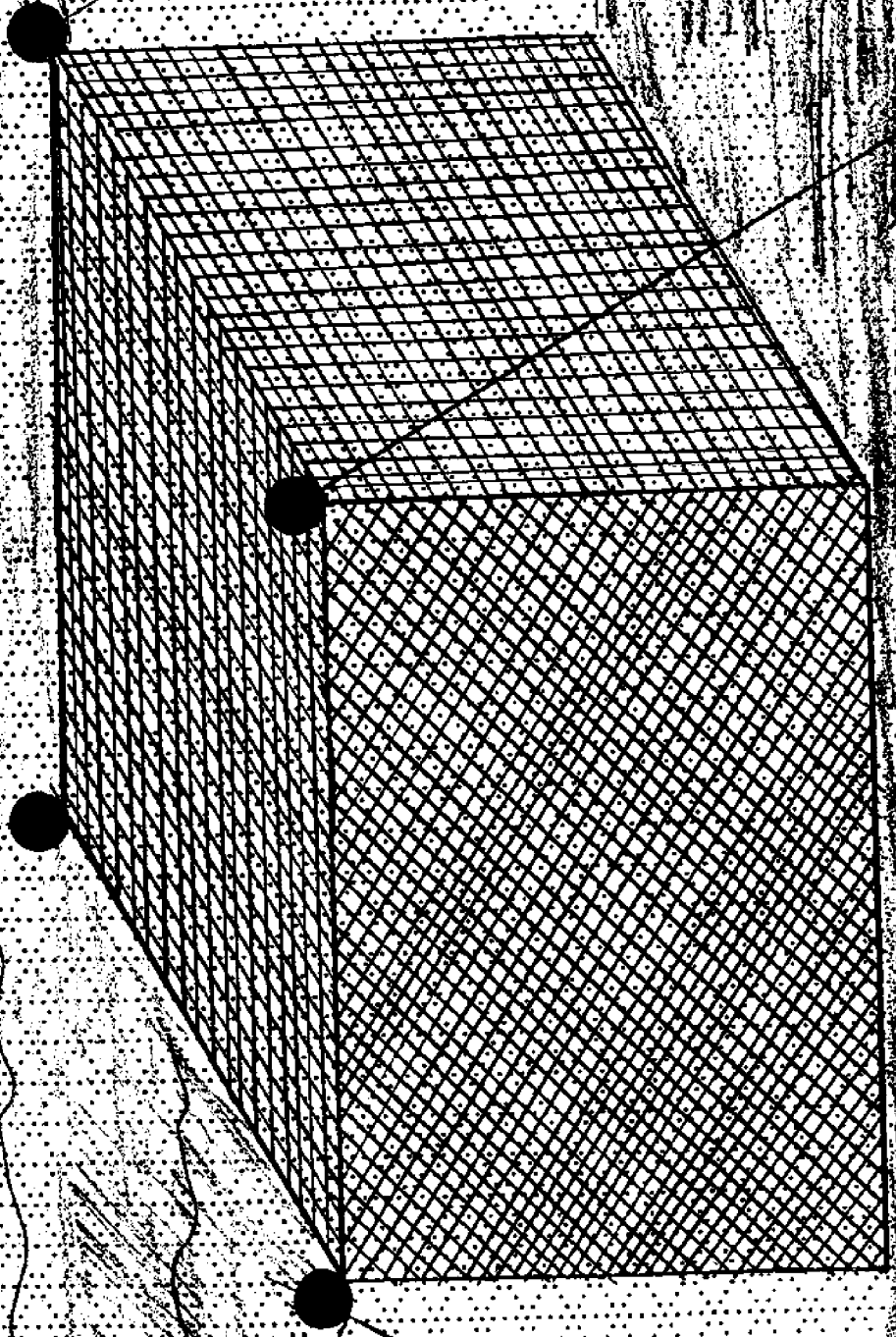
DRAWING: Conceptual Drawing

deemed extremely important that any design geometry be as circular as possible to assist in minimizing damage to the fish. The ring cage is moored at the surface which is where the largest wave forces exist. This system is undesirable because it is constantly subjected to the surface effects. Also, this consists of only a single unit which would be very difficult and expensive to manufacture and install on site because of its extremely large size to hold sufficient fish.

The second system considered was a cage which would be moored near the ocean floor (see figure 3). The most important advantage of this particular system is that the cage could be constructed of much lighter materials because it would not be subjected to the wave forces at the surface. Feeding the fish at the bottom would be possible through the use of an automatic feeder. However, from the information obtained in Eastport Maine it was deemed critical that the fish be visually monitored during feeding to maximize growth per unit of feed. A raising and lowering mechanism was incorporated into this design so that the fish could be visually monitored. Consideration of this system then terminated because of the extreme stress to which the fish would be subjected during transit up and down and because would take approximately two hours to raise and lower the cage from a depth of one hundred feet. There were additional concerns that binding of the guide wires would occur if the cage was not raised evenly raising would be difficult to control during rough surface conditions.

Another alternative considered was to fence an entire site from the ocean bottom to the surface (see figure 4). The fenced design is the most natural design because it would give the fish a normal environment with ample amount of room in which to swim. This approach has merit because it does not have a rigid structure on which the fish could be damaged. However, this design was not considered to be practical because it would be extremely expensive to net an area of ocean in one hundred or more feet of water from the bottom to the surface. Also, such a system is not as reliable as a system consisting of many smaller cages because if a hole developed in the cage, the entire fish crop investment would be lost. Because there is

Fenced Area Design



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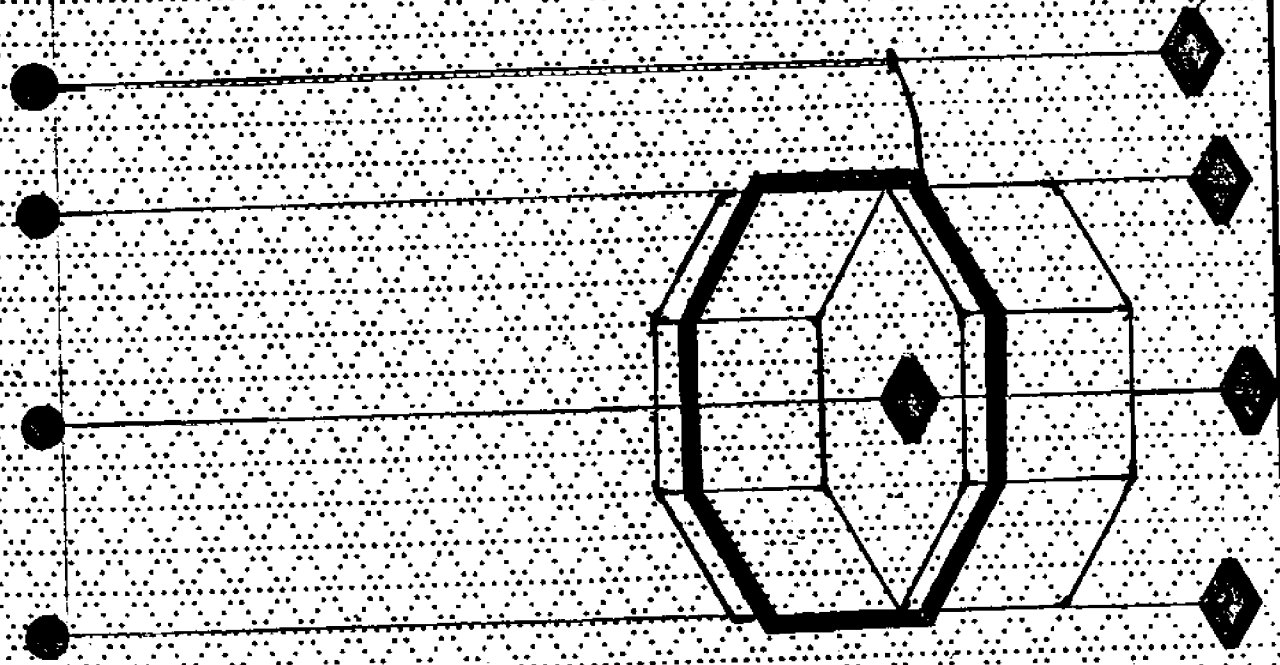
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Deep Water Design



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substantially more surface area associated with this design the drag and fouling effects needed to be considered in greater detail. Finally harvesting and grading in this type of cage are problems due to the enormous volume. Because this cage is being constructed specifically for cod which are known to be carnivorous, grading or keeping the fish separated by size is extremely important.

The spar buoy alternative which was also considered is a free-floating design with each spar moored from the side and the fence encompasses a large area (see figure 5). This particular design presents a rectangular cage which is not considered a fish friendly geometry. It is also moored at the surface where the wave forces are the largest, the spar design offers response dampening effects which put less stress on the overall system.

The last alternative calls for towing the cage to a protected area in the case of a severe storm. This particular design could be used for short term fair weather use which is of approximately six months in the Gulf of Maine. Fish would be caught in the wild and then held in the cage for short term growth and a better market price as Jonathan Moir (General Manager Sea Forest Plantation Company Ltd., Newfoundland) did in Canada. Because the cage is only being considered for short term use fouling should not be as critical problem as it is with most cage systems. The cage would be easier to clean on land during the months it will not be used. This alternative would use a single circular cage because it would be unstable during towing. Therefore a rectangular frame should be implemented to enclose two or more octagonal cages in a row which would stabilize the structure during towing. The increased loading associated with towing the cage will require it to be made out of stronger, materials than the other alternatives examined.

EVOLUTION OF GOALS

The original project goal was presented to the C-FARMS group by Professor Godfrey Savage and Professor Barbaros Celikkol in September of 1993. The original goal proposed that C-FARMS "design and build models of the three most promising

Spar Buoy Cage

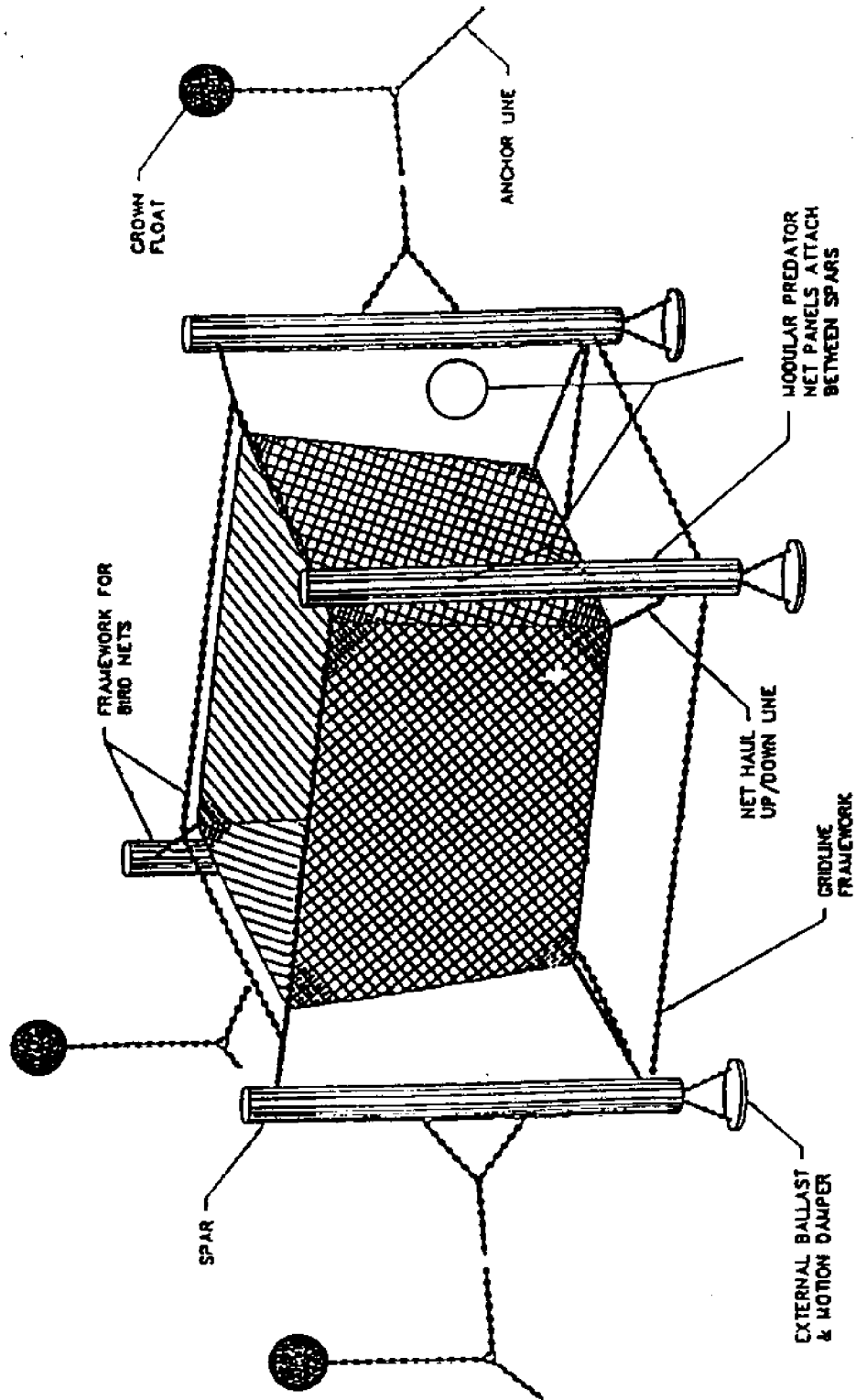


Figure 5 Conceptual Drawing

(Net Systems Inc.)

conceptualized solutions to be tank tested for recommendations for the next steps toward full scale testing of a salt water finfish cage system". The system was to be inexpensive, light in weight, easy to maintain, able to withstand *Beaufort state five seas, be capable of holding 250,000 lbs. of fish, and have an emergency system to avoid seas greater than state five. Since September, C-FARMS has altered the original project goals through information gathered from an extensive literature search, informative phone meetings, information learned at conferences and suggestions from faculty advisors. The majority of these "goal changes" stemmed from biological reasons which in effect changed the criteria for the cage design and its operation.

BIOPHASE I: Species Specificity

The net pen design criteria calling for any or all types of marketable finfish, as presented in the original goal, is simply unrealistic and unachievable. This is mainly due to the fact that the majority of marine fish families are unique in their biology (ie. morphology, physiology, habitat selection), which restricts them to unique conditions in order to survive. Therefore, the first criteria for the C-FARMS project became one of determining species specificity, and finding which species offered the most attractive commercial potential for offshore pen culture.

Eastport, Maine, the major east coast region for net pen aquaculture in the United States, has been raising Atlantic salmon, *Salmo salar*, in nearshore net pens for over ten years. Because of Eastport's success with rearing salmon and the disadvantages of being inshore, the C-FARMS project established its first goal on

* wave height of 10 ft., wave length of 220 ft., on sea state scale of one to eight designing an offshore salmon cage system which will add capacity to the Gulf of Maine's salmon proven industry. However, after an informative visit to Eastport, it was discovered that salmonid fishes possess a physostomous swim bladder morphology. This condition requires fish, such as Atlantic salmon, to make regular surface stops and "gulp" air in order to maintain buoyancy. Therefore, it was determined that salmon were not readily adaptable to an offshore-submersible cage system if at all.

Also, the Eastport salmon industry was finding itself overwhelmed by low cost foreign competition from Chile and in immediate jeopardy of "sinking" economically. Therefore, economic reasons also determined that a new species be selected for the C-FARM project. It was inevitable that, along the guidelines for a submersible cage system to be even potentially promising it had to be for fish which could withstand constant subsurface living conditions. This restricted the fish to those having physoclistous swimbladders (bladders which can be regulated by internal gas exchange), or to have no bladder at all, such as most groundfish and/or flatfish. Fish categorized as groundfish (Gadiformes ie. cod and haddock) and flatfish (ie. halibut, flounder, and plaice) have a high potential of being caged, however hatchery techniques are in early development. This causes difficulty in obtaining any available growth rates of certain species in captivity and in determining which species might be economically important candidates.

Comparisons between groundfish species and flatfish were made in order to define cage shape and general adaptability of the fish to various designs. A phone conversation with Dr. Ken Waiwood, a research biologist at St. Andrews Biological Station gave some insight into raising such fish. Dr. Waiwood works mainly with Atlantic halibut, *Hippoglossus hippoglossus*, a flatfish. Dr. Waiwood advised that cage shape is very important when considering both flatfish and groundfish. In order to maximize the volume of the cage and minimize the abrasive damage to the fish, the cages should be circular with a flat bottom. Whereas salmon tend to swim in circular motions it seems that cod exhibit non-directional milling within a water column, and flatfish will generally settle on the sides and bottoms of cages. At first it seemed that rectangular cages would be satisfactory. However, during times of high wave and current activity, the fish can be damaged due to net folding in rectangular cages; therefore corners should be avoided. The C-FARMS cage criteria called for a circular or near circular shape, and an octagon would maximize both volume and structural support (see Fig. 7).

On October 26, 1993, the University of New Hampshire hosted a cod sea

ranching conference where various topics of cod aquaculture were discussed. This conference expressed the need for more research in cod rearing and serious interest in rejuvenating cod as a major productive species in the Gulf of Maine. Up to the time of this conference, C-FARMS' goals vacillated between using halibut and/or cod as a model species. Shortly after the cod ranching conference, Professor Savage spoke with John Huegenen of the Massachusetts Maritime Academy on the telephone. In the conversation, he informed Professor Savage that halibut require a much different cage design than cod. Shortly after this conversation, the C-FARMS project selected Atlantic cod to be the single species for its consideration.

The decision to design a cage system for cod was based mainly on the growing interest within the fisheries community to enhance the culturing of cod. Atlantic cod,

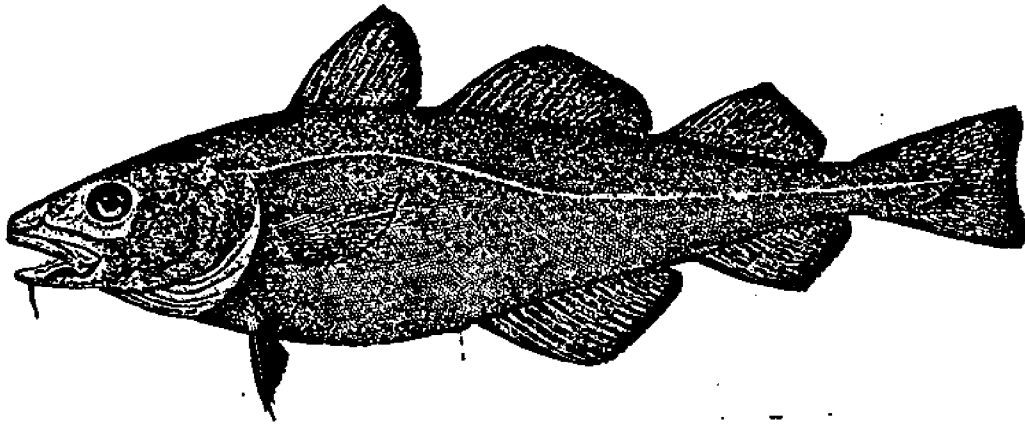


Figure 6. Atlantic cod (*Gadus morhua*), also known as codling, rock cod, scrod, Northern cod.* Average size at maturity - length = 18-24 in., weight = 4-7 lbs.* Distributed on both sides of Atlantic, from Greenland to Cape Hatteras on American coast.* (*From Rodger, 1991) Drawing by H.L. Todd, from Bigelow and Schroeder, 1970.

Gadus morhua, are also very similar to salmon with respect to size, feed preference, and temperature preference (see Fig.6). Most importantly, codfish have a physoclistous swimbladder which allows them to be submerged for extended periods of time at various depths. Therefore, C-FARMS' second goal change anticipated extensive cod research and design concepts, and evaluating a submersible, variable buoyant, offshore cod net pen. The cage system was to be placed in 150 feet of water (with a 50ft. to 100ft. operating depth). It was to be raised for feeding and cleaning regularly, and be able to withstand a Beaufort state five sea (see Fig.3).

BIOPHASE II: Cod Physiology

In order to proceed with a variable buoyancy cod net pen system a number of operational scenarios needed to be considered to maximize the benefits of the system for the fish and the fish farmers. The conceptualized C-FARMS cage at this point could either: 1) be left on the bottom for the majority of the time and raised only for harvesting and maintenance purposes or 2) be raised and lowered daily, from 150 ft., for feeding and observational purposes or 3) be left at the surface for the majority of the time and lowered for emergency storm situations. The advantages of leaving such a system on the bottom and raising and lowering on a daily schedule are that the cages are constantly below the higher wave forces of surface waters. However, a number of disadvantages to such a scenario outweigh the long term benefits. For example, pressure increases with increasing depth resulting in a decrease in water-oxygen levels. Therefore, the longer the fish are left in deep water the less oxygen they have for growth and essential swim bladder regulation. Also, visibility decreases with depth, and cod are known to be visual feeders. Furthermore, it is important for the system operator to be able to constantly view the fish for mortality, predatory effects, disease, cannibalism (cod are highly cannibalistic), and feeding needs. If the system is to remain on the bottom for the entire grow-out time, then expensive camera equipment and feeding mechanisms are needed. By raising and lowering the system daily, physiological and metabolic demands on the fish increase enormously, creating

stress and high mortality. Continual raising and lowering equals constant metabolic energy being wasted due to increased oxygen consumption. This wasted energy is then dedicated to useless swimming and buoyancy regulation instead of growth.

Raising and lowering on a daily basis can also be very time consuming. A model developed by Kanwisher and Ebeling shows that an average fish would need approximately five hours to safely descend to a depth of 150 meters (Hoar and Randall, 1970). This is based on an oxygen consumption rate of 0.4ml/hr. When a fish is descending it is using more metabolic energy, thus causing a build-up of lactic acid in the blood and muscle tissue. This acidification causes a fast transition of oxygen bound to hemoglobin to free itself in order to inflate the swim bladder. This phenomenon is termed the root-off shift. When ascending there is a decrease in venous pressure and less acidification (lower pH), therefore it takes longer for swim bladder oxygen to bind to hemoglobin. This is termed the root-on shift. The root-on shift is approximately twice the amount of time as the root-off shift. Therefore, lowering the fish would take less time than raising them. C-FARMS has estimated a lowering time of roughly one to two hours to a depth of 150 ft.

These findings mean the net pen be left at the surface and only lowered in case of emergencies. The advantages presented are several. Pressure at the surface is negligible; therefore it is easier for the fish to obtain neutral buoyancy. Also, the fish would experience photic warming and better visibility from being in surface waters where light can penetrate. Leaving the system on the surface also benefits the operator in that it is less time consuming than raising and lowering the cages every day. Finally, the fish farmer can rely on proven techniques of feeding and monitoring by being able to constantly assess damages and mortality. Lastly, the probable rate of fish growth to a harvestable size is much faster because the growing conditions can be controlled by simple means.

Final Goal

The final goal of building a shallow-submerged offshore cod cage was decided

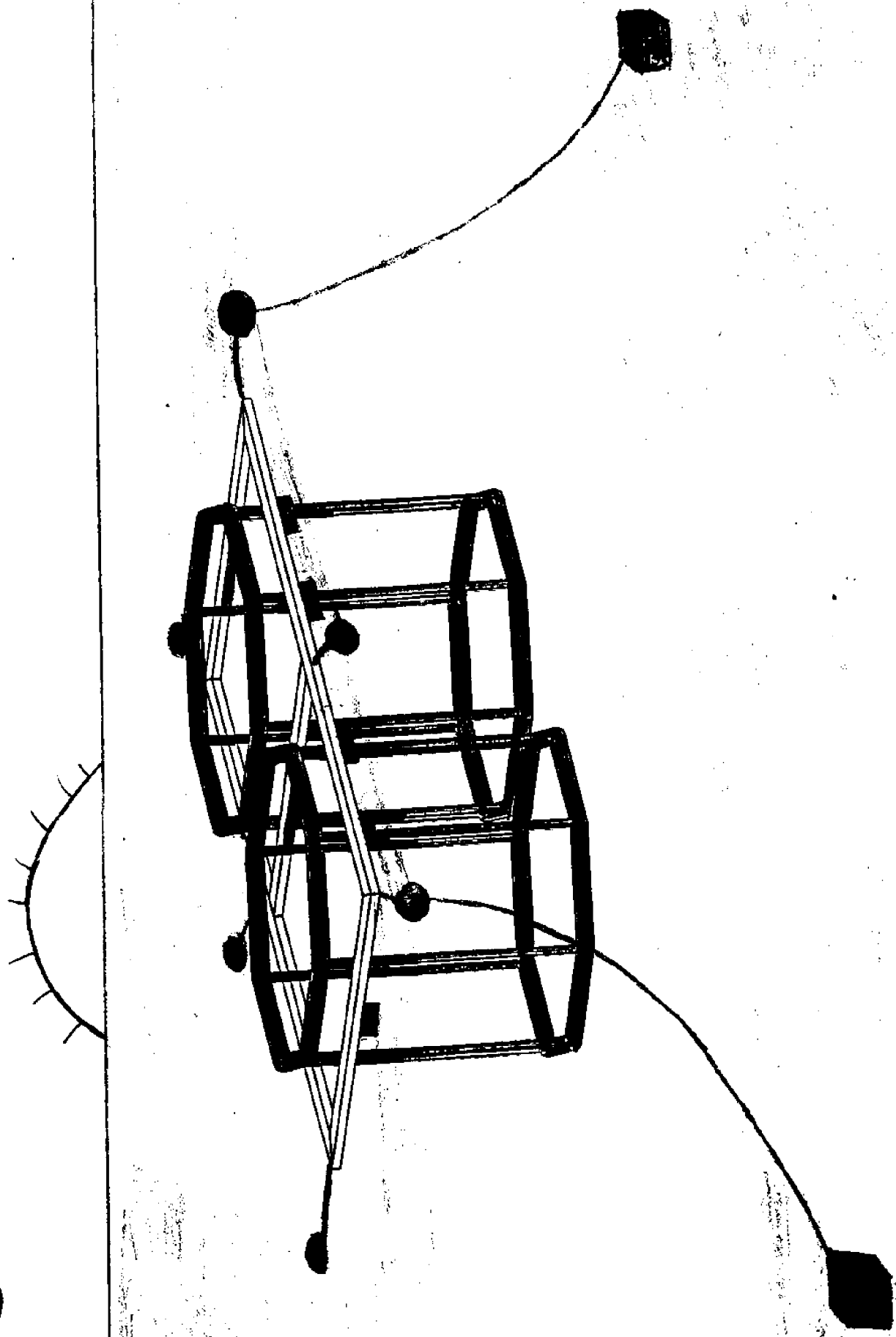
by the C-FARMS team after Professor Savage and Professor Celikkol returned from attending a mariculture conference in Newport, Rhode Island on February 10, 1994. It was reported by Dr. Savage et. al., that Jonathan Moir, the general manager of Sea Forest Plantation Company Ltd., Newfoundland, had obtained large scale test results of raising cod from 1 1/2 lbs. to 4-6 lbs. in a four to five month period. The system Jonathan Moir created was a towed surface cage that held high densities of cod. The fish were fed blocks of frozen herring to satiation every 24-48 hours. Jonathan Moir is currently working on a management framework for rural-based production of cod from cod farms to offset the catastrophic fisheries unemployment in Newfoundland.

C-FARMS has based its final goal and criteria on results of Jonathan Moir's outstanding cod growth rates. The system consists of two octagonal cages placed in a large rectangular framework for towability. The cages and framework will be moored in approximately 100 feet of water and submerged only ten feet below the surface. This shallow submersion allows for some reduction in wave forces and a compensation for the fishes' physiological needs. The system can be released from the moorings for quick and easy tow to shelter. The C-FARMS system will be able to hold 50,000 lbs. of fish and will only be operated from April to early September. The rest of the year, the cage will be available for maintenance for the next year's crop.

Final Solution

The design of the final solution incorporates positive aspects from each alternative considered, and consists of two octagonal cages attached to a wooden frame. (See Fig. 7). It will be possible to submerge the cages ten feet below the surface by using a ballast system. The cages will be lowered on a daily basis so that they will be kept out of the maximum surface wave actions. In the event that a storm is forecast, the cages can be towed to protected water. Each cage will be forty-eight feet between opposite sides and twenty feet deep. These dimensions allow for 33,000 pounds of fish per cage.

The cages are octagonal in shape to be compatible with the swim patterns of



the fish. Fish tend to swim in circular patterns. To protect the fish from doing physical damage to themselves by hitting the side of the cage, ninety degree angles and sharp corners were avoided. An octagonal cage was chosen over a circular cage when construction was considered. It was determined that forming circular rings for the top and bottom of the cage would be difficult and would require welding the ends of the frame material together. Construction would be easier for an octagonal cage rather than a circular cage because the fittings required for all joints are off the shelf.

The cages will be made out of two inch steel pipe. Pipe was chosen for the cages because it is cylindrical and creates less drag than angle or channel. The stress analysis performed on the cage at the surface under maximum wave forces yielded the results that steel pipe with a nominal diameter of two inches and a wall thickness of 1/4 inch would provide a factor of safety of 2.5.

The need for the cages to be towable led to the wooden frame idea. Towing a single octagonal cage would create yawing problems under tow due to drag. These problems would make towing the cage difficult and slow. The wooden frame will create the stability needed for towing by not allowing the cages to twist, and the rectangular shape would inhibit yaw. The wooden frame is also beneficial because it serves to decouple the cages from the effects of waves. The cages will be attached to the frame using chain; this allows the cages to move relative to the frame. Tires will be placed between the cages and the frame to absorb any shock loads. The wooden frame will also serve as a walkway around the cage and as a mount for the ballast tanks. The frame will be attached three feet below the top of the cage so that when at the surface, the cage itself will act as a railing. The wooden frame will be three feet wide, six inches thick, and it will be made from white oak. White oak will be used because it has the highest working stress when compared with other structural grade timber and it is very resistant to decay (Forest Products Laboratory, 1990).

The ballast system consists of fifty-five gallon plastic float drums as ballast tanks and air lines from the surface to the tanks. Each tank will have holes at the lowest point so that when air is blown in, water is forced out the bottom and the cages

will rise to the surface. To release the air and submerge the cage, the air valve at the top will be opened. All lines to the surface will be attached to an anchor buoy so that a service boat will have easy access to them, and the buoy will have a locking mechanism to deter vandalism. This method of raising and lowering requires that the service boat be equipped with an air compressor.

The mooring system consists of Norwegian type plastic mooring balls that are three feet in diameter anchored with one ton mooring blocks and chain. At each corner of the wooden frame, there are 1 1/2 inch rope lines from the wooden frame to mooring balls. From the mooring ball, there is 170 feet of line connected to fifty feet of 3/4 inch chain which is then connected to the mooring blocks. This set-up allows for the balls to be ten feet away from the cage when it is at the surface, and the balls will slide over and be directly over the cage when it is submerged. When the cage is submerged, the mooring balls will act as a means of keeping the system from submerging past the ten foot depth. Two more mooring balls are added in the middle of the frame to ensure this. The two mooring balls connected in the middle are only attached to the frame by ten feet of the line; they are not moored. The system will only be slightly less than neutrally buoyant so that the load on the mooring balls will be minimal when the cage is submerged.

Mesh size and material are important aspects when choosing a net and are a choice to be made by the operator of the fish farm. Smaller mesh nets retain smaller fish which when purchased from hatcheries are less expensive and easier to handle than larger fish. However, nets with a smaller mesh are more expensive and have a tendency to be fouled by organic matter quicker than larger sized mesh. Larger sized mesh is lighter, less expensive, and has a lower tendency to foul due to better circulation. In Maine, mesh sizes for smolt salmon tends to be 1 1/8" in diameter whereas mesh sizes for market size fish are 2 1/4" in diameter (Riley). The mesh used for the force calculations in this report was 1" polypropelene, which is a conservative estimate.

Dynamic Force Analysis

The total force on the C-FARMS cage design due to the dynamics of the ocean environment was determined using Morison's equation (Dean and Dalrymple), which makes the assumption that the cage remains fixed in space and does not respond to the wave action. This equation was developed to determine the total force on a vertical pile.

$$dF = \frac{1}{2} C_D \rho A u |u| + C_M \rho V \frac{Du}{Dt}$$

where:

- C_D = coefficient of drag
- ρ = density of salt water
- A = cross-sectional area perpendicular to flow
- u = horizontal velocity of water particles
- C_M = coefficient of inertia
- V = volume of object

Substituting the equations for u and the derivative of u with respect to time:

$$u = \frac{H}{2} \sigma \frac{\cosh k(h+z)}{\sinh kh} \cos(kx - \sigma t)$$

$$\frac{Du}{Dt} = \frac{H}{2} \sigma^2 \frac{\cosh k(h+z)}{\sinh kh} \sin(kx - \sigma t)$$

where:

- H = height of waves
- σ = angular frequency of the waves
- k = wave number
- h = depth of water
- z = distance from still water level to point under consideration
- x = reference distance
- t = reference time

the equation then becomes:

$$F = \frac{1}{2} C_D \rho \int_{-20}^0 \frac{h^2}{4} \sigma^2 \frac{\cosh^2 k(h+z)}{\sinh^2 kh} \cos(kx - \sigma t) \cos(kx - \sigma t) dz + C_m \rho A \int_{-20}^0 \frac{h}{2} \sigma^2 \frac{\cosh k(h+z)}{\sinh kh} \sin(kx - \sigma t) dz$$

integrating:

$$F = \frac{C_D \rho H^2 \sigma^2}{8 \sinh^2 kh} \cos^2(kx - \sigma t) \left[\frac{\sinh 2kh - \sinh 2k(h-20)}{4k} - \frac{-20}{2} \right] + \frac{C_m \rho A H \sigma^2}{2 \sinh kh} \sin(kx - \sigma t) \left[\frac{\sinh kh - \sinh k(h-20)}{k} \right]$$

This equation is adapted to the case of a floating cage by integrating from the surface ($z=0$) to the bottom of the cage ($z = -20$). Using Morison's equation in the case of a floating cage makes the assumption that the cage does not respond to the wave action. This assumption is justified because the worst case during Beaufort state 5 sea conditions was being analyzed. The worst case occurs when the mooring is pulled tight which would result in the cage not responding to the wave.

The pile examined using Morison's equation was cylindrical (Dean and Dalrymple). To determine the projected area, the diameter was integrated over the depth of the pile. Since the C-FARMS cage surface is far more complex than the pile, the structure and net are modeled by assuming each piece is a separate cylinder. The net twine is approximated by small cylinders that are either horizontal or vertical. Since it is one inch mesh net, there are twelve strands in each foot; ie, in one square foot there would be 24 one-foot-long strands. With this approach, the dimension that is integrated in the drag portion of Morison's equation is the projected area per unit depth. Thus the result will be the projected area of the component cylinders. Similarly the dimension that is integrated in the inertial portion of the force equation is the volume per unit depth yielding the total volume of the component cylinders. The projected area of the cage consists of all of the cylinders perpendicular to the flow. The cylinders that are behind the front face of cylinders are included in both the area and volume calculations. This produces a conservative total force estimate since the cylinders behind will actually experience a lower velocity and thus produce less drag.

The drag component of the force involves a cosine function and the inertial component involves a sine function. Therefore, the maximum drag and maximum inertial forces do not occur at the same time; they are 90° out of phase. In order to determine the maximum combination of drag and inertial forces, the derivative of the total force was taken with respect to the argument (kx_{i-st}). The maximum force occurred at cosine = 0.985.

In addition to the force calculated from applying Morison's equation, the drag force due to a one half knot current is added because there is often a current of this magnitude in the open ocean; i.e. tides. The total force calculated is then 26,144 lb.

The mooring system must be able to withstand half of the total force as there are four mooring points arranged as shown in the figure below, and at any point in time two of the four will be under tension while the others are slack. (see Figure 8 - following page) This translates to 13,072 lb. of horizontal holding strength for each mooring. Trigonometry was used to determine the necessary weight for each mooring to produce this force. The mooring line was assumed to be at 30° with respect to horizontal, thus the weight necessary to prevent "walking" is 4.5 tons. To provide a factor of safety, 5 tons of dead weight are used for each mooring.

When the cage is in the towing mode at 4 knots, the short side is the one which is subjected to the current. The force on the cage in this situation was estimated by adding the drag force due to the additional velocity of the water relative to the cage, 4.5 knots, to the force calculated for the moored cage. The resulting drag force produced by the increased relative velocity of the water is 92,344 lb.

Mechanics of solids is used to determine if the cage will withstand the forces to which it is subjected. The total force on the object was divided by the number of 20 foot sections that will be subjected to it to estimate the equivalent uniform load on one 20 foot section of steel. The section was assumed to be a fixed-fixed beam with a uniform load applied to it. This is a very conservative estimate because the joints which hold the section of steel fixed will actually "give" under the loading which will result in a lower stress on the steel section.

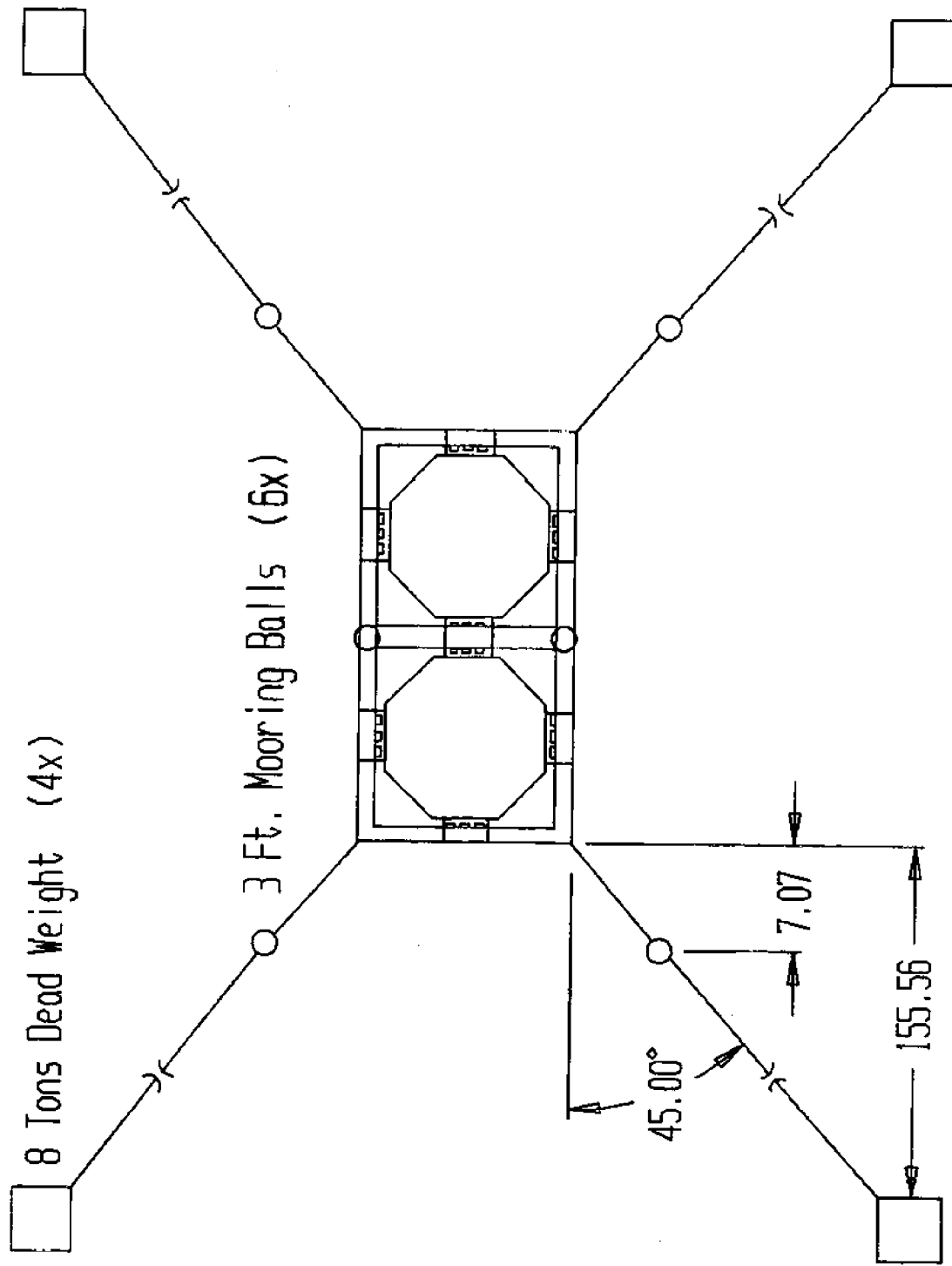
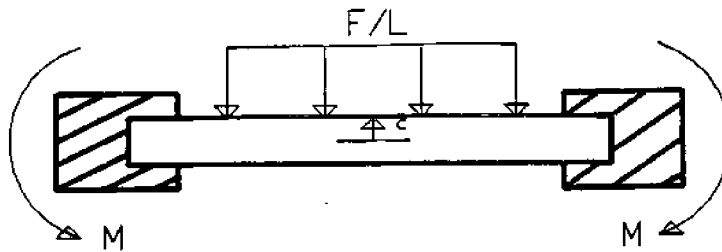


Figure 8: Mooring Top View Dimensions in Feet



The bending stress on the beam is then

$$\sigma = \frac{Mc}{I}$$

where: $M = FL/2$

$c =$ distance from neutral axis to fiber under consideration

$$I = \frac{\pi (d_o^4 - d_i^4)}{24}$$

The maximum tensile stress on any one member of the cage is only 4727 psi in the stationary case and 16,650 psi when in the towing process. Both of these stress levels are far below the yield strength of commercial steel which is 45,000 psi.

The shear stress on the 20 foot section is determined using

$$\tau = \frac{4V}{3\pi(r_o^2 - r_i^2)} \frac{r_o^2 + r_i r_o + r_i^2}{r_o^2 + r_i^2}$$

where: $V = F/2$

$r_o = 1$ inch

$r_i = 0.75$ inches

The maximum shear stress on one member of the cage is 1696 psi while stationary and 7,555 psi while being towed at four knots. The shear strength of commercial steel is 11,000 psi and therefore neither situation causes the steel to yield plastically.

This method of force analysis provides quantitative design criteria with which alternative cage materials can be chosen properly. The general form of this analysis

C-FARMS

can be used for an alternative design provided that the design can be broken down into component cylinders.

Static Force Analysis:

The static force balance is between the weight of the C-FARMS cage in water and the bouyancy force of the ballast tanks. The weight of the ballast tanks is neglected because it is small compared to the total weight of the cage. The following table lists the most significant quantities in the static force analysis.

Material	Volume (ft ³)	Weight Density (lb _f /ft ³)	Weight on land (lb _f)	Net Weight in water (lb _f) ¹
Steel	10.3	490	5051	4392
Wood	525	60 ²	31,500	-2100
Net	13.1	50 ³	655	-183.4

¹ accounts for the bouyant force created by the material's displacement of water

² 20% increase from dry weight density to account for water absorption

³ 150% increase from dry weight density to account for fouling

The net weight of the cage in water is 2108 lb_f, which means that five 55 gallon ballast tanks are necessary to raise the cage. As a safety factor, it was assumed that only half of the water in each tank will be blown out, doubling the number of tanks necessary. In order to keep the ballast tank layout symmetric, eleven tanks were used. (see Figure 9 - following page)

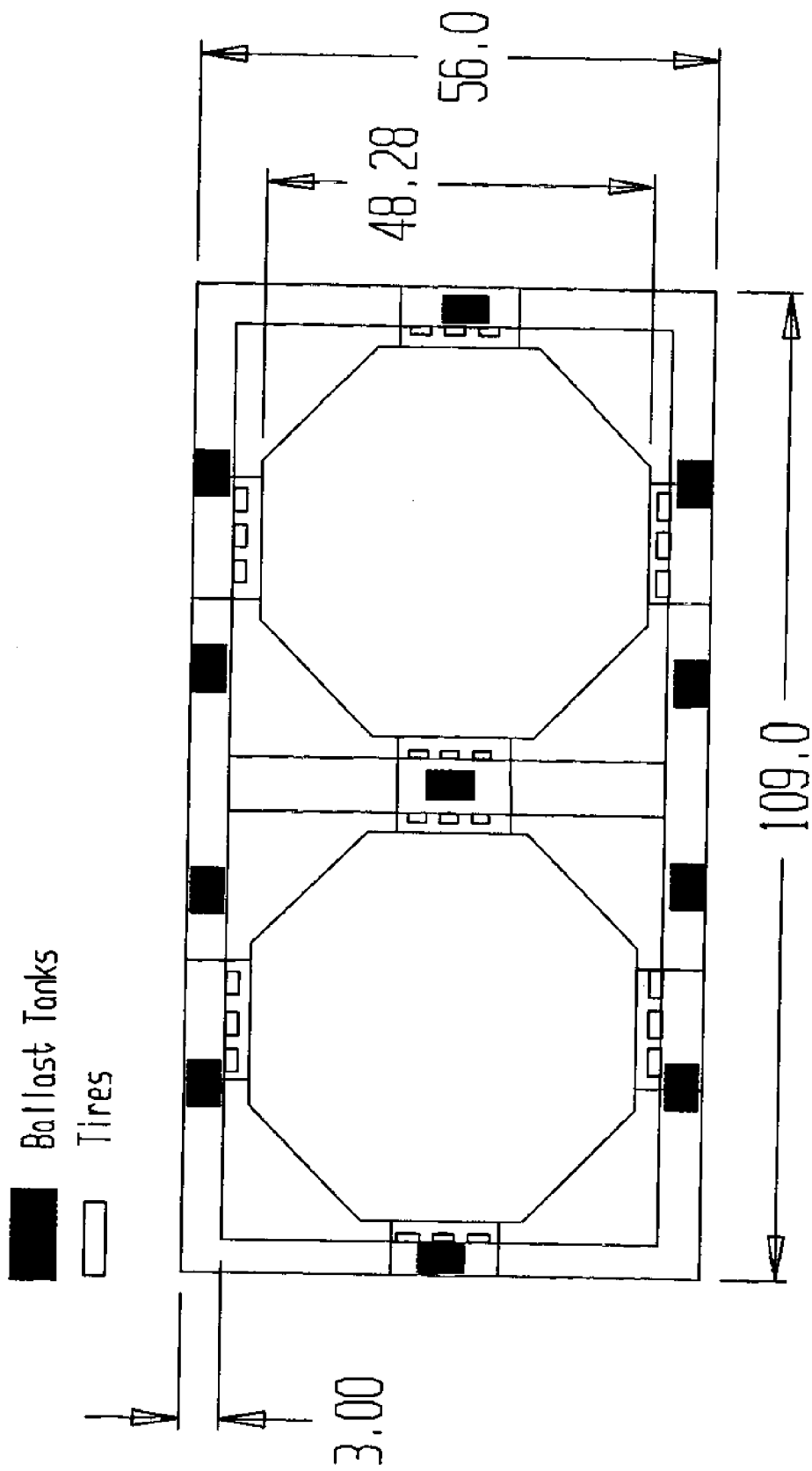


Figure 9: Ballast System Configuration Dimensions in Feet

Testing

The Model

The test model is 1/12.5 scale which makes it an even 8 feet long, 4 feet wide, and 1.6 feet deep. The steel was replaced by copper because steel pipe was not available in the necessary scaled dimensions (3/16" outer diameter). Copper pipe with a 3/8" outer diameter was used because it was readily available, easy to form into the shape of the cage, and, due to its larger size, more comparable to the weight of the smaller diameter steel. Pine wood was used instead of white oak because the densities are comparable and it was readily available in the scaled size needed. Common fiberglass screen was used to represent polypropylene net because the mesh sizes were comparable to the scale of the model.

The ballast system was simplified in order to avoid a custom order of expensive parts. The system consisted of eight toilet floats, home aquarium type air lines and manifolds, epoxy, and rubber stoppers. The toilet floats represent the 55 gallon drums. The hand-operated rubber stoppers were used to represent a complicated pneumatic valve system that would simultaneously open a valve on each ballast tank to release the air. The manifolds split the air supply into eight equal lines which go to each of the tanks.

Test Method and Results

The raising and lowering system was tested in the University pool two separate times. In the first test the model surfaced as planned, but it would not sink again because the air did not leave the ballast tanks. The apparent reason was that the small diameter air line presented too much resistance to flow. This problem was solved by drilling an additional hole at the top of each ballast tank and plugging it with a rubber stopper. During the second test the rubber stoppers were removed to begin the lowering process. Once the cage started to sink the rubber stoppers were replaced and the cage sunk. To raise the cage the compressor was attached to the main air line and turned on. The resurfacing process was rapid and smooth.

Conclusions / Recommendations

Economic Feasibility

The technical/economic feasibility of fish farming cannot be assessed until certain questions are answered:

- 1) What is the source of the fish?
- 2) What is the size of the source fish?
- 3) What percent will survive to maturity and remain in the cage?
- 4) How much and how often are the fish going to be fed?

There are two possible sources of fish - hatcheries and the ocean. If the fish are bought from hatcheries, the next logical question is how much they will cost. There is no answer to this question at the present because cod are not yet being grown in hatcheries. If the fish are to be taken from the ocean, then standards must be set governing the legal catch size and the share of the farmer's yield of mature cod which would be taken to restock the ocean.

The size of the source fish will have a determining impact on the economic feasibility of fish farming. It will take less time to grow the cod to market size if they can be bought from the hatchery at a larger size, but it would cost more to get the larger fish. On the other hand, although smaller fish cost less at the hatchery, they take longer to grow to market size.

The percentage of the initial fish which survive and remain in the cage until maturity directly relates to the return on investment of the fishing process. Obviously, if the farmer has a higher percentage of the fish he started with when it comes time to sell them, he will make more money. The amount of food that the fish are fed is nearly proportional to their growth so this also has a direct effect on the profit of the farmer. Therefore they can be fed less over a longer period of time or fed more over a shorter period to yield the same results.

Technical Feasibility

Developing a full-scale system that employs a ballast system seems to be technically feasible. Judging from the pool tests of the scale model, it appears that it

will be relatively simple to raise and lower a full-scale system simply, evenly, and quickly. The towing process for a large group of C-FARMS cages would be a complicated and time-consuming affair, but during the months of operation there will seldom be a storm that will require this process. In light of the fact that other offshore fish cages have been wrecked or lost their stock during storms, the towing process is not such a bad alternative.

Continuation of the Project

The first step for the continuation of this project should be to make a larger scale model capable of supporting 500 or more cod and test it for a few months in the open ocean, possibly off the Isles of Shoals. This test would realistically demonstrate the cage's performance in the actual environment for which it was designed, thus providing invaluable feedback on possible improvements to the design. It would also verify Jonathan Moir's growth and feeding claims for cod in cages, claims which have not been formerly documented or published in judged journals. Such growing test verification is absolutely essential before further investment is made in this approach to net pen aquaculture of cod.

Acknowledgements

We would like to thank the following people for showing special interest and for their assistance in the C-FARMS project: Professor Jeff Savage, Professor Barbaros Celikkol, John Pavlos, Ann Bucklin, Paul Lavoie, Dr W. Hunting Howell, Chris Bartlett, Dr. Larry Harris, Professor Gerry Sedor, Langley Gace, Tim Panagos, Roland Barnaby, Professor M. Robinson Swift, and Frank the salmon farmer from Eastport, Maine.

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Willinsky, Michael D. and Michael A. Champ. "Offshore Fish Farming: Reversing the Oceanic Dustbowl.", Sea Technology. August 1993.

C-FARMS

Appendix

C-FARMS

Constants:

$$\rho = 1.99 \text{ slugs/ft}^3$$

$$\text{length} = 83.35 \text{ ft}$$

$$A = 33.98 \text{ ft}^2$$

$$H = 10 \text{ ft}$$

$$k = 0.0285 \text{ ft}^{-1}$$

$$h = 110 \text{ ft}$$

$$\sigma = 0.9663$$

$$C_d = 1.2$$

$$C_m = 2.0$$

DECISION MATRIX: MOORING

CRITERIA	WEIGHT (1-5)	HORIZONTAL MOORING METHOD		VERTICAL MOORING METHOD			
		ALTERNATIVE 1 BOTTOM CRADLE	ALTERNATIVE 2 GUIDE WIRES	ALTERNATIVE 1 DEAD WEIGHTS	ALTERNATIVE 2 AUGERS	ALTERNATIVE 3 DANFORTH ANCHOR	ALTERNATIVE 4 MUSHROOM ANCHOR
MAXIMUM LOAD	4	12	12	16	16	16	8
SIMPLICITY	3	12	12	15	12	6	9
RELIABILITY	5	20	20	25	20	15	10
INSTALLATION	2	2	8	10	2	4	6
ADAPTABLE TO DIFF. BOTTOM SURFACES	3	6	12	15	6	9	9
PRACTICALITY	3	9	12	15	12	9	9
COST	4	4	16	20	8	16	16
TOTAL		65	92	116	76	75	67

ALTERNATIVES RATED ON A SCALE OF 1 TO 5 (5 = BEST) THEN MULTIPLIED BY THE WEIGHT FACTOR.

Decision Matrix: Cage Shape

Criteria	Weight (1 - 5)	Alternative 1		Alternative 2		Alternative 3		Alternative 4		Alternative 5		Alternative 6		Alternative 7	
		Octagonal	Vertical	Cylindrical	Vertical	Cylindrical	Horizontal	Spherical	Conical	Cubical	Pyramidal				
Dynamic Load Effects	4		12		12		12		16		12		12		12
Damage to Fish	5		15		20		15		25		10		10		5
Chance of Losses	5		20		15		15		15		15		20		15
Fouling	2		8		8		6		10		8		4		4
Adaptable for Diff. Fish	1		4		4		2		2		1		4		3
Build in Sections	2		8		6		6		4		4		8		6
Installation/ Transportation	2		10		4		4		4		2		8		8
Access For Harvesting	3		15		15		6		6		9		15		6
Net Installation	2		8		4		4		2		4		8		8
Cost	5		20		15		15		10		15		20		20
TOTAL			120		103		85		90		84		109		87

Alternatives rated on a 1 to 5 scale (5 = best) then multiplied by the weight factor.

DECISION MATRIX: RAISING AND LOWERING

CRITERIA	WEIGHT (1-5)	ALTERNATIVE 1	ALTERNATIVE 2	ALTERNATIVE 3	ALTERNATIVE 4	ALTERNATIVE 5	ALTERNATIVE 6
		POSITIVELY BOUYANT AND EXT. BALLAST	BALLAST TANK 2 WEIGHTS	BALLAST ONLY	DEAD WEIGHT MOORING	REMOVE WEIGHTS FROM WALKWAY	REMOVEDLY CONTROLLED WINCH
RELIABILITY	5	15	15	20	25	25	15
EQUIPMENT REQ'D	2	6	6	8	10	8	4
SIMPLICITY	2	4	6	8	10	10	2
ENTANGLEMENT	5	15	10	15	20	20	15
MIN. USE OF PULLEY	4	4	8	20	20	20	8
SURFACE EFFECTS	4	12	12	16	8	8	16
ABILITY TO MOVE TO BOTTOM	3	15	9	15	9	12	15
PRACTICALITY	4	12	8	20	16	8	8
TOTAL		83	74	122	118	111	83

ALTERNATIVES RATED ON A 1 TO 5 SCALE (5 = BEST) THEN MULTIPLIED BY THE WEIGHT FACTOR.

Mooring Lines & Chain

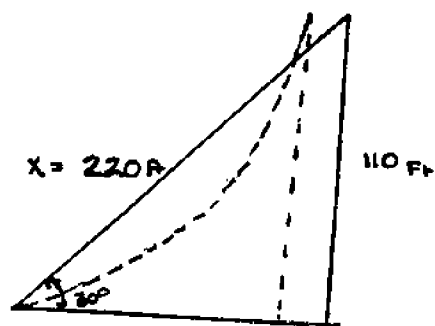
Each mooring will have the following

Chain = $6 \frac{1}{4}$ lb/Ft

Rope = $.45$ lb/Ft

170 Ft rope + 50 Ft chain

$$(170)(.45) + 50(6.25) = 389 \text{ lb}$$

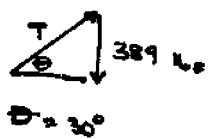


$$B = 190 \text{ Ft}$$

$$B = \frac{110 \text{ Ft}}{\tan 30^\circ} = 190 \text{ Ft}$$

$$X = \frac{110}{\sin 30^\circ} = 220 \text{ Ft}$$

Side View



$$T = \frac{389}{\sin 30^\circ}$$

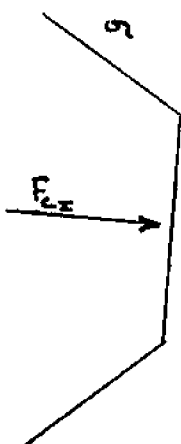
$$T = 780 \text{ lb}$$

Top View or Surface View



$$F_{\text{on cage}} = 780 \text{ lb} \cos 45^\circ = 550 \text{ lb}$$

$$550$$



$$F_{\text{on cage}} = 1100 \text{ lb}$$

Total

1100 lb is the force on the cage that is required to make mooring lines become taut.

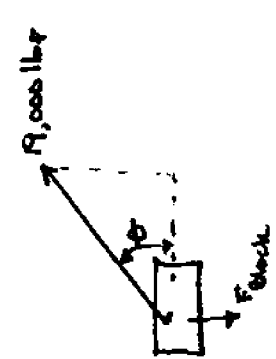


Forces

$$\frac{13,072}{\cos 45^\circ} = F_{\text{Tension}}$$

$$F_{\text{Tension}} = 19,000 \text{ lbf}$$

Side View



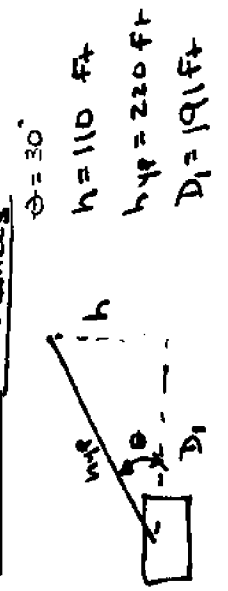
Forces

$$F_{\text{Block}} = \text{Sine}(19000 \text{ lbf})$$

$$F_{\text{Block}} = 9,000 \text{ lbf}$$

$$\theta = 30^\circ$$

Side View Distances

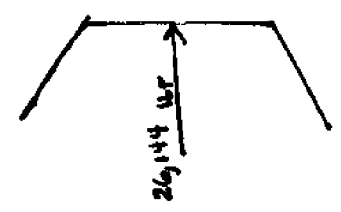
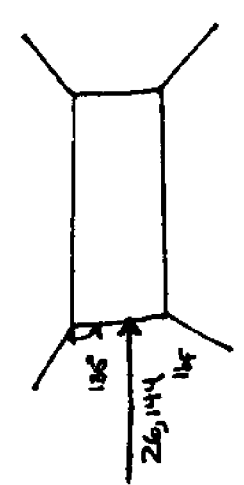


$$\theta = 30^\circ$$

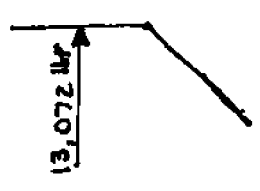
$$h = 110 \text{ ft}$$

$$w = 220 \text{ ft}$$

$$D_1 = 191 \text{ ft}$$



Using Symbology



Mooring Balls

Assume $\frac{1}{2}$ mooring ball out of water



$$V = \frac{4}{3} \pi r^3$$

$$\frac{1}{2} V = \frac{1}{2} \left(\frac{4}{3} \pi (1.5)^3 \right) = 7.06 \text{ Ft}^3$$

$$(7.06 \text{ Ft}^3) \left(64 \frac{\text{lb}}{\text{Ft}^3} \right) = 450 \text{ lbf for each ball}$$

Total buoyancy of mooring ball w/ 3ft Diameter below the surface

$$F_{\text{buoy}} = 905 \text{ lbf}$$

$$F_B - F_{\text{lines}} = 905 - 389 = 516 \text{ lbf}$$

Assuming 4 balls the displacement of the cage when lowering is

$$4(516) = 2063 \text{ lbf which is max force that can be applied at the surface using 4 3ft mooring balls}$$

Assuming 6 balls

6 = 4 with mooring lines + 2 as markers

$$4(516) + 2(905) = 3874 \text{ lbf}$$

Price Breakdown

	<u>Unit Cost</u>	<u># Units</u>	<u>Total Cost</u>
<u>Cage</u>			
2" O.D. Steel Pipe	\$ 6.15/ft	1120	\$ 6888.00
3-way 45° Joints	21.44/jt	32	686.00
T Joints	21.44/jt	16	343.00
<u>Wooden Frame</u>			
White Oak	28.20/beam	210	5922.00
<u>Net</u>			
1" Mesh Polypropylene			2352.00
<u>Mooring</u>			
3' Mooring Balls	145.00/ball	6	870.00
1 Ton Mooring Blocks	27.00/block	20	540.00
3/4" Chain	5.90/ft	200	1180.00
1 1/2" Nylon Rope	2.30/ft	720	1656.00
<u>Miscellaneous Hardware</u>			500.00
<u>TOTAL COST</u>			\$ 20,937.00

Dean F. Shre
Michael D. Shaw
Evan G. Spack
John Spaulding



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