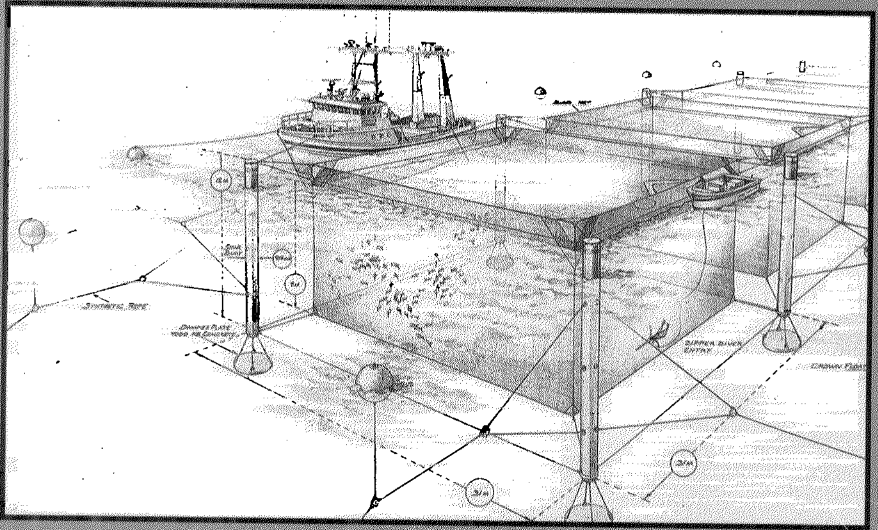
Open Ocean Aquaculture '97

Charting the Future of Ocean Farming



Proceedings of an International Conference

April 23-25, 1997

Maui, Hawaii

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Proceedings Editor, Charles E. Helsley

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Introduction

Open Ocean Aquaculture Conference Summary, Commentary, and Thoughts for the Future

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Summary

The transition to a sustainable global economy that has minimal impact on the global environment is a major challenge for all governments. Adequate food production is a crucial component in this endeavor. Developments in land agriculture have produced enormous gains in food production per unit area in the past five decades. However, this growth cannot be maintained into the future for production is now essentially limited by availability of suitable land and water.

Consequently, we must turn to the sea for our future additions to the food supply. Recent evidence of severe stress in many fisheries suggests that they already are being exploited at or beyond their sustainable capacity. Therefore, we must now apply agricultural practices learned on land to the utilization of the ocean. Cultivation, through open ocean aquaculture rather than simply continuing to harvest wild stocks, appears to be the way of the future.

Great strides have been made in the technology of marine aquaculture in the past decade. It is now possible to produce many species of fish in intensive culture systems at costs that are comparable to, or substantially below, those necessary for the harvesting of wild stocks. The Second International Open Ocean Aquaculture Conference, held on Maui, Hawaii, from which the papers for this volume are derived, addressed a number of key issues that need to be resolved before our move to fully utilize the oceans can take place. This paper, and those following in this volume, are a summary of some of the key issues addressed during the conference.

Introduction

Many fisheries have declined precipitously over the last 20 years. Japan's reported catches from their marine fisheries conducted around the world have declined more than 30% in the last 10 years (MAFF, 1995). In the northeast United States the National Marine Fisheries Service has systematically documented a downward trend in the size of many populations of the principal groundfish species over the last 30 years (NMFS, 1993). In response to these alarming declines, fishery managers have implemented strategies from restricting fishing efforts to outright closure of major fisheries and fishing grounds (e.g., Georges Bank). Although the long-term result of these measures should be recovery of some stocks, many fisheries may never attain their former levels of yield or, at best, will take many years to do so.

As international and domestic fishery landings are declining, demand for fishery products is increasing. In the United States consumption of seafood is about 15 pounds per person per year and, in Hawaii, with the highest per capita consumption of seafood in the country, it is today more than 45 pounds per person per year. The Hawaiian situation is extreme in another way, for despite our mid-ocean location, more than 75% of this seafood being imported. The net result in Hawaii and the rest of the U.S. is a situation of increasing demand coupled with decreasing supply of seafood. Without some positive action the ultimate result will be (1) further imbalance in trade deficits, (2) a loss in economic opportunities for commercial harvesters and processors, (3) a decline in the traditional lifestyles that are central to many fisheries, and (4) declines in the abundance of target species leading to shifts in species dominance with largely unknown ecological impacts.

Economically and ecologically we must reverse these trends. This can only be accomplished by a concerted effort to remove impediments, both social and scientific, to the rapid development of marine aquaculture activities.

Despite the imposition of stringent management regimes in many fisheries, it is conceivable that the necessary level of production to satisfy demand may never again be achieved from only the wild stocks of fishes, even with a substantial recovery of the resource. This is in part due to the little known fact that 98% of the wild catch comes from only 2% of the ocean. Why then can we not expand the area fished?

Wild stock fisheries are present only where there is adequate primary production to support the food chain in sufficient quantity to make the fishery economically feasible. Most of the ocean is oligotrophic, meaning that it is nearly saturated in dissolved oxygen and has inadequate nutrients to support abundant photosynthesis or primary production. With this in mind, one can immediately see how to make these watery deserts bloom, i.e. supply the necessary nutrients. This of course can be done, but maintaining applied nutrients in place in the upper ocean, in a high enough concentration for a time long enough to produce an end product, is a problem that as yet has no solution. Thus, the next best way to make the oceanic desert bloom is to provide the food and use the space in the oceanic desert to extract the other vital ingredient to fish culture, namely, oxygen. This is the focus of virtually all open ocean aquaculture endeavors currently envisaged.

Why haven't these technologies received more attention and been more successful? Among the problems are (1) a stifling regulatory environment which curtails mariculture and stock enhancement development in territorial seas, (2) a lack of commitment of financial resources to address the technical questions that must be resolved, and (3) the perception of many policy makers that when the economics are right, the technology will be developed by private industry. In the interim, while we wait, the wild-stock resources continue to decline.

The time is ripe for a global effort to spur the development of new aquacultural technologies which will address declining wild stock fisheries as well as increase the world's food supply. Because declining resource abundance translates into declining sustainability, an immediate effort must be made to include research and technology development, demonstration of economic viability by operation of prototype facilities, and technology transfer to the new generation of ocean farmers.

Summary of Conference

All of the above issues were covered at the Second International Conference on Open Ocean Aquaculture and papers that address many of these issues are presented in this volume. Several presentations focused on key policy issues and the papers by De Alessi, McVey, Corbin, Hayden, Curran, and Young focus on a number of policy topics, such as water tenure, rights of access, and associated regulatory issues.

Other presenters focused on the technology of cage and longline systems that are needed to assure performance of various cage and longline culture systems for both finfish and shellfish under open ocean conditions. Most of the ideas offered by these presentations are given in the papers by Chambers, Condron, Gignoux, Loverich, Merino, Petrusevics, and Savage.

Examples of successes of aquaculture efforts in nearshore and open ocean environments are given in the papers by Bonardelli, McElwee, Mihelakakis, and Tamaru. These papers, and the other presentations and discussions at the meeting, provide a persuasive case for the economic opportunity of this new farming frontier.

The biology of several current and future marine aquaculture species was discussed at the conference and two papers in this volume present some of the issues facing this growing endeavor (Drawbridge and Ostrowski). Finally, a number of speakers addressed provocative new ideas for utilization of ocean space and four of these are presented here as novel approaches to the management and farming of the ocean (Hotta, Liu, Markels, and Rechntenwald).

Setting the stage

Dr. James McVey of the National Sea Grant Office of NOAA set the stage for the conference by presenting the current status of aquaculture in the United States. His paper provides a background for the other presentations and lists a number of problems that need resolution. Among these, the permitting of offshore activities is identified as one of the major impediments. McVey also introduces the new NOAA initiative for Open Ocean Aquaculture that would focus the efforts of many institutions on rapidly developing the technology of offshore production systems, the understanding of the biology of potentially culturable species, and the policy and regulatory regime under which both demonstration and proof of concept experiments and limited production could take place. Several other authors, in addressing issues of marine tenure, ocean leasing, policy development, and enforcement of regulations, reinforce this view. These papers generally indicate that over-regulation of the fledgling industry is having adverse effects but they also generally agree that the emerging offshore aquaculture industry must accommodate the need for regulation and environmental stewardship at all steps in its development.

Public policy and regulatory issues

As pointed out by McVey, marine tenure, or ownership of rights to ocean water is a crucial issue that must be resolved before any substantial investment will be made in open ocean aquaculture. Although the issue of water rights to portions of the ocean needs much more discussion, two types of ownership are generally discussed. Exclusive ownership, in which rights of access by others can be excluded, and multiple use ownership, in which other users such as sport fishermen continue to have access to the site. Either is probably acceptable provided sufficient ownership right is present to assure the aquaculturist that the initial investment in anchoring systems and nearby hatchery facilities is warranted. Inasmuch as most coastal communities have had a past practice of considering the ocean a commons from which all can derive benefits, the path to provide adequate ownership assurance is not clear in many political jurisdictions. In the papers of this volume, ideas ranging from leases from the controlling state to outright ownership are discussed, as is the concept of a non-exclusive easement. Although outright ownership is clearly a favorite, it is the least likely to be achieved. Thus lease and/or easement issues appear to be more expedient and are considered by most authors to be satisfactory.

The regulatory regime in which ocean aquaculture can be undertaken needs rapid clarification. Inshore models for circulation and waste loading appropriate for calculating the carrying capacity of these protected and restricted circulation waters seem to be inappropriate for establishing the carrying capacity of the more open circulation conditions experienced in the open ocean environment. Thus we need new modeling efforts to establish appropriate carrying capacity for offshore areas. These models could then be used to establish guidelines for acceptable environmental impact criteria. But even if the criteria were established, in many cases, it is not clear what agency would do the watching. Thus it is suggested that the fledgling industry should attempt to set some best practice standard that would give guidance to the appropriate or future regulatory body.

Technology of cage and longline culture systems

The technology of growing fish and shellfish in open ocean environments received considerable attention at the conference and in the papers in this volume. Although no definition of the term "open ocean" was enunciated, many existing operations are exposed in at least one direction to a fetch of a thousand kilometers or more. Moreover, these facilities have withstood storms of major proportion and have survived. Facilities up to 10 km offshore are described and there appears to be general agreement that the added problem of higher sea state is acceptable in exchange for the benefit of better water quality that generally goes along with the increased exposure. Better water quality translates into better growth rates, less disease, and the minimization of the environmental impact of the waste products from the intensive culture systems.

Several authors exploit finite element modeling to examine the deformation of various cage types under high current and wave conditions. Anchor systems also are examined, as are the benefits and shortcomings of various cage designs. Structurally supported cages seem to have advantages (other than, perhaps, their cost) to gravity cages of more conventional design.

Examples of success or failure of open ocean aquaculture

Several examples of success were presented and discussed at some length at the conference and are included as papers in this volume. One (Petrusevics) involves the southern bluefin tuna operation in Boston Bay, South Australia, where more than 2,000 tons of fish are being raised in cages which were stocked with juveniles captured in the wild. Another (Bonardelli) involves experiences in offshore shellfish production and examines the economies of scale of a scallop-growing operation in eastern Canada.

Culture of salmon in offshore regions of Ireland is used as a model for offshore open ocean aquaculture of the future (McElwee). This paper is of particular significance for it demonstrates the ability to grow up to 300 tons of fish in a single cage in heavy sea states.

Mihelakakis discusses an extensive cage culture operation in the offshore waters of Greece. He also examines the economics and cost breakdown of the production of fish in the Mediterranean region.

Finally, the ups and downs of the Taiwan experience in aquaculture were summarized at the conference but are not presented in this volume. These sobering experiences provide a lesson on the cost of a too rapid expansion to high stocking densities before the culture of an organism and its diseases are fully understood, or without adequate development of the market.

Future directions

The biology, economic potential, and required physical environment for a number of potentially culturable open ocean species, varying from white sea bass to yellowfin tuna, moi (Pacific threadfin), mahimahi, pearl oysters, and seaweeds, were examined by various authors during the conference and most are considered in the papers of this volume. Of these, moi, Hawaiian pearl oysters, and mahimahi seem closest to being viable new commercial species for tropical waters at this time, but yellowfin tuna caught the attention of many with a more distant vision.

One of the clearest needs for the future will be the need to identify and resolve social and economic problems that are unique to marine aquaculture. Foremost among these is the social/political issue of rights to the water. This is critical to the financial viability of any open ocean aquaculture effort. We will also need to evaluate local and regional economic cost/benefit ratios of full-scale development.

In the more distant future we need to examine, and perhaps test, the feasibility of fertilizing the oligotrophic ocean by means, such as artificial upwelling or even the dispersal of nutrients from a ship. Either method appears to have potential for greatly increasing the production of biomass, and, indirectly, food fish, in regions of the ocean that are otherwise of little productive value. Finally, we must begin to address the economies of scale that may be available when aquaculture is used in conjunction with other oceanic endeavors, such as the use and reuse of oil drilling platforms or the use of very large floating structures as fish husbanding devices.

Recommendations

Based on the conference discussions, the near-term scientific and engineering objectives should include:

1. Selecting appropriate local species in a number of ecologically distinct regions for consideration for use in open ocean aquaculture programs and assessment of the status of available information for each of these species;
2. Obtaining adequate biological knowledge to remove impediments to the development of aquaculture for each of the selected species from spawning through the juvenile stage;
3. Developing conceptual designs, analysis, model testing and fabrication of containment systems appropriate for ocean mariculture;
4. Developing harvesting and feeding systems for use in open ocean environments;
5. Demonstrating the viability of regional ocean mariculture at appropriate scale(s);
6. Investigating the question of the dilution of wild-stock genetic pools by accidental releases of fish from offshore aquaculture systems.

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Public Policy and Regulatory Issues

An Overview of Offshore Aquaculture from the National Sea Grant Office Viewpoint

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Aquaculture production has increased dramatically over the past decade, while fishery production has remained static or declined for many species.

World population is expected to reach 8.3 billion by the year 2025 and the seafood demand, based on population alone, would be nearly 162 million tons or roughly twice what is available today (New 1997) (See Figure 1). Wild fisheries production is not expected to increase and will more likely decrease in the future as more active fishery management is expected. World wide aquaculture production rose from 11 million metric tons in 1985 to over 25 million metric tons in 1994, an increase of nearly 230%.(New 1997).

Global Seafood Demand

year	**population (billions)**	**demand (million t)**
1950	2.5	48
1990	5.3	101
2000	6.3	119
2025	8.5	162

Figure 1. Estimated world fishery production.

China is still the largest producer with production valued at nearly $11 billion, followed by Japan at $3.7 billion, while the U.S. was at $.685 billion in 1994. (Figure 2) Most of this increased production was in freshwater species but marine species production has begun to move forward over the latter part of that decade. In the United States aquacultural production is primarily with freshwater species such as catfish, trout and crawfish and species like sturgeon and hybrid striped bass raised in freshwater ponds. Marine culture has been slow to start because of opposition to placement of production

1992 FAO Aquaculture Values

China	$11.64 billion
Japan	$ 4.67 billion
Indonesia	$ 1.98 billion
India	$ 1.5 billion
S. Korea	$895 million
U.S.	$632 million
France	$555 million

Figure 2. FAO aquaculture values for 1992.

facilities in coastal waters, difficult permit and licensing procedures, lack of financing available for aquacultural endeavors, and lack of appropriate technologies for open water conditions. Two enabling technologies, offshore production systems and recirculating production systems, in addition to the more traditional methods of aquaculture, are being explored by the National Sea Grant College Program and other agencies, to facilitate aquaculture production for marine species. These technologies are considered more environmentally friendly and would result in reduced pressures on delicate estuary systems where most marine culture is taking place today.

Offshore aquaculture would have many broad benefits including the mass production of marine protein, creation of new jobs and industry, possible production of biomass for fuels and/or sequestration of CO_2 to alleviate global warming trends, and the reduction of stresses on inshore ecosystems and fish stocks. More specific benefits would include reduced objections by adjacent land owners, overall reduction in conflicts with other users, avoiding the ecological carrying capacity limitations of inshore waters, access to larger volumes of high quality water for filter feeding molluscs (human health concerns), possible reduction of regulatory and permit requirements, ability to culture high value, open ocean species, larger scale production systems and the corresponding benefit of higher profits that may be possible. These benefits are particularly important in view of the increasing demand for seafood throughout the world.

For the purposes of this talk offshore aquaculture is defined as aquaculture in locations that are exposed to open ocean on one or more sides. In discussions within federal agencies, offshore aquaculture is frequently defined as being outside of the three mile limit for state waters, but that is not the definition being used in this discussion.

Offshore technology development is occurring in several countries around the world as fish farmers are becoming more aware of the limitations of inshore culture. Norway, Sweden, Ireland, Russia, Italy, France, Israel and the United States, among others, are looking at this technology and several different systems are being investigated and developed. We will see many of these systems in other talks during this symposium.

In the United States, a survey of funding agencies for aquaculture indicates that we are spending a little over $4 million dollars on technologies that can apply to offshore culture. Sea Grant and the National Marine Fisheries Service spend the majority of dollars on this technology. (Figure 3)

1996 Research Funds

Agency	**1996 (thousands)**
Sea Grant	$2,800
NMFS SK	$918
NRAC	$292
WRAC	$20
CTSA	$190

Figure 3. Federal funding for 1996 research funds for offshore.

Constraints to Offshore Aquaculture

The constraints to offshore aquaculture, under the present developmental conditions are many. Offshore oceanographic and weather conditions can be extremely hostile and new engineering designs are needed to cope with these conditions. Larger scale of operations are necessary in order to justify investments in these larger and more robust systems. The logistics for maintenance will be much more difficult for offshore installations. We do not yet have control of many of the life histories of candidate aquaculture species for offshore culture. We do not have an infrastructure of marine fish hatcheries and nurseries to supply an offshore operation. There may be a long term problem with the availability of fish meal based feeds if the industry expands too rapidly. There is a lack of government policy concerning offshore aquaculture, although several agencies such as Sea Grant and the National Marine Fisheries Service are discussing this with other federal agencies using the Joint Subcommittee on Aquaculture as a forum.

The regulatory and permit requirements are not clear for those seeking to invest in offshore aquaculture operations. The insurance and liability questions are not clear for offshore structures, especially the existing oil rigs that could provide platforms for our first attempts to move into the offshore area. And finally there is still the factor of general opposition to something new by those that already use the oceans for other purposes.

Types of Offshore Aquaculture

Many types of offshore aquaculture technologies have already been attempted and futuristic systems are being contemplated. These include surface cages and pens with fixed and flexible moorings; submersible cages, pens and platforms with fixed and flexible moorings, longline culture of algae, scallops and mussels, and marine ranching of scallops, marine fish and crustaceans. In the future we might expect manned fixed, floating free, and powered facilities as well as remote-controlled production facilities. These latter systems would have to be at much larger scale than most existing systems in order to make them commercially feasible.

Candidate Species for Offshore Aquaculture

By moving offshore we could expect to increase our production of high value, larger marine species such as tuna, mahi mahi (dolphin fish), halibut, snapper, grouper, permit, pompano, cod, haddock, flounder, black sea bass, sea bream and sea bass; and we can expand our culture of scallops, mussels, abalone and marine algae. This diversity is necessary in that markets are very species specific and too much production of any one species leads to precipitous market value declines. This can already be seen with species such as sea bream, sea bass, hybrid striped bass and salmon, where the market price per pound has decline by as much as 50% since they have come onto the market as a cultured product.

Actions Necessary for Offshore Aquaculture

What are the actions necessary for the development of offshore aquaculture in the United States? First, we must develop a common vision for the future. We need to develop common goals for the various funding entities and develop multi-disciplinary, multi-institutional, multi-regional, multi-industry and multi-national plans and collaborations. We need to incorporate offshore goals in the National Aquaculture Plan that is being developed by the Joint Sub-Committee on Aquaculture, a federal panel of agencies that is responsible for setting the national vision for aquaculture and coordinating efforts in that area.

We need to integrate offshore aquaculture with existing fishery operations in order to maximize and optimize our seafood production sector. I believe this can be done in such a way that both sectors of aquaculture and capture fisheries will benefit. Better management of existing fish stocks is crucial to the future stability of the seafood industry and aquaculture is necessary to take some of the pressures off of the natural stocks and provide market stability.

Earlier arguments in this paper have already been presented that natural fishery stocks will not be able to meet human demand in the future and the optimization of production can only occur by integrating aquaculture and fisheries into a single production program. In order to integrate the two production sectors we need to determine carrying capacity of the different water masses and ecologies. We need to assure genetic diversity of stocks both for future aquaculture and enhancement programs and for sustainable natural fisheries.

We need to be sure that the technology we develop is environmentally appropriate and sustainable. One of the main reasons we are considering offshore culture is to move aquaculture into locations that are more sustainable. Once again the carrying capacity of the water mass that culture systems are placed in is one of the critical factors. It is conceivable that the added nutrients that fish culture represents could be the basis for overall increases in natural production if the production area was properly placed in relation to existing ocean current systems.

Industry partners that have already attempted to start offshore operations have stated that government regulations, policies and permits are their biggest stumbling block. We need to clarify and simplify the government regulations and permit procedures. A clear policy needs to be developed for Federal, State and local governments regarding the issue of offshore aquaculture.

We need to expand government research and finance supports for offshore aquaculture. Working in offshore areas is extremely risky, especially with unproven technologies. NOAA and other funding agencies can help reduce the risk to offshore entrepreneurs by partnering with industry and by developing new technologies for industry to try. Pilot scale tests will be necessary to prove new concepts and financial supports to new businesses focusing on offshore production would be helpful. Improved crop insurance availability will be crucial to future investments.

For the future development of offshore aquaculture it is imperative that we base development on science and not emotion. This is a time of change and traditional fishermen are under great pressures because of declining fisheries stocks. Other users of coastal areas are also concerned about the activities in near shore waters and those that wish to develop offshore aquaculture are going to have to have good scientific information in order to argue their case for use of the public resource represented by coastal ocean areas. Sea Grant is dedicated to funding good science in the many scientific disciplines that contribute to successful aquaculture.

National Institute of Marine Aquaculture

The National Sea Grant Program and the National Marine Fisheries Service have proposed a budget initiative for FY-99 to develop a National Institute of Marine Aquaculture (NIMA). The initiative is still in draft form but it is being considered for funding at this time. Regardless of whether this initiative is funded or not the type of partnerships advocated by the initiative is the direction we are moving today within the NOAA system. This Institute would be what is called a virtual institute consisting of agencies and institutions that are currently investing in aquacultural technology and development. There would be no new administrative structures or new facilities built, in order to keep costs low, but we would identify a regional coordinator and provide funds for support of that position. Several ecosystem based regions would be developed, roughly corresponding to existing NMFS and USDA Regional Aquaculture Center regions with individual Sea Grant Programs contributing as appropriate to regional efforts. We would develop a common vision for aquaculture research and development within a regional context and the primary focus would be on enabling technologies for marine offshore, recirculating and ranching systems.

The initiative provides for the establishment of Regional Steering Committees of equal partners linked to a National Steering Committee of Federal Agencies. Participation is by virtue of resources and expertise contributed. National goals and objectives would be based on regional inputs.

Scientific and engineering objectives for NIMA might include:

- Development of biological knowledge base and techniques for rearing species from egg to stocking and market size.
- Development of environmentally appropriate and cost effective engineering designs for marine aquaculture.
- Development and evaluate marine ranching protocols.
- Conduct of ecological and genetic impact studies related to marine ranching and aquaculture programs.
- Development of appropriate feeds and disease diagnostic and control technologies for use in marine aquaculture.

Social and regulatory issues for NIMA might include:

- Simplification of regulatory impediments to marine aquaculture at the local, state and federal levels.
- Exploration of the use of marine aquaculture and ranching technologies as a means of assisting U.S. fishermen in continuing traditional lifestyles and coastal economies.
- Development of economic and marketing analyses in relation to U.S. and world economies.

The key to how NIMA would work lies with the Steering Committees at both the National and Regional levels. Regional committees might be composed of Sea Grant Directors, NMFS administrators, Regional Aquaculture Center Director, State Research Institutions, private research institutions and foundations, regional Corps of Engineers and Coast Guard representatives and a Fishery Management Council Representative. National Steering Committee members could include Sea Grant, National Marine Fisheries Service, Coastal Zone Management, Sustainable Development Office, Economic Development Administration, USDA, Corps of Engineers, Coast Guard and other interested agencies. This Steering Committee at the National level could be part of the existing Joint Subcommittee on Aquaculture or linked to it in some way.

The final details of how NIMA would work will have to wait until we know whether or not the FY-99 budget initiative is accepted. However, we are already moving into these partnerships at the regional level by the direct interaction of Sea Grant, NMFS and USDA Regional Aquaculture Center managers.

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Ocean Leasing in Hawaii: Origins, Status and Future Prospects

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Introduction

It may come as a surprise that ocean leasing, in the conventional sense, is a relatively new and untried concept in Hawaii.

Hawaii is a Pacific state that is the most remote land mass on earth. A state that has:

1) The fourth longest coastline in the United States, at 750 miles.
2) Ocean area of 2.8 million acres, within state jurisdiction.
3) Coral reef area within the Main Hawaiian Islands only, of 410,000 acres, and
4) Area within its exclusive economic zone of 565 million acres.

Hawaii was recently declared an ocean state by Governor Benjamin Cayetano, who further stated it should be managed as an ocean state, that is, fully recognizing the importance of the ocean in our daily lives. Yet, Hawaii has not issued the first ocean lease, though an ocean leasing law has been on the books since 1986.

A brief history of ocean leasing in Hawaii and the reasons why no lease has been issued to date, are the subjects of this paper. It will briefly review:

1) The historical roots of ocean leasing or the ancient Hawaiian concept of *Konohiki* Rights.
2) The modern origins of the Ocean Leasing Bill and Law, which was spearheaded by the Aquaculture Development Program (ADP).

3) The legislative history of the Ocean Leasing Law, Chapter 190D Hawaii Revised Statutes.
4) The initial test case for law, and finally
5) The rising interest today in modifying the law to make it more user friendly for offshore mariculture and the issues that will need to be addressed.

The Roots of Leasing Ocean Space in Hawaii

It is interesting to note that existing side-by-side with the public trust doctrine in Hawaii state law today is a legalized system of exclusive fishing rights derived from ancient Hawaiian custom and usage. The system known as "*konohiki* fisheries," extends exclusive fishing rights to certain persons or families living in traditional land divisions known as *ahupua'a.* These were "self sustaining," pie-shaped strips of land usually coinciding with valleys and plains, and running from the mountain top to the sea, usually the edge of the reef. They were designed to yield a wide variety of food products to feed the residents (Kosaki, 1954).

The *konohiki* or manager for the *ahupua'a* was designated by the chief. He had authority to set apart one species of fish for his exclusive use, or to forbid all fishing during certain periods, while receiving one-third of all fish caught within the *konohiki* fishing grounds during the rest of the year. Otherwise, tenants of the *ahupua'a* had the right to fish freely (Kosaki, 1954). Conversations with old timers today reveal stories about modern-day *konohiki* standing guard over nearshore areas and discouraging trespassers with firearms and other means.

Approximately, 42 recognized *konohiki* fisheries remain in the islands, though little if any active management or enforcement is being carried out by the designated authorities. Earlier efforts by government to condemn all these fisheries for public use have ceased (Clay, et al, 1981).

It should be noted that in the past, private owners could and did lease out fishing privileges to outsiders. But consistent harvesting of these fisheries is predicated on subsistence practices and would not be considered practical today for commercial purposes. However, this system for private, exclusive use of marine resources is recognized in State law and does set a precedent for further consideration of a modern system of long-term tenure through ocean leases or other vehicles.

Ocean Leasing Study and Bill

The origins of the ocean leasing study and bill stem from actions by delegates to the 1978 Hawaii State Constitutional Convention. Amendments to Article XI of the Constitution provided that the State shall have the power to manage and control the marine, seabed and other resources located within the boundaries of the State. This amendment also added State-licensed mariculture operations to fishponds and artificial enclosures, which are excepted from the seawater fisheries of the State that are free to the public (Clay, et al, 1981).

However, in so doing, this amendment placed the responsibility upon the Legislature to establish guidelines for mariculture operations which shall protect the public's use and enjoyment of the waters and submerged lands. The tone of these deliberations, while positive, was to guard against inappropriate, exclusive use of the ocean.

In 1979 following the Constitutional Convention, the State House of Representatives passed House Resolution 474, which directed the State Administration to analyze the state of the law and develop guidelines for the licensing of mariculture operations in State marine waters. The resolution again had a mixed message of desiring to encourage mariculture, but control its development in offshore waters with a licensing regime.

About this time several important economic development efforts were occurring that spurred increased interest in offshore resources and the definition of property rights in the ocean.

The State had just published the first comprehensive aquaculture development plan in the nation and formed an

Aquaculture Development Program to implement it (Hawaii, 1978). Though the thrust of the plan was land-based culture, open ocean potentials did not go unnoticed. At the same time, culture technology for offshore production of seaweed was being perfected by Max Doty at the University of Hawaii and several small family growers had approached ADP to culture seaweed on reef flats (Moss & Doty, 1987). But, these individuals wanted exclusive use of the nearshore growing areas to protect against poaching or accidental harvesting by recreational seaweed collectors.

In other agencies, marine mining of manganese nodules on the seafloor and ocean thermal energy conversion systems for electrical power were being studied for implementation in the waters around the Hawaiian Islands. In particular, two Mainland companies were working on conceptual designs for a 40 megawatt shelf-mounted OTEC plant at Kahe Point, Oahu, and such a plant could cost as much as $300 million (Corbin & Brewer, 1981). It became very apparent that this kind of large-scale investment may require exclusive use of both submerged lands and marine waters in a single location for an extended period of time.

In this highly charged atmosphere of new economic opportunities, the ADP decided it would seek a grant from the Hawaii Coastal Zone Management Program (CZM) to develop the required mariculture licensing guidelines. Consultations with local ocean law experts, such as Kent Keith, then head of the State Ocean Resources Development Program, and John Craven, State Marine Affairs Coordinator, led to the realization that, though State law clearly permitted licensing or leasing of submerged lands, the State's authority to encumber the water column was questionable (Clay, et al, 1981).

ADP drafted a proposal to CZM to hire a consultant to study this issue and prepare licensing guidelines. Funding of $38,000 was received in the summer of 1980. As community interest in the study increased, the scope was broadened from consideration of mariculture alone, to investigation and analysis of ocean leasing, which included ocean thermal energy conversion devices, as well as fish aggregating devices or FADs.

FAD's in general are man-made floating objects placed, either anchored or free-floating, in the ocean to attract and concentrate certain pelagic fishes (Hawaii, 1983). The FAD aspect was later dropped due to special concerns related to privatization of this activity and limited study resources to address them fully.

Gerald Clay, a local lawyer with a strong interest in ocean law, was hired to carry out the study and put together a team of lawyers and marine resource professionals. The results of the study assessed: 1) the major policy issues related to ocean development, 2) the constraints to fostering commercial ocean activities, and 3) the current legal and regulatory issues which govern state jurisdiction over ocean uses.

Two publications were produced: 1) *Ocean Leasing for Hawaii*, which comprehensively analyzed the policy and legal areas, and 2) a technical supplement titled, *Mariculture and Ocean Thermal Energy Conversion, State of the Art Assessments*. A "shopping list" of legislative proposals were also included, which addressed possible legislative answers to the numerous legal and policy issues and recommendations raised in the main text.

The more significant areas addressed include the following:

Definitions of a "quick response" Administrative Lease, a Commercial Lease and an Experimental Lease
A License Application and Guidelines for License Approval
An Ocean Resources Liaison Officer to guide applications
A Leasing Procedure and Provisions, including terms, rents and royalties
Statements of Rights of the State, the Lessee and the Public
A Marine Parks Proposal
An Enforcement Approach

A Loan Program
An Insurance Program, and last but not least
A Zoning Proposal for Marine Waters

The reports were delivered in January 1981 to the State Legislature for consideration and action.

Legislative History

The history of the Hawaii ocean leasing law encompasses six long years (1981 to 1986) of contentious legislative debate. While many issues surfaced during this time, in large part, the problems and frustrations were due to trying to apply traditional land leasing concepts to the ocean, and they do not really fit very well.

As stated by John Craven in his 1980 critique of the ocean leasing report: "While some forms of ocean activity appear to fit neatly into the ocean leasing scheme, a broader examination of the technology will reveal that the key factor is not exclusive rights to the ocean floor, but rather exclusive use of the ocean resources." An example of this is in the case of mobile ocean mariculture technologies (Clay et al, 1981).

Issues Raised

Summarizing the issues from six years of legislative debate is difficult, so only the major concerns will be described.

Exclusive Use

Perhaps the most vehement concern was expressed over the basic concept of granting exclusive use of ocean space for mariculture or anything else. Many legislators felt that the ocean is traditionally a common property resource and should continue to be managed for all the people by assuring free and equal access. Granting exclusive control over the ocean surface, water column or substrate to a private, commercial entity was not popular with many legislators.

Subdivision and Development

Other legislators feared that leasing could lead to widespread subdivision of ocean space by large, financially well endowed companies. One Senator criticized the concept as a new form of *konohiki*, that would grant companies or individuals sole control over ocean resources, taking away their use and enjoyment from the general public. Access to the ocean and unencumbered use of the ocean were advocated by many legislators.

Location

Those legislators who were somewhat supportive of the concept had other concerns. Location of structures in the ocean would be critical or they would interfere with navigation and commercial, recreation and military activities. Others were concerned that ocean leasing to mariculture or OTEC would interfere with natural fisheries and the delicate marine ecology of the tropical environment.

Process and Hawaiian Cultural Concerns

Yet other concerns were voiced over the essential need for an open process in granting leases, including adequate public notice and numerous public hearings. Ability of the State to enforce lease provisions was questioned, considering the track record in other areas of marine enforcement. Finally, there were serious concerns over the possibility of negative impacts on native Hawaiian culture, its use of the ocean and the mandated collection of revenues by the Office of Hawaiian Affairs from use of ceded lands.

Overview of the Law

The 1986 Legislative session finally passed a version of the ocean leasing law, signed by the Governor in June, which was codified as Chapter 190D of the Hawaii Revised Statutes, the Hawaii Ocean and Submerged Lands Leasing Act. Responsibility for administering this law was given to the Department of Land and Natural Resources (DLNR).

What does Chapter 190D actually do? It does provide a process for private individuals to be granted leases for use of the ocean. However, the law is not effective and user friendly as shown by the following brief analysis.

Definitions are established for OTEC; mariculture; marine activities including research, scientific and educational endeavors; and non-commercial activities that are designated not-for-profit.

But taken together, the definition of mariculture, which limits activities to research, development and demonstration purposes, and the definition of non-commercial activities, which states the maximum size for a mariculture lease is four acres, severely limit what can be done under the auspices of the law.

The leasing procedure defined is a two step process and can be briefly described as follows:

Step 1 - This requires the applicant obtain a Conservation District Use Application Permit (CDUA), which is peculiar to Hawaii public lands administration. In essence, application must be made to the Board of Land and Natural Resources for approval to conduct specific activities (uses) in a specific area, in this case, in the ocean.

The CDUA requires an Environmental Assessment and may be subject to a full impact statement. It must be processed within 180 days.

It is expressly stated that the Board shall not approve an application unless it finds that: 1) the applicant has the capacity to carry out the entire project and 2) the proposed project is clearly in the public interest upon consideration of the overall economic, social and environmental impacts.

Step 2 - Once the CDUA is granted, the next step is a lease disposition. This section of the law describes procedures, and provisions such as bonding and protection of *konohiki* rights. However, the law makes granting of a lease by the Board of Land and Natural Resources subject to prior approval of the Governor and the prior authorization of the Legislature by concurrent resolution for the specific project. Also, the concurrence of the Director of the Department of Transportation is required.

As a practical matter getting the Governor's approval should not take a great deal of time. However, subjecting each lease to the legislative process for Concurrent Resolution is a daunting task. The Hawaii Legislature meets between January and April every year, so there is a timing factor. In addition, a Concurrent Resolution by definition must pass both House and Senate, which will require a significant lobbying effort by the applicant.

The last section of the law describes administration and enforcement—specifically revenue disposition, penalties, civil liability and criminal liability. These are for the most part handled by reference to other appropriate statutes.

What is the bottom line? An applicant may take between two to three years and a minimum of $50,000 for an Environmental Assessment, to obtain an ocean lease for mariculture research and development. Under this interpretation commercial mariculture would not be permitted.

The Test Case

The first company to try to get an ocean lease under Chapter 190D was not a mariculture operation or OTEC power plant. It was a new concept in ocean recreation —a tourist passenger submarine called Atlantis Submarines.

Submarine technology had reached a point where such a commercial activity was both technically and economically feasible. Moreover, it was a perfect match for the Hawaii ocean environment and its tourism-based economy that currently hosts seven million visitors a year.

Briefly, the Atlantis concept was to use existing ocean features and construct others, such as artificial reefs, to attract marine life for its passenger submarines to visit. The more varieties of fish and marine life the better the viewing. Depths of operation were in the 100 foot range, so well within the photic zone, and sites proposed were in the 5 to 8 acre range in size.

Atlantis officials thought a lease, that is, exclusive use of a site would be a necessary factor. After all, for safety reasons they believed they could not allow access by sport divers or fishermen while the submarine was operating in the area. Moreover, they wanted the structures they developed to attract increasing populations of marine life and reasoned that allowing fishing on the site would be counter productive (O'Halleran, 1997).

The first lease site proposed was off Maui, and it created a storm of protest. Many members of the ocean user community were against the project. The main concern (and there were others): exclusive use of any portion of the ocean. Recreational divers and fishermen, commercial dive tours, commercial fishermen and other ocean recreational users found the site was unsatisfactory. These groups advocated that the oceans are a common property resource, held in trust for the people of Hawaii, and should not be leased for exclusive, private or commercial purposes.

What happened? Atlantis withdrew the application and ultimately regrouped. It did a better job of community relations, and looked for less controversial sites on other islands.

It also abandoned trying to get an ocean lease for these sites. Instead the State granted them a Non-exclusive Easement to use portions of the ocean for submarine tours. It is interesting to note that if this easement document is examined, it reads like a lease; with a term of 40 years, periodic rental reopenings, and a percentage of revenues going to the State.

Atlantis currently has operations on Oahu, Kona and Maui. But, since the company cannot keep divers and fishermen off their sites, the safety and fishing issues remain today. Basically, these issues are actively managed by the company by making a concerted effort to develop formal user understandings, with all components of the diving and fishing communities to avoid any potential problems. Thus far, they have been very successful with this negotiated approach to exclusive use (O'Halleran, 1997).

Though this direct, non-exclusive easement approach does not appear to be very applicable to the commercial mariculture situation, it should be explored further.

Current Issues

Interest in offshore mariculture is rising nationally and this interest is being driven by breakthroughs in marine species culture and cage design (NRC, 1992). Likewise, interest is rising in Hawaii to examine Hawaii's ocean leasing law and amend it to make it more user-friendly, particularly for commercial mariculture.

Even a cursory consideration of the current Hawaii climate for ocean development suggests that many of the issues that were contentious earlier are still with us today, and may even be amplified and more difficult to resolve.

The major issues that must be addressed in any comprehensive review of the law are highlighted. Obviously, the complexity of these issues is going to be in large measure dependent on the specific sites chosen. Furthermore, every issue will require extensive input from government agencies, commercial interests and the general public before any resolution can occur.

Environmental Impacts - No doubt the environmental impacts of offshore mariculture operations are going to be a big concern. Pollution by fish feeds and waste, and damage to the substrate by mooring devices must be considered. Nearshore activities will not be allowed near coral reefs. However, enrichment in some locations may be considered a positive factor, since the tropical ocean around the Islands is nutrient poor.

Native species should be utilized in offshore culture to remove the potential for introduction of exotics through escaped stock. A more complex issue will be the potential for genetic alteration of the natural gene pool, when mariculture stocks are sourced from hatcheries and breeding programs.

Access/Multiple Use - Access and multiple use issues refer to conflicts arising from granting exclusive, long term use of ocean space. Exclusivity may be strongly criticized by certain segments of the community. To date, a few long-term ocean uses have been granted with easements or revocable permits, rather than leases. For example, uses in the public interest have been approved, such as oil pipelines and telephone cables, as well as the tourist submarine activity.

Review of the record indicates that the public trust and common property dimensions of ocean leasing will require a great deal of attention in any proposed modification of the law that allows easier and more widespread ocean use.

Navigation - In a related issue, surface navigation for military, commercial and recreational users must be carefully considered. The original study suggested that "the lessee shall provide reasonable means of public ingress and egress to and from the leased area."

Furthermore, the law specifies "the lessee shall if necessary, construct and maintain gates, openings or lanes at reasonable distance one from another, throughout a leased area, which includes surface waters and in which any type of enclosure is an obstacle to free navigation, unless public transit in or through the enclosed waters will cause undue interference with the operation being conducted by the lessee within the leased area." Clearly, what is reasonable to the ocean farmer and reasonable to the public is going to be a matter of serious debate.

Defense - Again in related issue, use of parts of the ocean around Hawaii are a matter of national security. The situation is that the Navy acknowledges these spots do exist, but, for security reasons, they cannot tell where they are. Similarly, the Navy's more overt ocean operations around Hawaii will always receive priority over civilian uses.

Native Hawaiian Rights - Concerning Native Hawaiian Rights, all submerged lands under State jurisdiction are ceded lands. This means that by law 20% of any revenues derived from these lands by DLNR, must go to the Office of Hawaiian Affairs to support its work with Native Hawaiians. Determining fair lease rents in this context will be an issue for any mariculture operation. Moreover, the entire ceded lands issue is being hotly debated in the Legislature today and may change.

In addition, a 1995 Supreme Court opinion on Native Hawaiian gathering rights has caused concerns over whether private landholders can legally exclude Hawaiians from their lands when they are exercising traditional subsistence, cultural and religious practices. The implications of this new issue are still being defined by the legal community and no doubt court challenges will be required to refine the concept. Nonetheless, by extension, this issue can also be considered for ocean waters and ocean leasing to cloud any claims of tenure.

Endangered Species - It can be assumed that issues will arise regarding mariculture and protected species in Hawaiian waters, such as green sea turtles, monk seals and humpback whales. For example, presently, the boundaries of a proposed Hawaiian Islands Humpback Whale Sanctuary are being defined. The draft designated Sanctuary consists of approximately 1,300 square nautical miles of Federal and State of Hawaii waters from the high water mark to the 100 fathom isobath around the main Hawaiian Islands.

Many commercial and recreational interests are very concerned that if this designation is adopted, it will affect their livelihoods and enjoyment of the ocean. The Governor has until June 1997 to accept the Federal proposal. Impacts on offshore mariculture will be subject to interpretation of any proposal that is approved.

Management and Enforcement - Adequacy of management and enforcement of ocean resource use are ongoing issues in Hawaii. Considering the large expanse of resource, and the limited number of DLNR personnel involved, the public will be skeptical that any new activities such as mariculture will have adequate oversight.

Conclusions

In conclusion, there are many complex issues and many interest groups that must be engaged to amend Chapter 190D, the Ocean and Submerged Lands Leasing Act, to allow commercial mariculture. However, the timing is right to begin the effort and attempt to define the numerous uncertainties and issues.

Changes to the Law

From this brief examination of the issues, beneficial changes to the law could be sought in the following areas:

Streamline the process for public and private agencies to conduct research and demonstration projects. Demonstration and adaptation of off-the-shelf, offshore technologies in the Hawaii environment are necessary steps, before commercialization can occur and should be facilitated by government.

Modify the law to allow commercial mariculture and let the nature of the project dictate the appropriate size of the site. Clearly, private support of research and development will be enhanced if there is a clear signal from the State that commercialization will be permitted if certain conditions are met.

Federal and State governments could combine efforts to identify and designate specific, environmentally appropriate sites for mariculture operations. This could take the form of establishing mariculture zones for pre-approved uses or it could go so far as to establish pre-permitted sites, or mariculture parks, that would allow research, demonstration and commercialization. If these zones or parks are established, the process of establishment should be recognized in the law.

Finally, the law should streamline the process for small commercial or subsistence projects that are of low environmental risk and do not have the financial or technical capabilities to obtain a lease under the current requirements. This could take the form, as suggested in the original study, of adding a quick-response Administrative Lease provision for commercial projects with gross revenues of no more than $150,000 in a fiscal year and site requirements of no more than one acre.

The Change Process

In terms of the whole process of change, modifying the law will require a large-scale, coordinated effort to involve Federal, State and County agencies, commercial interests, military interests, and the general public in a dialog to consider the issues; including acceptable technologies, sites, and restrictions on use of a leased area. It is clear from past experience that this will require a great deal of time and resources to conduct the many statewide public meetings needed to receive input from a wide variety of interests, as well as eventually carrying out official statewide public hearings on the proposed changes.

Leasing Federal Waters

Finally, while the framework for leasing State waters is somewhat clear, the process for leasing Federal waters off Hawaii is very murky. The process for leasing Federal waters and the role and jurisdiction of State government in the process needs clarification, so that the long-term opportunities for ocean leasing in the Hawaiian Islands can be considered in their entirety.

This conference is a good beginning to consider these issues for Hawaii. But to be successful it must lead to a clear plan of action and funds to support the implementation. Only through decisive action will commercial offshore mariculture be demonstrated and eventually become a major part of Hawaii's aquaculture industry.

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An Access System for Ocean Aquaculture: Influences of Current United States and International Law[1]

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World seafood consumption is rising while the wild fish harvest remains stable.[2] Ocean aquaculture (mariculture) operations as alternatives to traditional harvests in the exclusive economic zones (EEZs) are being proposed in U.S. offshore areas and are well established in other countries, particularly in Europe and Southeast Asia. Mariculture operations, unlike marine fisheries, are designed to constrain the animals being raised using fixed nets or pens. The site-specific nature of these operations requires some form of property right to designated areas of ocean space similar to those rights granted to offshore oil, gas, and mineral resources developers. Without a guarantee of tenure, other ocean users (for example, navigation, commercial fish harvest, recreational boating and fishing, national defense, and mineral exploration and development) will invariably impinge upon mariculture. Further, the availability of investment capital for mariculture operations is likely to be limited in the absence of some form of lease guarantee.[3]

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[1] Portions of this paper were abstracted from a proposal, Designing An Access System for Ocean Mariculture, by Porter Hoagland and Di Jin, researchers at the Marine Policy Center, 1996.

[2] Food and Agriculture Organization, United Nations, 1996. *FAO Fisheries Department Major Trends in Global Aquaculture production in 1994*, FAO Fisheries Circular 815, Rome. URL: http://www.fao.org/waicent/faoinfo/fishery/trends/atrends/aqtrends.htm. See also, National Marine Fisheries Service, 1996. Fisheries of the United States, 1995, Major Trends, US Aquaculture Production, Estimated 1983-1994. National Oceanographic and Atmospheric Administration, US Department of Commerce, Washington, DC. URL: http://remora.ssp.nmfs.gov/commercial/fus/index.html

[3] Cahill, P.W. 1993. Lending to the seafood industry: part I. *Journal of Commercial Lending* 75(5):43-55.

In its EEZ, and in some cases out to the extent of the continental shelf, the United States has sovereign rights for the purposes of exploring, exploiting, conserving, and managing both living and non-living natural resources of the seabed, subsoil, and ocean waters.[4] Jurisdiction with regard to the establishment and use of installations and structures in navigable waters has been historically vested in the U.S. Army Corps of Engineers.[5] The United States has exercised these rights through policies designed to manage wild fish stocks,[6] oil, gas and mineral exploration,[7] and other uses of the seabed and navigable waters.[8] However, there are no specific policies in the United States that govern the use of the EEZ for mariculture.[9] In particular, there are no policies providing security of tenure for mariculture operations.

In 1992, a Marine Board Committee of the National Research Council examined opportunities for growth in mariculture in United States federal waters.[10] The Committee concluded that:

> *. . . no formal framework exists to govern the leasing and development of private commercial aquaculture activities in public waters. . .*

Currently, offshore mariculture permits are proceeding on an ad hoc basis.

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[4] Exclusive Economic Zone of the United States, Proclamation No. 5030, *Federal Register* 48(50):10605 (1983).

[5] Rivers and Harbors Act, 33 USC 403, 504 et seq. (1899).

[6] Magnuson Fisheries Conservation and Management Act, 16 USC 1801 et seq. (1994). (Department of Commerce, National Marine Fisheries Service, Regional Fishery Mangement Councils, managers)

[7] Outer Continental Shelf and Submerged Lands Act, 43 USC 1301 et seq. (1953) (Department of Interior, Mineral Management Service, manager)

[8] Ibid., Rivers and Harbors Act.

[9] The Marine Aquaculture Act of 1995, S1192, was introduced in committee (Commerce, Science, and Transportation) to address the site permit and other off-shore issues. The bill did not leave committee.

[10] National Research Council (NRC). 1992. *Marine Aquaculture: Opportunities for Growth*. Washington: National Academy Press.

As the aquaculture industry moves offshore to avoid inshore water use conflicts and other coastal concerns, certain aspects of international law may come into play.[11] The Law of the Sea[12] and the ocean dumping conventions and laws[13] provide a legal framework for offshore operations. The Law of the Sea Convention identifies those species that are completely under the jurisdiction of the bordering nation-state. Often, some species like salmon (anadromous),[14] eels (catadromous),[15] and shellfish and crustaceans (sedentary)[16] are of interest to aquaculturists. The dumping conventions and the U.S. Ocean Dumping Act address:

> *. . . the deposit of oyster shells or other materials when such a deposit is made for the purpose of developing, maintaining, or harvesting fisheries resources . . .*[17]

This phrase, in any event, probably does not cover fish food waste or disease preventive drugs, necessary parts of a finfish mariculture operation. The United Nations Food and Agriculture Organization (FAO) recently issued a new code of conduct[18] for responsible fisheries' management, that includes a

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[11] Curran, D.A. 1997. Regional Legal Framework for Aquaculture, 17th Milford Aquaculture Seminar, February 24-26. Abstract in press, *Journal of Shellfish Research.*

[12] Law of the Sea Convention (LOS), adopted by the UN, into force on July 28, 1994. President Clinton signed the convention on July 29, 1994, subject to ratification. The U.S. Senate is expected to take action on ratification in 1997.

[13] London Dumping Convention as implemented by the Marine Protection, Research, and Sanctuaries Act (Ocean Dumping Act), 33 USC 1401 et seq. (1972).

[14] LOS, Part V, article 66.

[15] LOS, Part V, article 67.

[16] LOS, Part V, article 68.

[17] Ibid., the Ocean Dumping Act.

[18] United Nations, Food and Agriculture Organization, 1996. *Code of Conduct for Responsible Fisheries*, adopted by the twenty-eighth session of the FAO Conference, October. See also, Edeson, W.R., Senior Legal Officer, FAO,

section (9) on environmentally acceptable aquaculture, in an attempt to set international voluntary standards for sustainable fisheries including aquaculture. In addition, aquaculture trade issues already involve the World Trade Organization.[19] Other international bodies may become involved as the growth of the coastal and offshore aquaculture industry accelerates.[20]

A first step toward a U.S. mariculture policy should be a review of existing access systems for scarce natural resources. There are lessons to be drawn from the design of access systems for public reosurces including offshore oil and gas; offshore hard minerals; natural resources in general; and cultural resources. A systematic approach to the design of an access system for U.S. mariculture should include a legal description of the ocean space and establishment of priorities and policies that include, among others, property rights; revenue generation; performance requirements (including time limits and fees); information management; environmental protection; and fairness or equity considerations.

There is the need for an innovative approach to derive the best value from a marine resource harvest, (salmon and scallops are good candidates for a study), while creating sustainable development opportunities. An economic and policy analysis should include the place of mariculture in the wild fisheries

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[19] AP-Dow Jones News Service, 1997. WTO to Rule on US-Asia Shrimping Law Dispute, *Dow Jones Business News*, February 25.

[20] General Accounting Office, 1995. *International Trade: Canada's Restrictions on Certain Salmon Imports*. GAO/GGD-95-117, Washington, DC, April 20. See also, Cooper, Helene, 1997. Governor of Maine Gets Grilled by Atlantic Salmon Processors, Wall Street Journal Interactive Edition, February 20, An example of one existing convention is the Agreement on the Network of Aquaculture Centres in Asia and the Pacific, Bangkok, 8 July 1988. URL: http://sedac.ciesin.org/pldb/texts/aquaculture.asia.pacific.1988.htm

management program. A government advocate, a single coordinating agency with enabling legislation, could avoid the protracted and often very expensive permit process. The various government agencies, responsible for federal maritime activities, have different, and often conflicting, agendas. An assessment of alternative management systems and resolution of user conflicts should be included. Like the mineral access systems, there is a need to develop cost-effective approaches for advancing environmentally sound private aquaculture that include regulatory requirements. The time has come to establish a priority for mariculture among the other open ocean uses.

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The Importance of Secure Marine Tenure

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Open ocean aquaculture offers many engineering and biological challenges, but the linchpin for the industry is surely the issue of marine tenure. The legal and social institutions that define marine tenure are what will set the rules of the game, and these rules will determine just how every other challenge will be addressed (publicly, privately or not at all).

Aquaculture output has boomed in recent years while wild fisheries have stagnated exactly because they play by different sets of rules. But without secure marine tenure, the difference between aquaculture and traditional marine fisheries begins to fade.

When Garret Hardin first coined the phrase "The Tragedy of the Commons" he used the oceans as an example of an unowned resource destined for overexploitation. Thirty years later, little has changed, and many of the ocean's fish stocks are faring poorly. But aquaculture is different. Output is rising because entrepreneurs are trying to *produce* as many fish as possible instead of simply trying to *catch* as many as possible. The reason — private ownership and secure tenure.

Wild fisheries and aquaculture are two perfect examples of the importance of institutions. They operate under two very different sets of rules and produce two wildly different results.

The institutions that govern most fisheries tend to be either open-access or government control. That is beginning to change in some cases with the introduction of transferable quotas for fisheries, most notably in New Zealand, but the norm is still the rule of capture. Until a fish is hauled up on deck, it is fair game for everyone. Understandably, this does not encourage people to husband resources. If every fish that one person lets go is simply grabbed by someone else, then everyone will try to catch as many fish as they can, as quickly as they can. This is the tragedy of the commons.

Fortunately, there is no tragedy of the commons in an aquaculture facility. Fish can be left to safely mature because they will still be there tomorrow if they aren't harvested today. The difference is private ownership. It is the single most important predictor of resource productivity and conservation.

Technology has played a large part in the increases in aquaculture output, but only because private ownership encouraged this kind of innovation. Traditional fishers are rewarded for innovation as well, but only by allowing them to circumvent the latest regulation or to harvest fish faster than their competitors. Instead of increasing fish populations, traditional fishers only try to increase their own harvests, often destroying fish stocks and landing lower quality, smaller fish. It sounds crazy, but it is the natural result of poor institutional arrangements.

Technological innovation will be a crucial factor in the development of an offshore aquaculture industry, but secure tenure is paramount, for it is what will drive much of this technological advancement. The frontier American West offers an interesting parallel. Much like the oceans today, when the first settlers arrived and began to use the land, the West's natural resources seemed inexhaustible. But sure enough, before long, they began running out of space. One of the biggest problems they faced was how to keep track of their cattle. They all looked pretty much the same and it was impossible to fence in one's land — the raw materials to do so were simply not there.

But because they owned the cattle, and the land, frontier entrepreneurs were encouraged to come up with innovative, effective solutions to this problem. Their first innovation was to devise complex branding systems and to organize cattlemen's associations to keep track of branding registries that identified cattle. The second, and most significant development, was the invention of barbed wire. Suddenly, land could be fenced inexpensively, and the character of the frontier landscape changed dramatically.

A little ownership begets more. Initially in the West, boundaries could not be enforced, but because there was clear title to the land (no question of tenure), owners invested in and devised ways to effectively define and enforce those boundaries.

The open ocean is a harsh, rugged environment, much like the frontier American West was not so long ago. In many cases the technology may not quite be there yet for offshore aquaculture, but with the proper ownership arrangements in place, it will come quickly, and offshore aquaculture will surely have its own version of barbed wire before long.

The ownership of marine resources is rare, but not without historical precedent. Throughout Oceania coral reefs have been protected and productive for centuries due to a clear notion of marine tenure. Robert Johannes, an Australian who has studied coral reef conservation around the Pacific, found that many cultures clearly understood the link between exclusive control and stewardship. The complex arrangements that evolved to control the harvest of marine species around these coral reef communities may be the oldest example of a private (albeit community controlled) aquaculture operation. After all, a coral reef is essentially a natural fish farm.

In the United States, the Washington state oyster industry has also benefited from secure tenure. Washington is the only state with fee-simple ownership of subtidal lands, and the oyster industry there has been incredibly innovative. They have withstood the decline of the native Olympia oyster, introduced new varieties and weathered some very serious pollution problems in the 1940s and 50s, to become leading oyster producers in the United States.

The Maryland oyster industry, on the other hand, has proceeded down a very different path. Since the 1800s watermen in Maryland have relied on the state to manage their harvests, with the predictable result that harvests have been falling for almost a century. Even before the onset of disease in the 1970s, the Maryland oyster industry was crumbling. Watermen were more interested in government sponsored bailouts and subsidies for oyster bed maintenance than in taking steps to improve their harvest. In the 1970s, before the diseases, two economists from the University of Delaware compared the Maryland and Virginia oyster industries (Virginia is another Chesapeake Bay state) and found that in Virginia, where leased oyster beds were common, the oysters produced tended to be larger, healthier, and of better quality than their Maryland counterparts.

The Maryland government responded to this crisis by continuing to limit the harvest. As a result, while the Washington state oyster growers have improved their beds and increased their harvests with high-tech hatcheries, Maryland is left with the only commercial fishing fleet left in the country still powered by sail. People have been clamoring for Maryland to lease more of its oyster beds since before the turn of the century, but to little avail.

The Maryland oyster industry demonstrates that no matter how flawed a system is, changing it is difficult. There will always be people doing well under any given system or, at least, a large number of people who do not believe that they will be better off under a new system, which creates vehement opposition to change. This underscores how crucial it is for the offshore aquaculture industry to demand secure tenure arrangements from the get go. Barring outright ownership agreements, offshore entrepreneurs should fight for leases that last as long as possible, and for a minimum of political or regulatory intervention.

Political assistance is often very attractive, especially for a burgeoning industry, but in the long run it rarely pays off. Maintaining subsidies and beneficial regulations requires constant attention and creates an outlook for the future fraught with uncertainty and the potential for a reversal of fortune.

Such was the case for Pacific Ocean Farms Ltd., an open ocean abalone farming company that used to operate in California. Ocean Farms leased about 50 acres $2^{1}/_{2}$ miles offshore of Monterey, where in 100 feet of water they anchored a series of fiberglass boxes to rear abalone that they called condominiums. The company started off well, not only producing a valuable species, but counting among its allies groups like the Friends of the Otter, who hoped that the farm would increase the numbers of their namesake's favorite delicacy.

Then, the state of California stepped in. First, they rejected a bid to increase the number of Ocean Farm condominiums because they did not have garages. Then they required all of Ocean Farms' divers to use the same gear required of oil rig welders. And the final straw came when, according to the owner, the state demanded that the farm reveal its trade secrets to renew its permit, then turned around and set up its own hatchery operation. No wonder the business packed up and left.

Certainly regulators are not always such a problem, but even when they do try to craft institutional arrangements that encourage innovation and stewardship, things often go awry. Transferable quotas for fisheries have been one such attempt to change the system to get the incentives right. These quotas, or ITQs, assign the right to harvest a certain percentage of a total catch, encouraging fishers to behave more responsibly. Unfortunately, trying to institute this kind of system has proved very tricky. In the United States a broad coalition of fishers, managers and environmentalists believe that ITQs would be good for the fisheries, but there has been so much haggling over the initial allocation process that very little progress has been made.

Even in New Zealand, where the quota system has been in place for over ten years, many problems persist. One study of the paua (abalone) industry determined that "the spectre of too many fishermen chasing too few fish has been removed by the ITQ system, only to be replaced by special interest groups fishing politically on land for a share of the resource. The spectre now is of government carving and recarving a pie whose worth is diminishing steadily in proportion to the time and effort spent squabbling over who is to get what."

Economists call this behavior rent seeking, and it occurs everywhere that valuable resources are allocated politically. Aquaculture facilities may not be subject to the same kinds of harvest allotments that traditional fisheries are, but any sort of favorable regulatory environment or generous subsidy program could be a ripe target for political redistribution.

Considering the interest that environmentalists have recently taken in the aquaculture industry, the vagaries of political control should be obvious. Much of the environmentalists' attention has focused on near shore aquaculture, particularly in developing countries, over the issue of pollution and habitat destruction. Fortunately, secure ownership arrangements can address these problems as well.

Of course, aquaculture operations not only create some pollution, but are subjected to it as well. In Washington state, the oyster growers have long had title to their tidelands, which turned them into the staunchest defenders of water quality in that state long before anyone had even heard of the word environmentalist. Their industry, like every marine farming industry, depends on clean water to produce a quality, edible product. So in one sense, the creation of any aquaculture operation also creates a pollution watchdog.

On the other hand, aquaculture does produce some byproducts of its own. Moving operations offshore addresses many of these problems, but many in the environmental community will not be satisfied until there is zero discharge from a facility, so the problem will continue to haunt the aquaculture industry wherever it goes.

At the heart of the matter is liability, or a lack of it. An example is the artificial reef program in the state of Alabama, where private individuals can create artificial reefs in certain designated areas. Reefs may be privately created, but as soon as they hit the water, the reefs become public property and the state assumes all liability. Not surprisingly, reef creators have devised very effective artificial reefs for attracting and producing fish, but have taken little interest in the long term effects of these reefs. Many of them disintegrate quickly or get blown away in storms, much to the dismay of the local shrimpers when they rip their nets on stray shopping carts and automobile hoods.

In Japan, on the other hand, fishing cooperatives often have clearly established subtidal rights. They are very active artificial reef builders, and over the years have developed an amazing array of specialized reef designs, all of which are very durable and closely monitored. Some reefs close to shore even have guards watching over them 24 hours a day, and the cooperatives are vigilant of any pollution problems.

Unfortunately, Japan is the exception and most aquaculture facilities are subjected to the same kinds of rules as the reef creators in Alabama are. Any pollution created generally enters an unowned commons, and so there is no one like the oyster growers in Washington to take any directed action. When no one owns a resource, for example clean water in a river, a bay or part of the ocean, individuals do not bear the costs of depleting that resource.

When shrimp farmers in developing countries destroy mangrove forests, even when it is clearly in their best interests to have them around to provide broodstock and clean water, the tragedy of the commons must be at work. When no one can be held liable for destroying the mangroves, they will quickly disappear. Statutes and regulations are one way to impose liability and impose costs on producers, but another, more effective way is to increase ownership rights and rely on the common law to resolve conflicts.

The common law states that any damage to another's property must be fully compensated and that the offending activity must cease immediately. Common law suits are between two private parties. If, for example, it could be proved that someone was breaking someone else's windows, under the common law they would have to cease and desist the offending activity (breaking windows) and replace the broken ones, not because there was a specific law against breaking windows, but simply because property was damaged. In England and Wales the right to fish for salmon in many rivers and streams has been well defined for centuries, and the owners of these rights have used the common law to prevent pollution. In many cases the worst polluters were municipalities — the very people charged with keeping the water clean.

Oyster growers in Washington are beginning to learn the limitations of statutory pollution control right now. When they first began to fight pollution they relied on the state to set and enforce strict guidelines. This worked well for point-source pollution, such as the outfall from a lumber mill, but now that most pollution problems stem from non-point sources of pollution such as agricultural runoff or leaky septic tanks, they have little recourse. It is too difficult to apply any regulations on this type of activity across the board, so that even though in most cases the oyster growers know exactly where the offending pollution is coming from, there is nothing they can do about it, as statute law supersedes the common law in the U.S.

The common law relies heavily on precedent and can help to resolve causes and effects. Such was the case in Ireland when riparian river owners sued nearby offshore aquaculture operations, claiming that they were responsible for decreasing their trout runs. This turned out not to be the case, and so the suit was eventually dropped. Now a precedent has clearly been established and any similar suits in the future are unlikely.

One advantage of the common law is it allows precedents and rules to evolve over time. It also does not stipulate that there must be zero pollution, only that it may not damage someone else's property. This may sound vague but in the United States at least, strict pollution control regulations often turn out simply to be a license to pollute. And even if pollution *does* cause harm, it does not necessarily have to stop as long as the two parties involved can come to an agreement.

To conclude, offshore aquaculture entrepreneurs should push for as much private ownership and responsibility as possible. The fewer restrictions the better – subsidies should be spurned today for they can easily become restrictions tomorrow, and pollution control should be left to the market and the common law doctrine of nuisance. When no one owns any part of the seas, Greenpeace can claim to be the guardian of the seas and target aquaculture with fears about pollution and escapes. No one knows where political power will reside in the future, and no doubt the aquaculture industry would not fare very well if that power rested with Greenpeace.

Clear ownership rights preclude political redistribution. Commercial and recreation fishers are always fighting over fish stocks, and today the anglers are winning. There are simply too many of them, and when resources are allocated from the ballot box, sheer numbers are the best indicator of success. If all the SCUBA divers in Hawaii decided they didn't like offshore aquaculture, the prospects would be dim indeed.

Both government managers and aquaculture entrepreneurs need to realize the importance of ownership and the danger that a reliance on political control presents. If offshore aquaculture is to be a success, ocean farmers must be able to rely on secure marine tenure.

Current and Potential Regulation of Open Ocean Aquaculture

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Regulation of open ocean aquaculture in the United States is one of the largest hurdles facing open ocean aquaculture in the U.S. and, I suspect, elsewhere. Advances in both engineering and culture practices now make open ocean aquaculture feasible. Fixed gear, or moored farms, are now operational in several locations around the world. In a new development since last year's conference, unmoored or drifting farms are in the design stage. It is anticipated that such farms would be employed in oceanic gyres. They may be manned or fully automated. They may have some form of propulsion or be completely free floating and redirected by boat as necessary.

The following are advantages of open ocean aquaculture:

- economies of scale can be achieved with open ocean aquaculture, an important factor for those species sold in competitive global markets;
- there is no organic enrichment due to the volume of water available for dilution; and
- there is less predation if facilities are sufficiently removed from shore.

This should make it easier to permit open ocean aquaculture but this is not likely to be the case. Permitting has been and will be difficult because state and federal agencies have not developed regulations that specifically address open ocean aquaculture. Ironically, this lack of regulation is an even greater obstacle to the establishment of offshore farms than the regulatory burden felt by inshore farmers. Without guidance on how to proceed, regulatory agencies are and will be reluctant to act on requests for open ocean farms.

It is in the interest of open ocean aquaculturists to anticipate the issues regulators will face. Proposals for offshore farms must provide credible, scientific support for their claims that the activity will not have adverse impacts.

Current regulations address navigational and environmental issues, and at the state level, the transfer of property rights that allows the aquaculturist exclusive use of an area. They do not address transfer of property rights in federal waters or regulate unmoored pens in either state or federal waters. With regard to the transfer of property rights in federal waters: At last year's conference in Portland, we heard a presentation from Cliff Goudey regarding the experimental Westport scallop project proposed for federal waters off of Massachusetts. The project was permitted fairly rapidly by the Army Corps of Engineers because of the short-term nature of the project (18 months) and because its use of native, filter feeding species eliminated most environmental concerns. The hang up for this project was transfer of property rights: they needed exclusive use of the project area. They planned to seed the bottom with juvenile scallops and didn't want draggers going through it. In August of 1994 they applied to the New England Fisheries Management Council for closure of the area to fishing activities. They chose the Fisheries Management Council because the wild fishery for scallops is managed by the Council. In addition, the fisheries management councils are the only bodies able to deal with conflicts associated with use of federal waters. However, the Council had no experience with aquaculture and was forced to address the application for closure on an ad hoc basis. In a process that took 2-1/2 years, the closure was granted this past February and the project is finally underway.

What about unmoored pens? What should you do if you want to put fish in a pen and set it adrift? I have talked to some who feel you would be home free because there are no regulations addressing unmoored aquaculture facilities. It would be a big mistake to assume, however, that because there aren't any regulations no one is going to care. Putting an unmoored facility in the water under this assumption would give new meaning to the phrase: "if you build it they will come." If regulations are not currently in place to address unmoored pens they will be almost as soon as the need arises. I believe that the Coast Guard already has the authority to regulate unmoored pens because of the hazard they pose to navigation. And the National Marine Fisheries Service has the authority to regulate activities whose impact "may" affect endangered marine species, such as whales.

State and federal regulations are in place for moored facilities but criteria for judging permit and lease applications have been based on nearshore facilities. Regulators will need to reassess these criteria in light of the different circumstances posed by open ocean versus nearshore facilities. In order to anticipate regulators' concerns regarding open ocean aquaculture it is important to review government's interest in aquaculture. This past year I had the opportunity to help draft a strategic plan for aquaculture for the State of Maine. The State's interest in aquaculture was defined and is probably representative of governmental interest in aquaculture generally. It consists of two parts: stewardship of publicly owned resources including marine waters and living marine resources; and promotion of economic development.

These two responsibilities can and do conflict. As a result, regulators must carefully balance environmental protection and economic development. Where uncertainty exists about environmental impacts or impacts on politically powerful traditional uses, regulators are reluctant to permit new activities.

What about aquaculture in international waters, that is, 200 miles offshore? I think it is fair to say that of the hundreds of bilateral, regional and international agreements addressing the marine environment, none directly address open ocean aquaculture. However, I think the same principle applies here as well as in waters under national jurisdiction: lack of existing regulation does not mean that no one will care if you want to farm in international waters.

The United Nations Convention on the Law of the Sea, which entered into force in 1994, establishes a comprehensive framework for the regulation of all ocean space and resources. Its most well known provisions address limits of national jurisdiction over ocean space, establishing the 12 mile territorial sea and the 200 mile exclusive economic zone. By laying down the basic legal regime for the conservation and utilization of marine resources, the convention provides a basis for regulating aquaculture in international waters, should the need arise. The Convention has addressed other specific high seas issues including highly migratory fish stocks and the large-scale pelagic drift net fishery. The Convention also includes a Code for the Responsible Conduct of Fisheries. So there is precedent for addressing issues such as open ocean aquaculture.

The following are regulatory issues likely to be raised by open ocean aquaculture:

Navigation

Navigational issues inshore relate to protecting ingress and egress from anchorages. Offshore, the issue is likely to be interference with shipping. If an unmoored facility is proposed, will it drift into sea lanes or otherwise be a hazard to navigation? In a storm will it be driven into shore, anchorages or other facilities?

Environmental

Nearshore farms are scrutinized for their potential contribution to organic enrichment. Offshore farms are more likely to be reviewed regarding release of disease organisms and theraputents.

Impacts on marine mammals and other organisms

This has the potential to be real trouble for offshore farms. The humpback whale is an issue here in Hawaii. In the Gulf of Maine we are currently experiencing a crisis over the right whale. There are only 300 right whales remaining; apparently only a very small number of these are breeding females. A law suit by a local activist has forced the National Marine Fisheries Service to develop regulations reducing the risk of lethal take of right whales by lobster gear to less than one per year. The proposed regulations call for drastic regearing, including use of break away buoys, replacement of floating line with sinking line and limits on the number of buoys on trawls. The cost of implementation is estimated to be up to $70 million and many feel that the industry may go under as a result. We are talking about Maine's lobster industry, a cultural heritage and important economic activity that is synonymous with the State. Can you imagine what they would say about a new and little known idea such as open ocean aquaculture? Moored pens would have to be sited away from known or suspected whale habitat. Unmoored pens would need a system of relocation to keep them out of such areas.

Salmon provide another example of the potential impact of open ocean aquaculture on other species. Transmission of disease, disruption of spawning areas by escaped fish and the introduction of non-native genes are all concerns regarding the impact of salmon aquaculture on wild stocks. Aquaculture is prohibited altogether in Alaska over concern regarding potential impacts on a significant wild fishery. In Maine, salmon aquaculture is under siege from groups seeking to restore Atlantic salmon to former habitat. International law recognizes the right of the nation of origin to prohibit harvesting of its salmon on the high seas. Would it therefore allow such nations to regulate open ocean aquaculture to protect wild populations of salmon? It remains to be seen.

Use conflicts

Will the farm interfere with commercial or recreational fishing or other use of offshore waters? Fishermen in Maine and elsewhere are extremely leery of aquaculture because they see it as an infringement on the commons. Aquaculture statutes in Maine prohibit farms from areas where traditional fishing occurs and Maine fishermen are growing accustomed to farms in nearshore waters. The prospect of open ocean aquaculture may raise anew the specter of privatization of the ocean and get fishermen up in arms. In some areas, charter boat captains have the same concerns.

Yesterday, Jim McVey called for the development of an integrated marine policy, one that would result in the comprehensive, ecosystem-based management of coastal waters and resources. I second Jim on this; such management would go a long way towards resolving the regulatory hurdles described above. Comprehensive management of marine resources will have to be conducted at the scale of large marine ecosystems. If such an ecosystem is not wholly within a nation's jurisdiction, the Law of the Sea Convention provides the legal framework for bilateral or regional agreements on conservation of living marine resources within the ecosystem.

Examples of ecosystem level management include the convention for the conservation of Antarctic Living Marine Resources and management of the Great Barrier Reef. Management should be based on knowledge of the structure and function of the ecosystem including its carrying capacity. Conflicting uses must be balanced based on their sustainability, exclusivity and benefits provided. Socioeconomic and cultural factors must be considered as well. Very importantly, stakeholders, including aquaculturists, fishermen and environmentalists, must participate in the development of comprehensive management plans.

The advent of geographic information systems (GIS) has made comprehensive marine management feasible. GIS is useful for analyzing complex factors synoptically, including physical, chemical, biological, economic, social and cultural data. GIS can be used in problem solving where diverse factors have to be considered, where these factors differ in importance, and where the factors are quite variable.

Nova Scotia, in the Canadian Maritimes, has initiated comprehensive coastal management using GIS. Generation of maps identifying potential and existing aquaculture sites in relation to traditional fishing grounds has allayed many fears regarding development of aquaculture. Public opposition to new farms has dropped dramatically since the effort began.

Comprehensive management can also identify suitable sites for aquaculture. In Scotland, using biological and physical criteria, data on bathymetry, current, shelter and water quality were used to determine the suitability of a given site for finfish aquaculture.

Such analyses could also incorporate areas where aquaculture is inappropriate such as near endangered species habitat, shipping lanes, etc.

Economic data can be a factor in comprehensive management. On Prince Edward Island, the potential value of shellfish in closed areas is used to prioritize removal of pollution sources.

In conclusion, open ocean aquaculture would do well not only to anticipate the concerns of regulatory agencies but to initiate discussions with government officials and other stakeholders regarding the need for a comprehensive management plan in their area.

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Selecting Nearshore and Open Ocean Mariculture Technologies for Hawaii

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Abstract

The State of Hawaii places a premium on maintaining its ocean environments in a sustainable condition for future generations. Given this philosophical approach and a strict regulatory climate to support it, as well as incomplete knowledge of nearshore and offshore oceanography and topography by farmers, the aquaculture industry has developed exclusively on land. With the increasing cost limitations for onshore sites and declining capture fisheries feeding local markets, nearshore and offshore marine technologies and sites must be carefully chosen for the next stage of the industry's development.

Considering the Hawaii marine environment and the host of technologies available worldwide, we describe a few deep water culture systems and species for future consideration. Our approach in our choice of systems is to anticipate potential problems and suggest credible solutions. Of great importance is whether the cage systems can withstand Hawaii ocean conditions. The existence and ease of transferring marine biotechnologies that foster species with short development times are critical for success and potential profitability.

Introduction

One aspect of the aquaculture industry, which has not been tried within the State of Hawaii, is that of ocean cage culture. Pen or cage culture is most familiar to aquaculturists when done within lake or ponds for a variety of species worldwide. The movement of this production system to sheltered nearshore and more recently into exposed offshore areas has been limited initially to Japan and Europe (Norway, UK, Ireland). The next wave of development has occurred on the western coasts of South American (Chile) and most recently, Singapore and others in Southeast Asia (http://www.sea-world.com/hotnews/singapore/january.htm) have tried these large-scale cages in more exposed situations. The commercial species of choice has been salmon in Europe and South American or yellowfin tuna in Japan. A novel concept with much commercial success is the culture of wild capture bluefin tuna in cages located offshore (http://www.nexus.edu.au/Schools/PLHS/tuna).

To date, inquiries for offshore development projects in Hawaii have been minimal, but this trend will change within the next few years. Clearly, offshore aquaculture is growing in other countries, but has not taken off within the United States. This discussion is a broad brushstroke forecast of the challenges and evolution of a land-based Hawaii aquaculture industry moving offshore. Briefly we examine the advantages and disadvantages of open ocean aquaculture; positive solutions as related to site selection considerations; stepwise solutions for this kind of development; technology available and thoughts for a demonstration project.

Toward Distinctive Challenges

The Hawaii aquaculture industry will be faced with distinct problems and challenges for innovative solutions when going offshore. This step represents a movement away from an easier working environment to one where planning and logistics are very important. These technical problems will not be unique to Hawaii, and have been met by the offshore aquaculture industry in other parts of the world (see McElwee, 1997 in this volume). Rather than re-inventing the wheels, Hawaii ought to critically evaluate what is good and in actual use, prior to expending capital investments.

To be sure, the industry will be using an existing biological knowledge base developed from ongoing laboratories and research efforts to raise high-valued products. However to take advantage of unlimited space for expansion and to surmount the previously limiting factors, we also need to incorporate new perspectives and skills. The active workforce will be more nautically inclined and knowledgeable about working at sea. There will be need for site specific oceanographic knowledge and interpretative skills, for example, in site selection or facility design and maintenance. Of great important would be a system of forecasting and alerts of incoming climatic conditions that would adversely affect an offshore farm of cages. Thus, we can move away from land-based projects to go to offshore-based aquaculture production.

Hawaii has stringent environmental regulations based upon a strict interpretation of Federal regulations. Our offshore State waters are classed as AA or A class waters owing to the oligotrophic waters in the tropics. On the continental U.S., the offshore waters are not as restrictive. More difficult hurdles to overcome are the public use customs and perspectives which become more stringent when incorporating Native Hawaiian access and gathering rights. As you travel along the shoreline note that property owners can not block access to the shore. This is for the use by all people for swimming, surfing and other water-recreational activities. Tied to many permitting procedures are public hearing processes. Gather enough negative declarations and one watches a project go down in flames or be regulated to a gulag.

The high business cost of offshore aquaculture must be offset by a new paradigm. The volume of production must be high, as well as, the value of the products and their market, substantial. In addition any methods or conditions, which can lead to a short and quick turnover rate, will allow for greater cashflow and project longevity. Yet what is most important is that the consumer demand for the products produced or niche markets where the supply is insufficient, will increase over time.

To date, the only successful species produced using open ocean aquaculture technology has been salmon, and on land, shrimp. In Japan, the focus is for yellowfin tuna production and in Singapore, sea bass. The world market is glutted with aquaculture salmon and with a depressed price for wild caught salmon. For Hawaii to enter this market where one cage will produce upward to 300 to 400 mT of finfish, salmon as a culture species is not a logical choice. Rather, we should capitalize on the strengths of our research and develop methods for species found in Hawaii. Thus, we can market new species in a non-competitive mode, as compared to salmon. Mahimahi and moi are on the horizon and ready for technology transfer, and other species have already been targeted for future research, if not already in progress. This is a similar pattern of research for finfish biology in Europe.

Issues

Positive incentives for offshore development would lead to new opportunities for fishermen on limited seasonal catches or closed fisheries; opening of positions requiring more technical skills; relief from limited sites for land-based development; and most importantly, increased revenues from expansion of an ocean-based industry sector.

Disincentives can include potential for nutrient loading owing to farm location and currents; conflicting uses of a proposed site; high startup costs; and risks inherent to the industry.

Currently no laws permit individuals or companies from using a common resource for private ends, nor protect the property rights and interests of an open ocean farm. A review of the Hawaii statues governing the leasing of ocean bottoms has been reviewed by Corbin and Young (1997) elsewhere in this volume. To be able to lease or use a site for a set amount of time is incomplete. For a farm to be created on the open ocean, there need to be rules for ownership over the resources created onsite whether by culturing and holding finfish in cages; ranching free roaming finfish held to one location by conditioning and a feeding station; or by artificially enriching a localized area (see Markels [1997] in this volume).

Site Considerations

A large part of establishing an enterprise will include finding a site to farm. The technical overview for a good site will require information on depth, bottom composition, winds, and current patterns. A general indication of where to pinpoint a site can be found using information from http://satftp.soest.hawaii.edu/atlas.html. The physical parameters for site selection are critical for risk reduction. The next stage potentially can include an environmental assessment or impact statement with public inputs. The problem solving aspects of coping with these "market forces" of public concerns, governmental concerns — Federal and State — and physical environment realities may be overwhelming. We need to determine means of reducing conflicting uses through dialogue and public forums, a very difficult process. Government regulations should meet the public good, but sometimes at great expense. The current status for securing a lease or an easement for a site is costly and lengthy. This process is not the feint-hearted, nor easily fatigued investor.

Discussions with Pierre Flament (Dept. of Oceanogr., Univ. of Hawaii at Manoa, pierre@soest.hawaii.edu) on the physical environment for cage culture suggested these following sites. Bathymetry and wave activity as related to seasonality, are calmest on the leeward side of all islands. Potential areas for development within the State include protected embayments, the Penguin Banks area, and the ocean area encompassed by Molokai, Maui, Lanai and Kahoolawe.

Stepwise Development and Technology Considerations

The question at this point is how to incorporate a will for development which allows for offshore aquaculture to begin? Ultimately, the process begins with and involves ocean bottom leasing and the State law has not been fully tested, nor defined. The logistics and integration with the State, county and Federal regulation must be worked out.

We propose to begin with Hawaiian fishpond sites. Where a firm could work within or offshore from a fishpond. This area would provide a staging site for on-land planning and logistics for moving offshore. There a firm could locate hatchery, nursery ponds, storage for equipment, supplies and personnel. These areas are generally within protected offshore areas of the coastline. Fishponds could represent a small jump to an offshore site. These areas unfortunately may or may not be within view planes where resorts and private homes are located. As experience is accumulated, more exposed offshore and oceanic areas could be utilized.

Alternatively as in the case of industrial or agricultural parks which exist in many places, an offshore site could be readily demarcated and permitted ahead of time. Thus an enterprise coming to Hawaii can lease a portion of an offshore aquaculture park site for its activities with minimal costs for meeting regulatory requirements. Staging areas could also include planning for waterfront wharfage and warehouse space to be leased. This turnkey process and infrastructure building by local government would require some insight and commitment for future prospects. Such actions would allow for companies to have a quick startup with lower costs in a short period, all factors portending likely success.

We have identified five kinds of technologies to consider. Within the fishpond or in shallow nearshore and protected embayments, one can use pen enclosures continuous with the bottoms. Moving to areas of greater depth, floating cages can be used in places where the sites are protected and not exposed to fast currents or much wave activity. Floating cages can be made with easily replaced local materials (see http://www.ansc.purdue.edu/aquanic/images/photos/sing/ flfarm.htm as an example). In higher energy environments, the floating cages are engineered to withstand the physical environment and materials and designs may need to be imported. There are proven ocean cage designs by Bridgestone Corporation (Japan), Dunlap Corporation (UK) and others. An example is a salmon farm in Maine with onshore and offshore facilities and various kinds of floating cages related to their experiences (http://www.MajesticSalmon.com). In yet more exposed and open ocean areas, one uses submersible cages, which can take the violent environment (see http://www.interviz.com/editions/World-Aid/82351.htm as an example). More complete information is found elsewhere in this volume (Bougrova, Matveev and Bugrov, 1997) for submersible cage systems.

Another alternative is to consider an offshore location for logistics as in a Spanish floating platform, which is designed to sustain upward of 450 mT on finfish production per year (see http://pegasus.cambrescat.es/msi/msi_fish.htm). Platforms can serve as a center for holding supplies and managing various cage systems anchored offshore in proximity. There are many oil production platforms in the Gulf of Mexico, Europe and elsewhere in Southeast Asia. Elsewhere in this volume are the experiences of a Texas group in using oil platforms (Chambers, 1997). A more extreme example of intensive capital investment is the example of converted ships or barges for finfish production. Like the platforms, motorized vessels can serve as a staging area and have the added advantage of being mobile. Thus, prior to a severe storm arriving at a site, the vessel can tow its cages to a more protected area — minimizing the risks of losses.

To efficiently pursue development, all technology, experts and material parts ought to be taken off the shelf from where it is being used successfully. This will cut down the cost of development and startup. There can be an infinite variety of design and solutions for problems, but the pilot-scale, field testing and modification processes are expensive costs.

Future Action

With this rapid review of issues and technology, what is immediately possible? The State has a research corridor of NELHA, at Keahole Point, perhaps a less desirable demonstration site for scaling a pilot project. Alternative sites upon consultation with many interested parties ought to be pursued. The best approach is to engage fishermen with boats and others with experience in aquaculture, not unlike the South Australian farming of bluefin tuna. These companies corral fish at sea and rear them for growout in more sheltered bays. This practice has spread to the Mediterranean and Croatia.

Prior to getting started, individuals ought to generate a business plan and examine the numbers for profitability and sustainability. If the internal and external factors do not have profit to support the project for longevity, it is not sustainable. There is no need to expend money for a project without positive cashflow other than validating its potential. Important is the selection of a local species with known biological characteristics and closed lifecycle methods for entry into a world market. The point is not to compete against other countries where production costs may be lower for what is a commodity product like salmon. Offshore aquaculture can be a sustainable activity which will require working out technical, legal, political and social details (Stickney, 1997).

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Technology of Cage and Longline Culture Systems

Potential Offshore Cage Culture Utilizing Oil and Gas Platforms in the Gulf of Mexico

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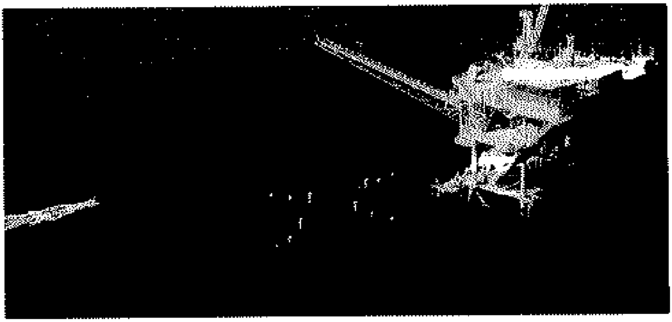

Figure 1.

Abstract

MNE, Inc. is a wholly owned subsidiary of a major petroleum corporation that was engaged in offshore mariculture research. The concept was to develop an economical method to convert abandoned oil and gas platforms in the Gulf of Mexico to fish farm sites. The platform provides an excellent permanent anchor and base to house feed and automatic feed systems, monitoring equipment, and conduct daily fish culture activities. An overview of the six year project and test cages on platforms seven to 35 miles offshore will be discussed.

The MNE Concept

Since 1989, MNE has researched, designed, and tested six offshore, open water fish containment systems and invested approximately $6.5 million. The project was spearheaded by Wilbur Johnson, President of MNE Inc. and the principle investigator was Dr. Russell Miget, Sea Grant Specialist from Texas A&M University. The MNE concept was to use abandoned oil and gas platforms as production facilities for warm water, marine fish farming. The platform provides an excellent, existing base to house automated feeding systems, monitoring systems, and personnel activities. Structurally, the platform provides a permanent anchor for fish containment systems. Most platforms are constructed to withstand 20' storm surges and 100 year storms (hurricanes). Thus, the containment system(s) is attached directly to the legs of a platform, thereby eliminating costly, sophisticated mooring or anchor configurations (Breed, 1994). MNE's test systems have employed this methodology on platforms ranging from 70' of water, seven miles from shore, to 270 feet of water, 25 miles from shore.

Background

Oil Industry's Offshore Problem

The Minerals Management Service (MMS) currently estimates that more than half of the 4,000 oil & gas platforms in the Gulf of Mexico will be removed by the year 2000. These structures range in age from brand new to roughly 35 years old; in size from single caissons to large, multi-pile; in water depths from a meter to over 350 meters, and in distance from shoreline to more than 130 miles offshore (Dougall, 1994). Platform design, construction, and deployment may cost an oil company between $10-30 million. The cost of removal ranges between $4-10 million. As the Gulf of Mexico reaches its maturity in the oil & gas production life, the industry has begun to incur the legally mandated costs of plugging well bores, removing platforms and restoring the seabed to its natural state. The $8-10 billion oil industry for traditional, "pristine" restoration coupled with persistent low oil & gas prices have motivated operators to develop several cost mitigating methods for platform removal (Breed, 1994). These methods include:

- Dropping platforms in place as a artificial reef.
- Platforms can be donated to the state as an artificial reef and hauled to an approved sinking site (Rigs to Reefs Program).

- Improved salvage methods and cheaper service rates have made complete removal and pristine seabed restoration for nearshore, shallow water platforms.
- Platforms with sound structural integrity have been hauled to and reused at other oil & gas fields.

The Mariculture Opportunity

The U.S. commercial fishery is declining dramatically. Many traditional regions have been closed to commercial fishing or severely restricted. The global catch of fish has leveled off at 100 million metric tons/year. This quantity does not meet the demand today, let alone the demand that will exist in the future. The Food and Agriculture Organization (FAO) has projected that the industrialized nations of the world will require an additional 22.5 million and the non-industrialized nations another 5.9 million metric tons of fish and seafood products by the year 2000. If the world's oceans cannot naturally produce the 28.4 million metric tons needed, then perhaps aquaculture can (Moore, 1994).

The Offshore Concept

- Seafood Supply and Demand
  - ~ Limited capacity from wild harvests (100 million metric tons/yr)
  - ~ Increasing demand for seafood
- Growth of Aquaculture
  - ~ Fastest growing sector of U.S. Agriculture
- Problems with Land-based Aquaculture
  - ~ water costs
  - ~ low temperatures during winter
  - ~ water quality
  - ~ water access (user conflicts)
  - ~ pollution
- Oil Company Interests
  - ~ prevent/postpone dismantling of platform
  - ~ diversification
  - ~ positive public relations through partial release of fish produced on platform

Advantages to Offshore Mariculture on Platforms

- Existing Technology
  - ~ salmon cage culture technology (i.e., feed systems and cages)
  - ~ existing platforms in place
- Biological
  - ~ clean, oceanic water absence of nearshore pollution
  - ~ rapid growth rates due to constant year-round temperature and salinity
  - ~ the capability of raising high-value marine species
  - ~ the capacity for greater harvest density due to higher dissolved oxygen rates
- Financial
  - ~ no pumping or aeration costs
  - ~ expansion capacity
  - ~ existing infrastructure from oil industry (i.e., boats, cranes and workforce)
- Political Support
  - ~ Minerals Management Service (MMS)

Disadvantages to Offshore Mariculture on Platforms

- No Proven Cage Technology (in the Gulf of Mexico)
  - ~ cages that can withstand hurricanes
  - ~ constant current and wave action on cage system
- Biological
  - ~ biofouling on cage creates weight and stress, reduces water flow
  - ~ bottleneck in hatchery technology to produce high-value seedstock
- Financial
  - ~ weekly transportation in service boats
  - ~ platform maintenance ($10-12,000/yr)
  - ~ high operating costs offshore
- Political Opposition
  - ~ recreational
  - ~ navigation
  - ~ regulators
  - ~ fishing Industry

- Liability
  - ~ accidents
  - ~ lease abandonment

Ideal Parameters for Offshore Culture of Warm Water Species

- Stable water temperatures ranging between 21- 260° C.
- Oligotrophic / pollutant free waters
- Water depth between 35-70 meters
- Infrastructure in place (i.e., service boats, feed mill, and markets)
- Timely permitting process that will allow a commercial venture to succeed

Fish Pen History

The chosen site for the initial test cage was on a multi-pile platform, located 35 miles off the Texas coast in 270' of water. An experimental cage, called the gerbil cage, was designed and built by petroleum engineers and, as a result, was as strong and as expensive as a platform (Figure 2). Two steel frame cages

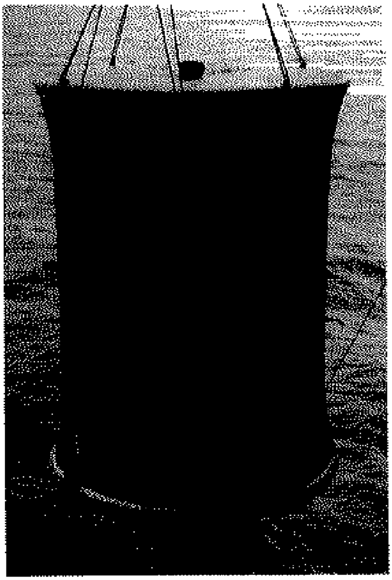

Figure 2.

were constructed and suspended by a 4" Dacron rope within the confines of the rig. The Dacron rope was attached to the main deck and threaded through the center of each cage. The cage was then secured in the water column by a 30,000 lbs. clump weight. One cage was suspended 10' while the other was suspended 20' below the surface. Each cage had an inner 1/2" mesh net that could be removed (by zipper) as the fish grew. The middle net was 1" mesh while the outer consisted of a 4" predator net. The top and bottom of the cage was covered by a 1/2" perforated steel plate.

A total of 8,000 red drum (*Scianeops ocellatus*) were delivered by Red Fish Unlimited to Harbor Island in Port Aransas, TX. The fingerlings (30 g ea.) were transferred offshore and stocked 4,000/cage. A commercial deer feeder (1,000 lbs.), equipped with an automatic timer, delivered feed five times/day through a 4" pipe. A solar panel on top the platform powered a bank of batteries that ran the feeder, timer, and water flush system that moved feed down the pipe. Results of the gerbil cage trial are listed in the Table 1.

Table 1. Production Data for the Gerbil Cage

Parameters	**Cage 1**	**Cage 2**
Cage Volume	99 m^3	99 m^3
Stock Date	8/22/90	8/22/90
Stock Mean Weight	30 g	30 g
Estimated Fish 8/29	1,500	3,500
Duration	1 year	1 year
Total Harvest Weight	699 kg	2777 kg
Harvest Mean Weight	783 g	922 g
Harvest Density	7 kg/m^3	28 kg/m^3
% Survival	59%	85%
Weight Range	553-1640 g	706-1860 g
FCR	3.8	3.8

The gerbil cage trials educated MNE staff on aspects of cage integrity, rate of fouling, feed delivery systems, growth and survival, and the logistics of working offshore with an oil company. The next step was to escape the confines of the rig and utilize the vast amount of water surrounding the platform. A larger, more economical system could then be implemented to make such a venture profitable.

As a result, an Ocean Spar Net Pen was then tested at the platform. This 500 m^3 square, floating system consisted of four 30' corner spar buoys (Figure 3). Each spar included a damper weight which gave integrity to the net. The net system was moored in place by 10,000 lbs. anchors off each spar. The net was stocked with 10,000 red drum from Red Fish Unlimited. Unfortunately, during heavy seas and storms, the anchors would drag or the turnbuckles holding the net to the spar would break and collapse the system. This Ocean Spar Net Pen was then moved nearshore to a closer, unmanned rig. A site was chosen seven miles off of Port Aransas, TX in 70' of water in an area that was thought to be much calmer than the previous site. This site, being much closer to the boat harbor, would also reduce the costs of operating offshore. The Ocean Spar Net Pen was tested several more times at the nearshore site and similar failures occurred.

After consultation with the oil company, a semi submersible pen was designed and patented from high density polyethylene (HDPE). This system utilized a collar that could be inflated with air to raise and lower the pen in the water

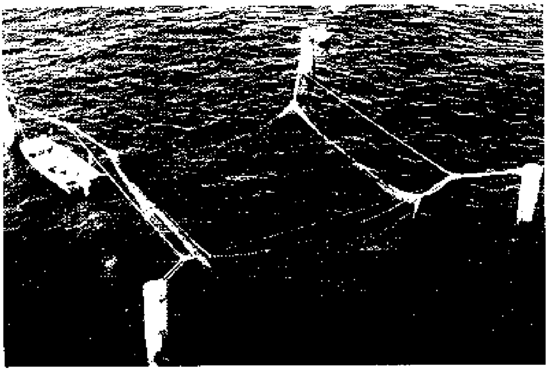

Figure 3. Ocean Spar Net Pen.

column. The HDPE frame gave the system flexibility in the water, and the slick surface retarded biofouling. This system, unfortunately, was too flexible and cross bracing broke from the frame during heavy seas. As a result, a stronger aluminum frame (octagon) was constructed and deployed. Within a month, a severe storm tore the containment net from the frame. Mooring anchors outside the platform moved during the high seas allowing the octagon pen to relocate. The entire project was re-evaluated at that time. (Miget, 1994).

The decision was then made to design a cage that would combine the sturdiness of the gerbil cage and encompass the water around the platform. The result was a 200 m^3, stainless steel, octagon frame that clamped onto the side of the rig 15' below the surface (Figure 4). The cage was covered with a plastic coated 1-1/4" mesh net and was attached by stainless steel bands.

This test cage lasted approximately 85 days in the ocean before Mother Nature (storms and biofouling) took her toll (Figure 5). The strength of this nearshore environment bent the frame, broke the stainless steel bands, and peeled the wire net completely off.

The next cage design utilized the same principle as the last cage but was fabricated from different materials. This system was constructed by a local contractor from carbon steel

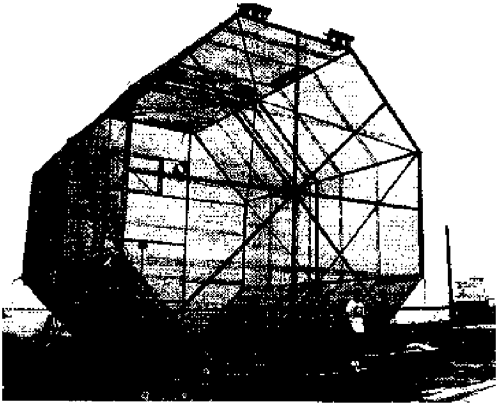

Figure 4.

in the shape of a hexagon frame (schedule 80) with a fiberglass skin. This 4 m^3 prototype was clamped on the leg of the platform, 20' below the surface and stocked with 500 Florida pompano (*Trachinotus carolinus*). This system was fed via a solar powered deer feeder on top of the rig. The pompano were fed 5 times/day on a Rangen Redfish pellet and grew from 30 g to 445 g in 11 months.

The 4 m^3 prototype worked so well that a scale up version was created to examine these same components on a larger, commercial size cage. This new design was called the Fibergrate cage and had a volume of 95 m^3 (Figure 5). The shell or skin consisted of 36, 3' by 10' fibergrate panels. Each panel was 1" thick, had 1-1/2" square mesh, and was dipped in an anti-fouling paint (cuprous oxide base). A container unit (20'x8'x8') was renovated into a mini lab/feeder unit. This unit comprised of bunk beds, generator, computer with telecommunication, and automatic feeder with flush system. The entire system was solar powered and could be controlled from shore with another computer.

Feed amounts, times fed, and total amounts fed to date were transmitted back to shore daily. Ocean parameters such as current speed, direction, and wave height were also monitored and recorded through the use of an Inter Ocean Probe. The cage and container unit were deployed by lift boats. Lift boats are common in the Gulf of Mexico to service oil platforms. They

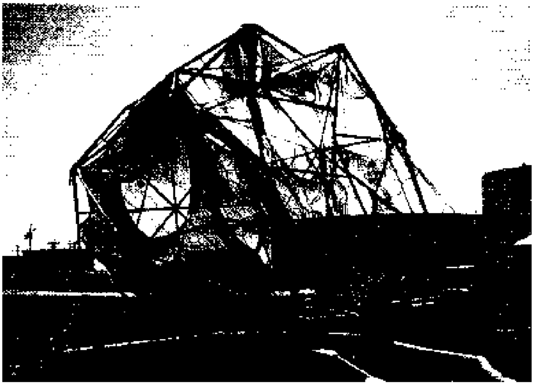

Figure 5.

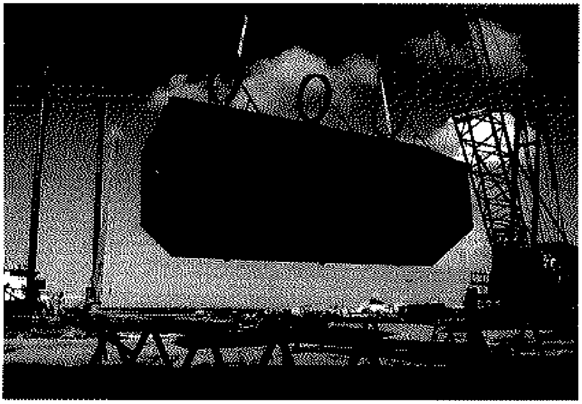

Figure 6.

consist of a barge with living/working quarters, cranes, and three 100-150' legs with pads. These legs are hydraulically lowered till they hit bottom and lift the barge completely out of the water, thus creating a stable platform from which to work. The Fibergrate cage was deployed and attached onto the rizor leg of the platform by three metal brackets, 30' below the surface. The cage was stocked with 5,300, 85 g red drum and they were fed a rangen redfish diet 4 times/day via a 6" hard pipe that extended down to the top of the cage. Results from the fishbone cage are presented in Table 2.

Table 2. Production Data from the Fibergrate Cage

Parameters	Cage
Cage volume	95 m^3
Numbers of Fish	5,300
Stock Mean Weight	85 g
Duration	6-12/95
Temperature Range	10-31° C
Harvest Mean Weight	1,021 g
Total Harvest Weight	3,847 kg
Harvest Density	40.5 kg/m^3
% Survival	71%
FCR	2.0
SGR	1.4%

Conclusion

MNE's six year research project was successful in developing the first cage in the Gulf of Mexico to produce and sell fish to market. Since the project, new cage companies from around the world have developed and tested systems that could prove to be commercially viable in the open Gulf. Today, the potential for offshore mariculture on platforms is more feasible than ever. The permitting process is in place and most of the hurdles have been overcome. The next step is for big business to get involved to make this type of venture reality. As Joseph McElwee from Galway, Ireland, quoted "the successful ingredients for offshore mariculture are: big investments, big cages, big returns."

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A Deep-Water Mooring Concept for Open-Ocean Aquaculture

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The expansion of aquaculture activities to the offshore environment requires a reliable and cost-effective mooring system effective in a wide variety of bottom types. Current deep-water mooring systems are typically 10-100% of platform costs. This project investigates the use of hydrodynamic research results for fast-moving submerged projectiles to develop a remotely operated deep-water mooring system.

Recent domestic and Ukrainian hydrodynamic research has explored the physics of a phenomenon labeled supercavitation. Proper design can minimize the drag on a submerged projectile, yielding "supercavitation drag reduction," which allows the projectile to attain speeds in excess of 1,000 meters/second, rendering deep penetration of the sea floor possible. This phenomenon involves the formation of a vapor cavity at the point of minimum pressure on the submerged body. This vapor cavity can envelop the projectile and extend quite a distance downstream of the minimum pressure point. Drag can be reduced on the projectile because skin friction over the projectile surface within the vapor cavity is negligible due to the reduced density and viscosity of the vapor.

The proposed deep-water mooring concept uses a supercavitating projectile to embed an anchor within the sea bottom. Such a moor requires no divers or extensive underwater operations to set and should have better reliability than traditional drag embedment anchors. This paper develops the feasibility of such a mooring concept.

Introduction

One of the significant challenges facing the expansion of aquaculture offshore is the development of effective deep-water moorings. Intensive human involvement in mooring placement escalates cost and increases liability. While explosive bottom-penetrators present a possible solution to the deep-water mooring challenge, they require extensive licensing due to their hazardous nature. Technology based on the study of moving bodies at high underwater speeds could provide a lower-cost, less labor-intensive approach to mooring aquaculture containment systems in offshore waters.

The phenomenon of interest is supercavitation, which is the formation of a vapor cavity at a point of minimum pressure on a body. This vapor cavity can envelop a projectile and extend quite a distance downstream of the minimum pressure point. Drag can be reduced on the projectile because skin friction over the projectile surface within the vapor cavity is negligible due to the reduced density and viscosity of the vapor. The base drag on the body is the integral over the projectile surface of the differential pressure force. Proper design can minimize this drag component, yielding "supercavitation drag reduction," which allows a projectile to attain speeds fast enough to render penetration of the sea floor possible.

Research of supercavitation drag reduction has been performed in the Ukraine by Dr. Yury Savchenko and associates at the Institute of Hydromechanics, Kiev. The result of this research was a projectile speed in excess of 1,000 meters per second. High speed projectiles approaching Mach 1 underwater were shown to be possible. Work has also been performed in the United States by Dr. Ivan Kirschner at the Naval Undersea Warfare Center (NUWC) Division Newport, Rhode Island. This work included testing the Adaptable High Speed Undersea Munition (AHSUM) in a tow tank at NASA-Langley in Hampton, Virginia.

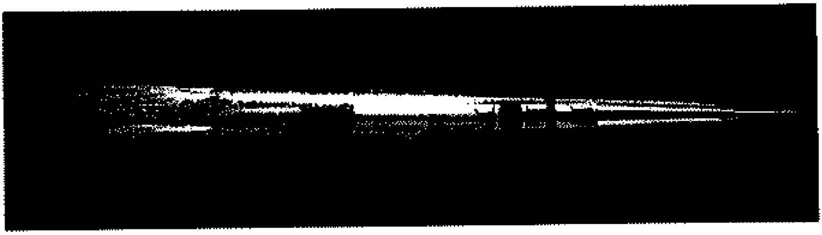

Figure 1. Supercavitating Projectile Laboratory Test. *Photo courtesy of Naval Undersea Warfare Center*

Stanley Associates has built upon the work performed by the Ukrainian Institute of Hydromechanics and NUWC to develop commercial applications for supercavitation drag reduction technology. The embedment anchor application may be of particular interest to the offshore aquaculture industry.

Embedment Anchor Concept

A gun could be developed to shoot a supercavitating projectile anchor from the surface (in shallower waters) or from just off the bottom (for deep water). Experimental guns have been used for laboratory testing. The guns use either gunpowder or hydrogen gas to provide the kinetic energy necessary for muzzle velocities up to 1,500 meters/second. Small amounts of propellant are actually needed, increasing with projectile mass. Table 1 shows the propellant loads for a 30 millimeter laboratory test projectile (Talley, August 1996).

Table 1: Propellant Loads

Propellant	Peak Chamber Pressure (kpsi)	Muzzle Velocity (m/sec)
90g WC-890, Lot 120	17.5	950
150g WC-890, Lot 120	30.7	1215
117g WC-867, Lot 50	64.2	1503

Table 1 shows an important result. An existing manufacturing capability can produce a self-contained cartridge to propel the projectile anchor. A projectile sized as an anchor for aquaculture cages could be fitted with a cartridge which supplies sufficient kinetic energy for the anchor to achieve the velocity needed to penetrate the ocean bottom. This allows the anchor to be transported safely and compactly to the anchor site.

An embedment anchor launcher would consist of the gun, a handling/support frame, and tether cable housing, shown in Figure 2. This is typical of many embedment anchors which have been patented (see references). What makes the supercavitating projectile anchor concept unique is the anchor projectile itself (Figure 3).

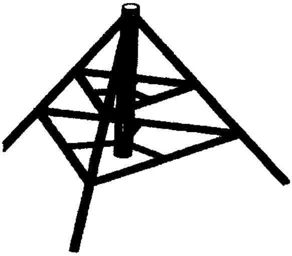

Figure 2. Launcher Concept.

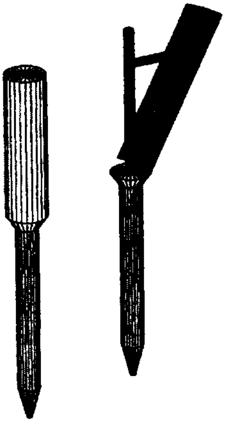

Figure 3. Anchor Projectile.

This projectile concept is modeled from the design of similar bodies fired from laboratory guns at speeds up to 1,500 meters/sec. The distinctive flat nose of the projectile makes supercavitation drag reduction possible by forming the vapor cavity during flight. This phenomenon can be induced with nothing more than the kinetic energy of the anchor itself at depths up to 2,000 meters (Condron, 1997). This kinetic energy is used to penetrate the ocean bottom with a tether line. In very soft bottom types, the anchor will deploy two flukes as load is applied to the tether, increasing the pullout resistance.

Bottom Penetration

Initial studies of bottom penetration effectiveness centered around an analysis of strike velocity as a function of the strike range at constant depth. The LeDuc ballistics equation was used to determine the underwater strike velocity at range (Kirschner, 1996).

$$x_S = \frac{2m \ln(v_L/v_S)}{\rho A C_D} \qquad \text{Eq. 1}$$

Solving for v_S:

$$v_S = v_L e^{-[\rho A C_D x_S/(2m)]} \qquad \text{Eq. 2}$$

Where: v_L = Launch Velocity
v_S = Strike Velocity
x_S = Strike Range
m = Projectile Mass
ρ = Water Density
A = Cavitator Cross-sectional Area
C_D = Drag Coefficient

Bottom penetration is dependent on the strike kinetic energy. For a given projectile mass, this reduces the problem to one of determining the strike velocity for a given launch velocity (or muzzle velocity, Vm). Figure 4 plots strike velocity vs. strike range for a projectile mass of 0.28 kg, cavitator diameter 2.5 cm, and a constant depth. The cavitator is the nose of the projectile.

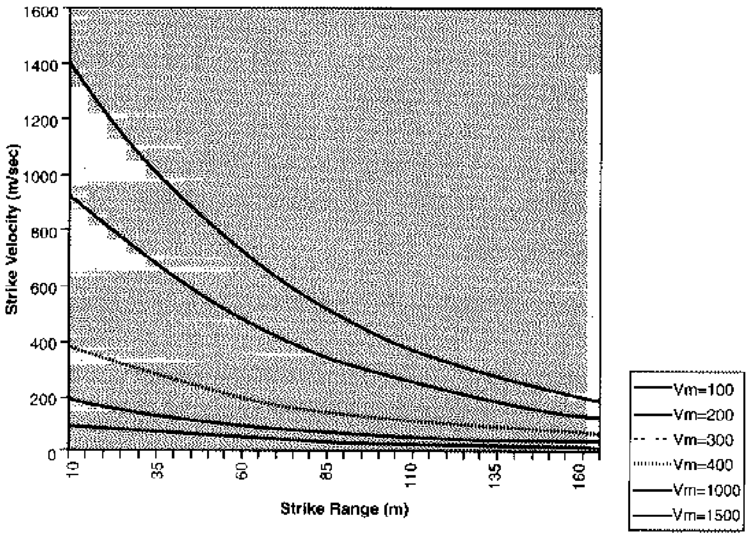

Figure 4. Strike Velocity for Various Muzzle Velocities.

A muzzle velocity of 1,500 m/sec at short range gives the anchor maximum penetration velocity. In hard bottom types, the anchor could ricochet. In laboratory tests, however, this has proven unlikely. A supercavitating projectile was shot at a steel wall with resulting penetration shown in Figure 5. Note the "petaling" of the steel as it deformed to allow the projectile to lodge within its structure.

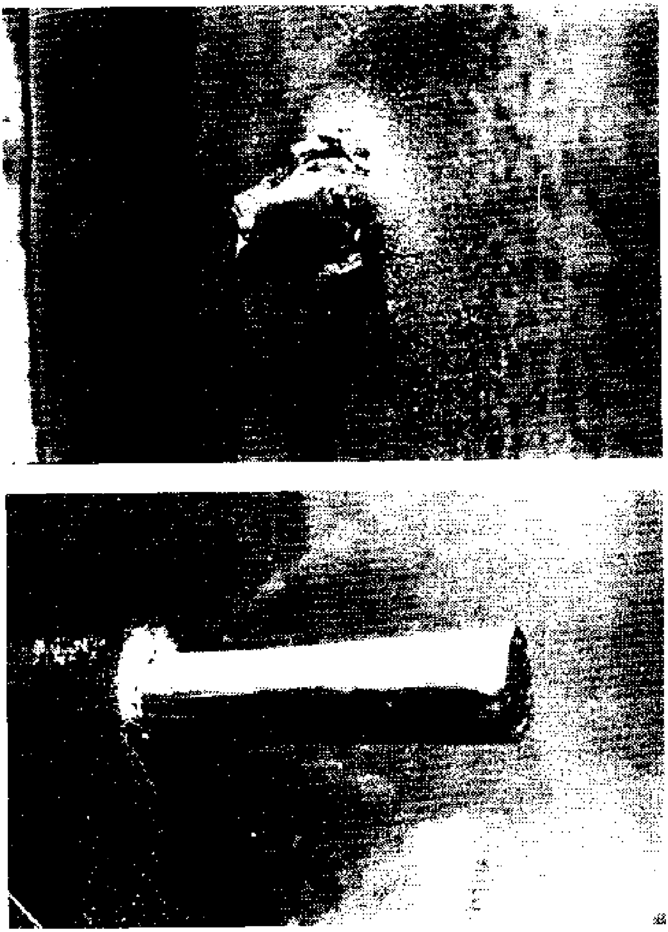

Figure 5. Steel Wall Penetration.

Photos courtesy of Institute of Hydromechanics, Kiev

Suitability for Deep Water Mooring

Preliminary studies of depth effects on the supercavitation phenomenon show that the vapor cavity can be formed at depths up to 2,000 meters. Computer modeling at the Institute of Hydromechanics, Kiev, resulted in the maximum depth profile shown in Figure 6. This was for a 300 kg projectile with a cavitator diameter of 2 centimeters. Simulated launches were made from initial depths of 0, 1,000, and 2,000 meters.

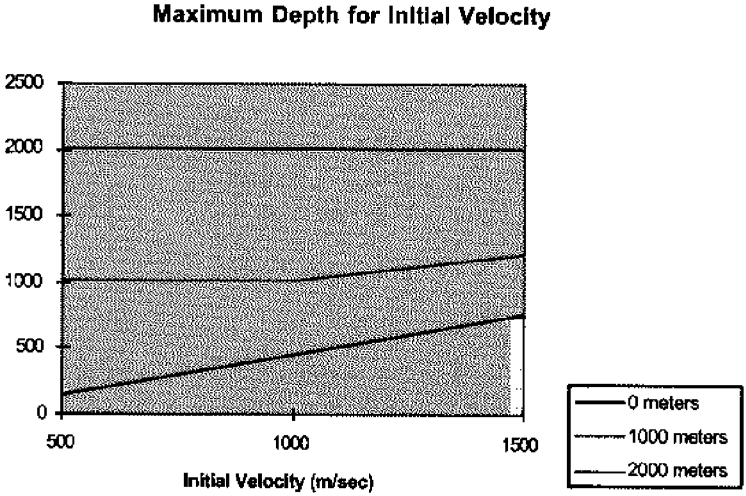

Figure 6. Maximum Depth Profile.

Combining the results of Figures 4 and 6 gives a rough boundary for the depth effectiveness of a projectile anchor. At depths up to 100 meters with muzzle velocity of 1,500 m/sec, an anchor could be fired from the surface and still reach the bottom with sufficient velocity for mooring penetration. Deeper mooring depths probably require the launcher assembly to be lowered to the bottom prior to firing.

It should be noted that most testing to date has been performed with the launcher aligned horizontally immersed in a tank such as the one shown in Figure 7. Some vertical launches have been observed for the water entry effects shown in Figure 8. No experimental data has been collected on the depth effects of vertically oriented vapor cavities. The computer modeling available only gives appropriate boundaries for the behavior of supercavitating projectiles at depth.

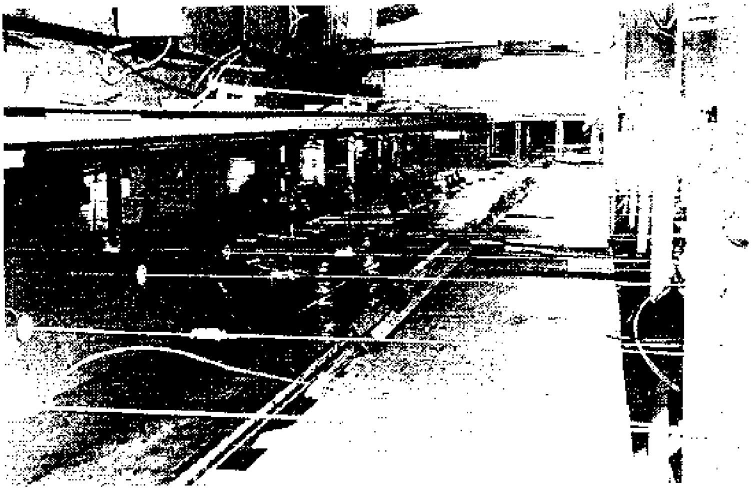

Figure 7. Launcher Laboratory Tank.

Photo courtesy of Institute of Hydromechanics, Kiev

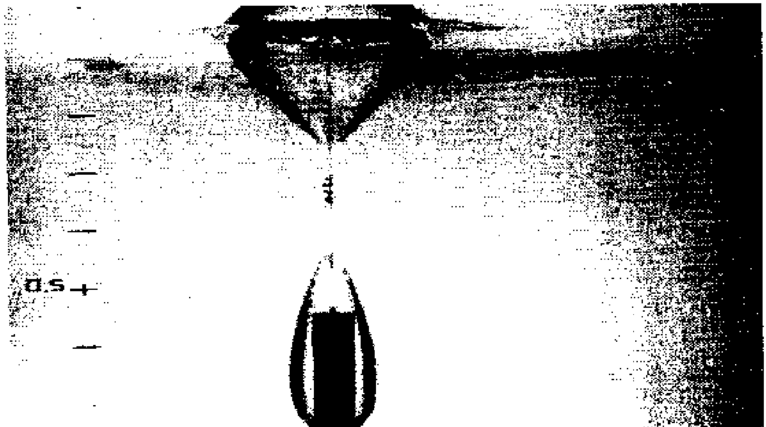

Figure 8. Water Entry of a Supercavitating Projectile.

Photo courtesy of Institute of Hydromechanics, Kiev

Another concern for deep water mooring is the ability of a projectile anchor to carry a tether of sufficient strength to withstand the loads associated with a typical fish cage. Projectile size and mass will be limited by the amount of propellant which can be safely and effectively packaged in the cartridge. To date, only small-scale projectiles have been tested in the laboratory, as depicted in Figure 9. Synthetic tethers, such as Nylon rope, make the use of small projectiles possible. A typical 24 mm diameter Nylon rope has a wet breaking strength of 126.7 kN (28.5 kips) (McKenna, 1979). Such a tether is necessary, given the small diameter of supercavitating projectiles.

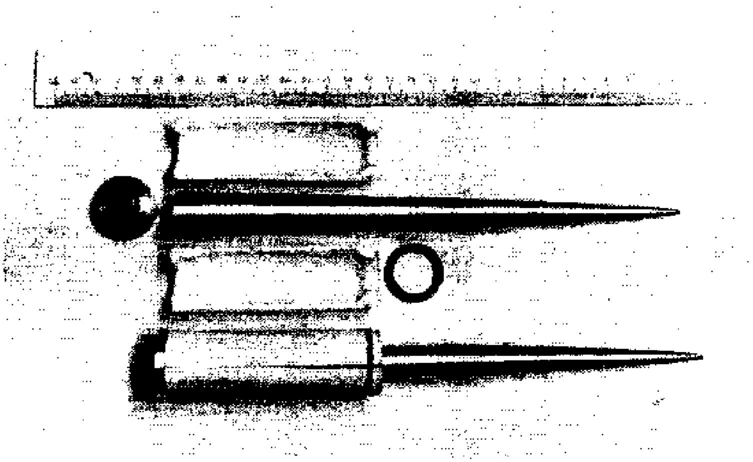

Figure 9. Small Scale Supercavitating Projectiles.

Photo courtesy of Institute of Hydromechanics, Kiev

Typical Sea Cage Loads

Development of a typical sea load was calculated using a 12 m spherical, submerged net pen. Figure 10 provides a schematic of the system evaluated. This net pen arrangement is modified slightly from the arrangement provided by Willinsky and Huguenin (1995).

The loads associated with the system will be in both the horizontal and vertical directions. Primary horizontal loads include the horizontal component of the wave orbital velocity (F_{WH}) and the current force (F_C). Vertical loads include the vertical component of the wave orbital velocity (F_{WV}) and the net pen's buoyancy (F_B).

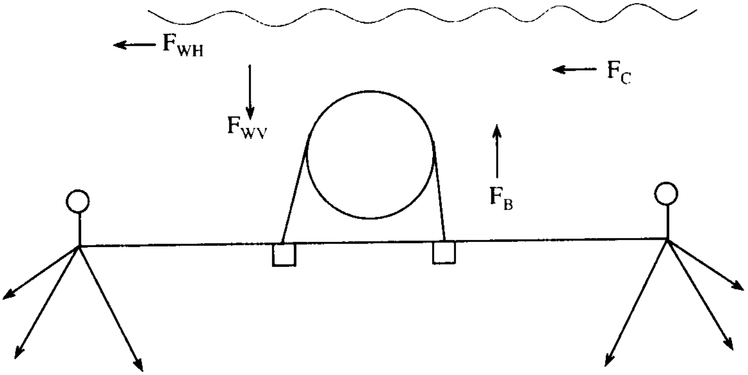

Figure 10. Schematic Drawing of Submerged Spherical Net Pen.

Horizontal Forces

$$F_H = F_{\text{wave (horizontal)}} + F_{\text{current}} \qquad \text{Eq. 3}$$

The equation for the horizontal component of the orbital wave load ($F_{\text{wave (horizontal)}}$) was developed by Tamura and Yamada (1963) and reported by Milne (1970) as:

$$F_{\text{wave (horizontal)}} = 2.15\mu_{MAX}\,(\text{Underwater Surface}) \quad \text{Eq. 4}$$

Where: μ_{MAX} = maximum horizontal orbital velocity

For the purpose of this study a value of 1.5 m/s associated with significant wave heights of 2.5 m and a 6 second modal period was used (Newmann, 1966).

Underwater Surface = (Underwater Surface_{SPHERE})(% Obstructed)

The surface area of a 12 m sphere is 452 m^2. An assumption was made that between the structure, net and fouling in worst condition, 44% of the area was obstructed.

$$F_{\text{wave (horizontal)}} = 2.15(452\ \text{m}^2)(0.44) = 0.64\ \text{kN} \qquad \text{Eq. 5}$$

The resistance due to current flow for net pens was developed by Kawakami (1964) and presented in the equation below:

$$R = \frac{C_d \rho v^2 S}{2} \qquad \text{Eq. 6}$$

Where: R = resistance of net (N)

Cd = coefficient of drag of mesh = see Equation (7)

ρ = density of water = 1025 kg/m^2

v = velocity of current = 4 knots = 2.06 m/s

S = projected area of net = 2ad

a = nominal mesh size

d = diameter of twine

Cd was further defined

$$C_d = 1 + 3.77\left(\frac{d}{a}\right) + 9.37\left(\frac{d}{a}\right)^2 \qquad \text{Eq. 7}$$

Values of a = 45 mm and d = 3mm were used for the mesh size although d was assumed to be fouled to a diameter of 9 mm.

$$C_d = 2.12 \qquad \text{Eq. 8}$$

Substituting into Eq. (6) yields,

$$R = F_C = 18.1\ \text{kN} \qquad \text{Eq. 9}$$

This produces a total horizontal force (F_H) = 18.7 kN.

Vertical Forces

$$F_V = F_{\text{wave (vertical)}} + F_{\text{buoyancy}} \qquad \text{Eq. 10}$$

The equation for the vertical component of the orbital wave load ($F_{\text{wave (vertical)}}$) was presented by Milne (1970) as:

$F_{\text{wave (vertical)}} = 1.80v_{MAX}$ (Underwater Surface) Eq. 11

Where: v_{MAX} is defined as $0.82\ \mu_{MAX} = 1.23$ m/s

$F_{\text{wave (vertical)}} = 1.80v_{MAX}$ (Underwater Surface) = 0.45 kN Eq. 12

The force of buoyancy (F_B) will be dependent on the design of the system and is therefore difficult to determine to any certainty. It is expected that the design will be performed in a manner that makes the system as close to neutrally buoyant as possible. For the purposes of this report a buoyancy of 2.5 kN was used.

F_V = -0.45 kN + 2.5 kN = 2 kN Eq. 13

Total Forces

Combining these forces produces a total load on the system of 18.8 kN. Assuming this entire load is supported on two of the three anchor lines, from one end of the system, yields a load/line of 9.4 kN. Assuming a factor of safety of 5 yields a total force of 47 kN per line.

The total calculated value of 18 kN for a 12 m submerged system appears to agree with values reported by Bougrova and Bugrov (1994) for 18 m submerged cages of 30 kN.

Anchor Pullout Resistance

Any anchor is only effective if it maintains its position under platform loading. Pullout resistance is a good measure of an embedment anchor's effectiveness. This is the force required, in excess of its weight, to remove the anchor. The pullout resistance depends on the soil failure mechanism illustrated in Figure 11.

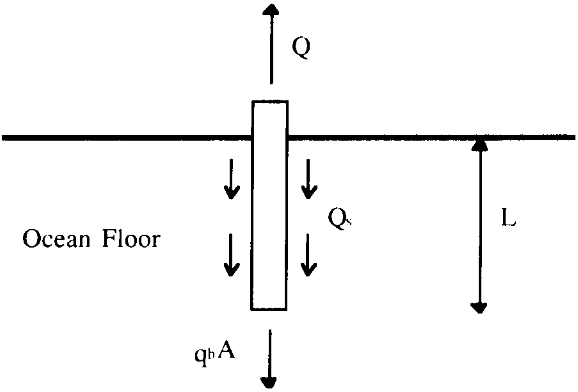

Figure 11. Soil Failure Diagram.

$$Q = q_bA + Q_s \qquad \text{Eq. 14}$$

Where:

Q = Allowable load on anchor tether cable
q_b = Bearing capacity at the anchor toe
A = Area of anchor base
Q_s = Shear force
L = Length of cable beneath ocean floor

It should be noted that the weight of anchor cable and projectile are neglected, as well as the weight of the displaced soil.

For undrained loading of the soil the bearing stress can be computed from

$$q_b = S_uN_c \qquad \text{Eq. 15}$$

S_u = Undrained shear strength, in kPa
N_c = Bearing capacity factor (a soil property)

Shear forces can be calculated by integrating over the length of the anchor cable

$$Q_s = \pi D\int_0^L \tau_s \, dz \qquad \text{Eq. 16}$$

Where: D = Diameter of the anchor cable
τ_s = Shear stress on anchor cable

For undrained clays, $\tau_s = \alpha S_u$, with α constant. Assuming a linear variation of S_u with depth of soil penetration $S_u = \sigma z$, an expression for Q_s can be obtained (Atkinson, 1993).

$$Q_s = 0.5\pi D\alpha\sigma L^2 \qquad \text{Eq. 17}$$

It is now possible to relate the cable load Q to the soil forces on the embedment anchor by substituting into Eq. 14:

$$Q = \sigma L(N_c A + 0.5\pi D\alpha L) \qquad \text{Eq. 18}$$

Typical values (Young, 1988) for clay soils are:

$\sigma = 0.95$ kPa/m

$N_c = 9$

$\alpha = 0.5$

After the anchor flukes deploy as displayed in Figure 3, A = 0.0157 square meters for a 5 cm diameter, 10 cm long projectile.

With these assumptions, an approximation of projectile penetration depth necessary to resist pullout under the expected loading can be made. This result is shown graphically in Figure 12.

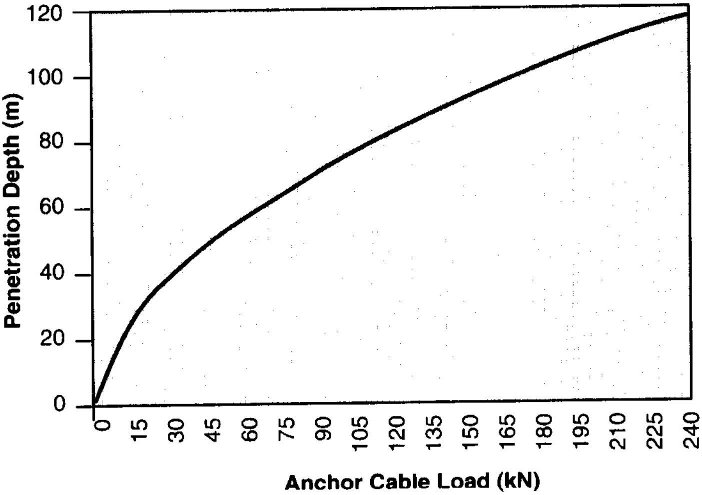

Figure 12. Penetration Depth Necessary for Minimum Pullout Resistance.

The preliminary analysis of Sea Cage loads provided a safe cable load of 47 kN (10.6 kips). From Figure 11, such an anchor would have to penetrate about 50 m into soft clay to provide the minimum pullout resistance. No experimentation has been performed on the soil penetration capability of supercavitating projectiles. Such work is necessary to further define the role of projectile anchors in mooring applications.

Conclusion

As aquaculture activities move into deeper water offshore, new mooring solutions will be necessary. A supercavitating projectile anchor may be one alternative. Important advantages of a such an anchor include low anchor weight, no need for divers, and transportability. Multiple-point moors provide the reliability demanded by the oceanic environment. Preliminary analysis shows that such an anchor is technically possible given the strike velocities achieved in the laboratory with small-scale projectiles. The loading expected from typical fish cages also indicates that a small Nylon tether could be used as the anchor cable. Further work remains to show a projectile's effectiveness in penetrating actual soils encountered in mooring applications.

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Computational Model of Aquaculture Fin-Fish Net-Pens

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Introduction

This work is sponsored by Sea Grant, the School of Marine Sciences at the University of Maine and Defense Advanced Research Project Agency (DARPA) and was completed at the University of Maine, Orono, Maine from September 1996 to May 1997. This work is an outgrowth of work done by Messier and Thompson [1] for DARPA in modeling Very Large Floating Structures (VLFS). The dynamic structural response of a VLFS and typical floating net-pen designs are similar, though of vastly different scales. With a few notable exceptions, net-pens are typically made up of structural beam elements assembled to form a buoyant frame that supports the net pen.

In the last 10 years aquaculture of salmonids has expanded from 5.7% (1985) to 34.5% (1994) share of worldwide production. Originally developed in the Norwegian fjords, the industry has expanded to protected and exposed locations in Canada, Ireland, Peru, and the United States to name a few major salmon producers. With the collapse of many traditional fisheries worldwide, market forces are pressing development of the aquaculture of market species such as cod, fluke, and halibut. Recent developments in the New England area show promising startup projects of these species with the backing of both public and private capital. Similar projects are occurring elsewhere in the world. Due to environmental, regulatory, and user conflict constraints, future expansion of fish farming will be in more exposed, high energy locations.

This shift requires improved analysis of net-pens to determine their performance and survivability in a high energy locations.

To provide an additional tool to evaluate the performance of net-pens, computational models using Finite Element Analysis (FEA) method were developed and applied to net-pen designs used in salt water aquaculture. A commercial FEA software package, ABAQUS AQUA™, was used in developing these models. The objective of this research is to identify failure modes and predict estimated life cycles of net-pen designs in different ocean environments. Successful application of this analysis will provide aquaculture managers, operators and regulators with increased understanding of the performance and survivability of a particular net-pen design under the applied sea state. This paper describes the development and application of this tool on two different net-pen designs.

Theoretical Considerations

The theoretically important aspects of this research are discussed below. They include: nonlinear dynamic finite element method, Airy wave theory and its application through Morison's equation, and the mapping technique used to model the containment nets.

Nonlinear Dynamic Finite Element Method

When studying the dynamic response of a structure using the finite element method, a determination of the appropriate solution algorithm, implicit or explicit, is required. Belytschko [2] suggests that the problem be classified as either an inertia or wave propagation problem. Wave propagation problems require an accurate reproduction of the wave front (e.g. the response of an impact) and are best solved using an explicit time integration scheme. Inertia problems, or structural dynamic problems, are low frequency response problems such as large displacement. These are best solved using an implicit time integration scheme. Clearly the structural response of net-pen in an ocean environment is of an inertia type requiring an implicit solution technique. Due to the large deformations of the netting and relatively large wave heights to be modeled, nonlinear, non-symmetrical analysis was selected. This allows the stiffness matrix to be reconstructed at each time step to account for the geometric changes in the structure. The finite element solution algorithm uses a modified Newmark family of equations as the basis of the implicit nonlinear solution algorithm. The nodal equations are:

$$M^{NM}\bar{u}\big|_{t+\Delta t} + (1+\alpha)\left(I^N\big|_{t+\Delta t} - P^N\big|_{t+\Delta t}\right) - \alpha\left(I^N\big|_t - P^N\big|_t\right) + L^N\big|_{t+\Delta t} = 0 \qquad \text{[Eq. 1]}$$

$$\dot{u}|_{t+\Delta t} = \dot{u}|_t + \Delta t\left[(1-\gamma)\ddot{u}|_t + \lambda\ddot{u}|_{t+\Delta t}\right] \qquad \text{[Eq. 2]}$$

$$u|_{t+\Delta t} = u_t + \Delta t\dot{u}|_t + \Delta t^2\left[\left(\frac{1}{2}-\beta\right)\ddot{u}|_t + \beta\ddot{u}|_{t+\Delta t}\right] \qquad \text{[Eq. 3]}$$

where: $-\frac{1}{3} \le \alpha \le 0$; $\beta = \frac{(1-\alpha)^2}{4}$; $\gamma = \frac{1}{2} - \alpha$;

The consistent mass matrix is defined as:

$$M^{NM} = \int_{V_o} \rho_o N^N \cdot N^M dV_o \ \text{(2.1.4)} \qquad \text{[Eq. 4]}$$

The internal force vector is defined as:

$$I^N = \int_{V_o} \beta^N : \sigma dV_o \ \text{(note } \beta^N \neq \beta\text{)} \qquad \text{[Eq. 5]}$$

The external force vector is defined as:

$$P^N = \int_S N^N \cdot t dS + \int_V N^N \cdot F dV \qquad \text{[Eq. 6]}$$

The Lagrange multipliers are defined as: $L^N = \Sigma$ *Lagrange Multiplier Forces.*

The parameter, α, controls the numerical damping of the system. Hibbitt and Karlsson [4] have empirically found the most effective value for α to be -0.05. This reduces the “ringing” caused by the automatic time stepping and gives good agreement with analytical solutions.

Airy Wave Theory

Airy wave theory is a linearized adaptation of the flow potential, ϕ. This method allows multiple wave trains to be superimposed over each other to build a good approximation of typical sea state spectrum found at any particular site. This method was used in the analysis presented here. Airy wave theory makes the incompressible, inviscid, irrotational flow assumption over a flat bottom. It further assumes that the waves are planar and the wave amplitude is “small” compared the water depth. This allows the flow potential, ϕ, to be defined as:

$\nabla^2\phi = 0$, with the fluid particle velocities defined as:

$\mathbf{v} = \dfrac{\partial\phi}{\partial\mathbf{x}}$. Solving for equilibrium yields:

$$\rho\left[\frac{\partial^2\phi}{\partial\mathbf{x}\partial t} + \frac{\partial\mathbf{v}}{\partial\mathbf{x}}\cdot\mathbf{v}\right] = -\rho\frac{\partial G}{\partial\mathbf{x}} - \frac{\partial p}{\partial\mathbf{x}}, \qquad \text{[Eq. 7]}$$

where

ρ	Fluid density
p	Pressure
g	Gravity constant
$G = g(z - z_0)$	Potential energy per unit mass

Applying the boundary conditions and throwing out the higher order terms to linearize the theory yields the following set of equations that define the fluid particle attributes.

Horizontal fluid displacements;

$$u_i = \frac{g}{2\pi}\sum_{components} d_{Ni}\,\frac{a_N\tau_N^2}{\lambda_N}\,\frac{\cosh\left[(2\pi/\lambda_N)(z - z_b)\right]}{\cosh\left[(2\pi/\lambda_N)(z_s - z_b)\right]}\sin 2\pi\left(\frac{s_N}{\lambda_N} - \frac{t}{\tau_N} + \frac{\theta_N}{360}\right)$$

[Eq. 8]

Vertical fluid displacements;

$$u_z = \frac{-g}{2\pi} \sum_{components} \frac{a_N \tau_N^2}{\lambda_N} \frac{\sinh\left[(2\pi / \lambda_N)(z - z_b)\right]}{\cosh\left[(2\pi / \lambda_N)(z_s - z_b)\right]} \cos 2\pi \left(\frac{s_N}{\lambda_N} - \frac{t}{\tau_N} + \frac{\theta_N}{360} \right)$$

[Eq. 9]

For these equations to be valid, the following inequalities must be true:

$\frac{H}{d} < 0.03$, $\frac{d}{\lambda} > 20$, and the Ursell parameter,

$\frac{H}{\lambda}\left(\frac{\gamma}{d}\right)^3 << 1$,

where H is the wave height, λ is the wavelength, and d is the water depth. Figure 1 portrays the nomenclature for a single wave train.

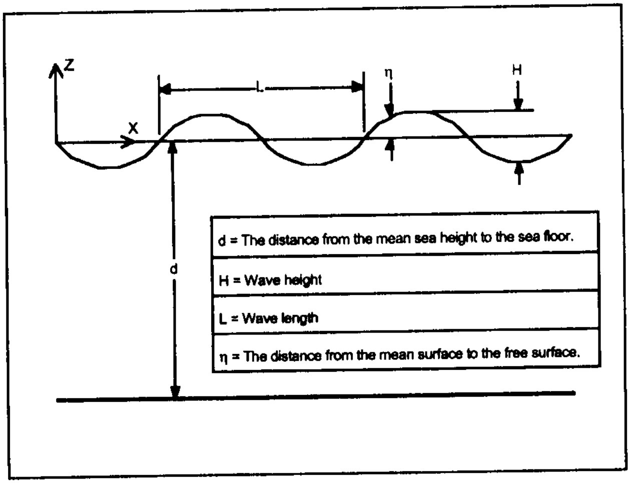

Figure 1. Wave Train Nomenclature.

By superimposing multiple Airy wave functions, the model can replicate the wave spectra of a particular net-pen site. The wave history of a typical Sea State 5 is shown in Figure 2. Additionally, the FEA code allows constant velocity currents to be modeled variable with position as well.

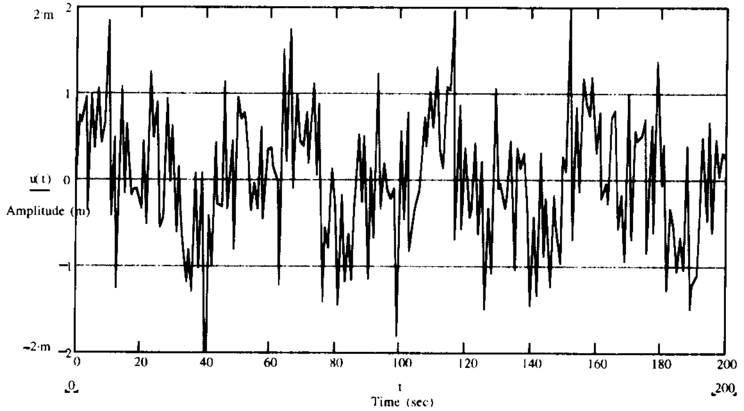

Figure 2. Generic Sea State 5 Time History.

Morison's Equation

The FEA code uses Morison's equation (Morison et al. 1950) to apply the wave and current forces to the structure. This is an uncoupled scheme that applies the buoyancy, drag, and inertia forces, due to the fluid, to the immersed beam elements of the structure. Morison's equation for a vertically aligned cylinder of differential length, dz, that is displaced a horizontal distance, η, is:

$$dF = \frac{\rho C_d D}{2} dz\,(u - \dot{\eta})\left|u - \dot{\eta}\right| + \frac{\rho C_m \pi D^2 a}{4} dz - \frac{\rho \pi D^2}{4}(C_m - 1)\ddot{\eta}\,dz$$

[Eq. 10]

where:

a	Horizontal fluid acceleration
C_d	Drag coefficient
C_m	Added mass coefficient
dF	Horizontal force per unit length of the cylinder
D	Effective cylinder diameter
dz	Unit length of the cylinder
u	Horizontal fluid velocity
$\dot{\eta}$	Horizontal velocity of the cylinder
$\ddot{\eta}$	Horizontal acceleration of the cylinder
ρ	Water density

The program determines whether a beam element is immersed, and then applies the appropriate buoyancy, drag, and inertia forces as defined below. Buoyancy forces are applied only to vertically aligned cylindrical beam elements. To apply buoyancy forces to a beam element that is not vertically aligned, fictitious vertical beam elements are added to the model as appropriate. The buoyancy force per unit length of a beam element is calculated as:

$$\begin{aligned}\mathbf{F}_b &= -\left(f_1 \rho_w r_o^2 - f_2 \rho_f r_i^2\right)\pi \mathbf{g} \cdot [\mathbf{I} - \mathbf{tt}] \\ &+ \left(f_1 (z_w - z)\rho_w r_o^2 - f_2 (z_f - z)\rho_f r_i^2\right)\pi g\left[\mathbf{n}_1 \frac{d\mathbf{x}}{dS} \cdot \frac{d\mathbf{n}_1}{dS} + n_2 \frac{d\mathbf{x}}{dS} \cdot \frac{d\mathbf{n}_2}{dS}\right]\end{aligned}$$

[Eq. 11]

where

$$f_1 = \begin{cases} 0 & \text{if the elevation is above } z_w, \\ 1 & \text{otherwise} \end{cases}$$

$$f_2 = \begin{cases} 0 & \text{if the elevation is above } z_f, \\ 1 & \text{otherwise} \end{cases}$$

and

$\mathbf{g}$	gravitational acceleration
$\mathbf{n}_1$	first normal of beam cross-section
$\mathbf{n}_2$	second normal of beam cross-section
r_o	outside radius of the pipe section
r_i	inside of pipe section
S	distance along beam centerline
z_w	free surface elevation of fluid outside of pipe
z_f	free surface elevation of fluid inside of pipe
ρ_f	mass density of fluid inside of pipe
ρ_w	mass density of fluid outside of pipe

Drag forces on immersed beams is broken into the transverse and tangential drag forces to the beam element. The transverse drag force per unit length is calculated as:

$$\mathbf{F}_D = \tfrac{1}{2}\rho C_D D \Delta\mathbf{v}_n \sqrt{\Delta\mathbf{v}_n \cdot \Delta\mathbf{v}_n}\,. \qquad \text{[Eq. 11]}$$

For tangential drag forces, the force per unit length is given by;

$$\mathbf{F}_T = \tfrac{1}{2}\rho C_T \pi D \Delta \mathbf{v}_t \left|\Delta \mathbf{v}_t\right|^{h-1} \qquad \text{[Eq. 12]}$$

The inertia force per unit length for a submerged beam element is given by;

$$\mathbf{F}_I = \tfrac{1}{4}\rho \pi D^2 \left[C_M(\mathbf{a}_f - \mathbf{a}_f \cdot \mathbf{tt}) + C_A(\mathbf{a}_p - \mathbf{a}_p \cdot tt)\right] \qquad \text{[Eq. 13]}$$

where

$\mathbf{a}_p$	Acceleration of a point on a beam
$\mathbf{a}_f$	Fluid particle acceleration
C_A	Transverse added mass coefficient
C_D	Transverse drag coefficient
C_M	Transverse inertia coefficient
C_T	Tangential drag coefficient
h	Tangential drag exponent
t	Unit vector defining the axial direction at a point in a beam
$\Delta\mathbf{v}_n = \Delta\mathbf{v} - \Delta\mathbf{v}_t$	Relative transverse velocity of the fluid
$\Delta\mathbf{v}_t = (\Delta\mathbf{v} \bullet \mathbf{t})\mathbf{t}$	Relative tangential velocity of the fluid
$\mathbf{v}_f$	Fluid particle velocity
$\mathbf{v}_p$	Velocity of a point on a beam
$\Delta\mathbf{v} = \mathbf{v}_f - \alpha_R \mathbf{v}_p$	Relative fluid velocity
α_R	Structural velocity factor

The specific coefficients for drag and inertia of a beam element are determined experimentally, or analytically for certain shapes.

Net Mapping Equations

Typically a net mesh panel subjected to uniform distributed force acts like a two dimensional catenary, i.e. the net strands have little or no bending stiffness, but have measurable axial stiffness in tension. The FEA code applies drag and inertia forces due to a fluid to be applied to beam elements. To remove the artificial stiffness in beam elements and to reduce the number of elements required to model the containment net, a net mapping algorithm was devised.

The individual net mesh strands are collapsed into a coarser net mesh. Figure 3 shows the process and the terminology used. Typically for grow out of salmonids, 63.5 mm (2.5 inch) nets are used. This gives an average strand length of 31.7 mm. The mapped strand length is typically in the one meter range.

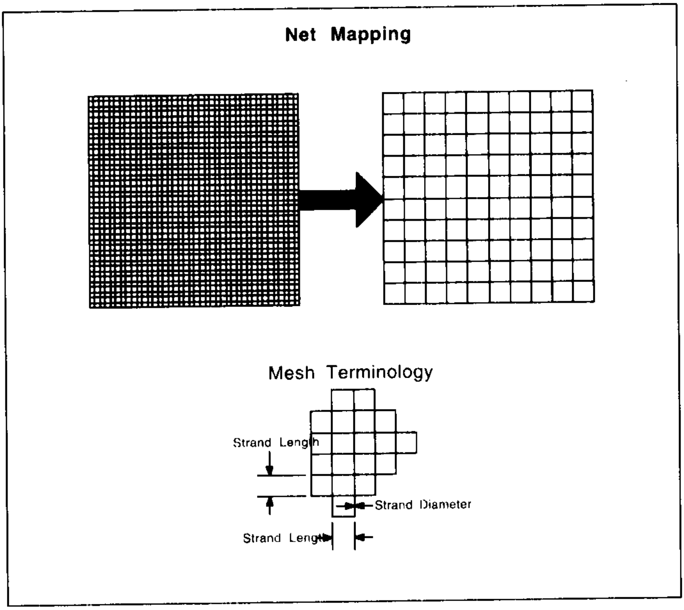

Figure 3. Net Mapping Terminology.

This yields a mapping ratio, $\alpha = \dfrac{LS_{mapped}}{LS_{org}}$ [Eq. 15]

For the structural response, the key parameter is the cross sectional area.

$$A_{mapped} = \alpha A_{org} = \alpha \pi r_{org}^2 \qquad \text{[Eq. 16]}$$

For the drag forces, the key parameter is the effective diameter:

$$D_{mapped} = \alpha D_{org} \qquad \text{[Eq. 17]}$$

To reduce the structural response due to bending, the moment of inertia for the strands are set near zero.

To validate this method, a test panel of the actual mesh and the mapped mesh was modeled and run under different current scenarios. The reaction forces from these tests were compared to the test results of actual nets is a test tank conducted by Mannuzza [3]. These validation checks showed excellent correlation, less than 5% difference.

Model Development

Development of the FEA net-pen models was divided into three tasks for each model:

- Structural frame development,
- Containment net mapping and development,
- Sea state and current extraction.

Both FEA models use the metric (MKS) system of units. All information that is in non MKS system units was converted to MKS to assure consistency. The structural frame development was performed using ABAQUS Pre™ preprocessor software. This software provides the basic input file that ABAQUS AQUA™ uses to define the initial geometric, structural, and material properties of the FEA model. MathCad 6.0+™ was used to develop the net mapping algorithm and sea state properties. This information was used to revise the input file as required.

Model One Development

Model One is an octagonal floating net-pen design that is 20 m across with a pen depth of 10 m. Figure 4 shows the layout excluding the moorings. The floating support ring is a steel box fabrication, one meter (m) wide by _ m deep. It provides the structural rigidity and attachment points for the mooring system and containment net.

The mooring system consists of eight mooring blocks connected to the mooring buoys by chain. Poly-steel cable (0.038 m. diameter) connect the mooring buoys to the corners

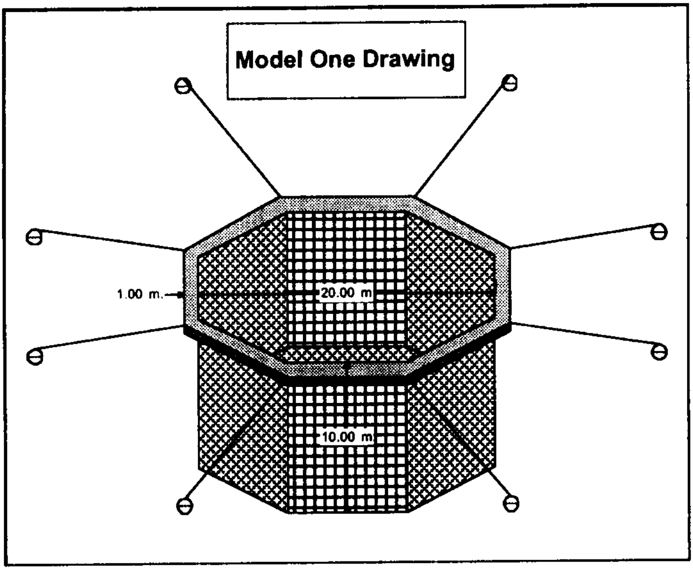

Figure 4. Model One.

of the frame. The net-pen is moored in 30 m of water. To simplify the model, the mooring chain is modeled as a non-linear spring that mimics the response of an actual mooring chain acting as a catenary connector.

The containment net is made up of eight, 8 m by 10 m panels hung square from the frame. The net mesh modeled is 63.5 mm (2.5 in) square, knotless nylon mesh. A steel octagonal ring is fastened to the bottom edge of the containment net to stabilize the containment net in high currents. The bottom of the containment net was not modeled to reduce the effects of numerical buckling. The mapped containment net has a strand length of one m yielding an a ratio of 31.

Model Two Development

Model Two, designated the Pull Up Pen (PUP), is a prototype submersible design being developed by the Ocean Engineering Center of the University of New Hampshire. It is designed for deployment in an open ocean environment with water depths in the 60 to 120 m range. It consists of a 20 m long by _ m diameter spar buoy moored to the bottom in a tension leg configuration. A 4.5 m long aluminum frame slides over the spar buoy. The frame can be raised and lowered from the surface to the ocean bottom. Attached to the frame are four, 3 m diameter by 3 m deep cylindrical net pens arranged symmetrically around the sleeve. Figure 5 shows the layout.

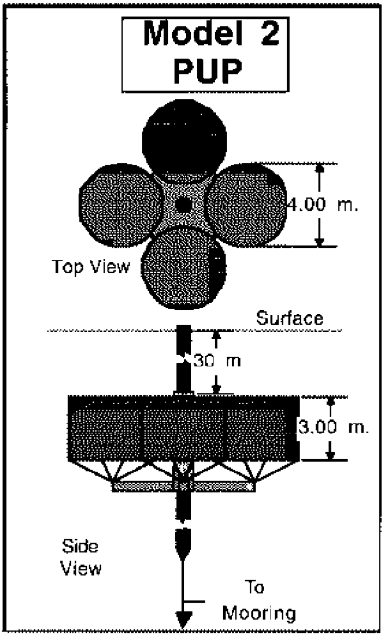

Figure 5. Model Two Layout.

Each containment net is made up of three parts, a floatation collar at the top, a steel ballast collar at the bottom, and the containment net connecting the two. The floatation collar is made up of two, 76 mm (3 inch) diameter high density polyethylene (HDPE) tubes formed into 4 m diameter rings separated vertically by a _ m. Trawl floats are attached to the containment net between the HDPE rings to provide positive buoyancy to the containment net. The upper ring is shackled to the frame. A steel ring forms the bottom perimeter of the containment net to stabilize the containment net shape. Steel cables secure the bottom ring to the lower frame. The net mesh modeled is 63.5 mm (2.5 inch) square, knotless nylon mesh.

The mapped containment net has a strand length of 0.3 m yielding an a of 9.5.

Results and Conclusions

The FEA models provide nodal displacement and stress and strain information at the element integration points for each time step. The wealth of data available can be overwhelming. What will be discussed here are the significant data for the elements that are key to visualizing its response and predicting its life cycle.

To predict the expected life cycle of a net-pen, the endurance limit or fatigue strength of its materials need to be determined. If a material is subjected to cyclical stresses greater than its endurance limit, the material will eventually fail due to fatigue. To determine the endurance limit of a material, the tensile strength of that material is modified by a number of factors that take into account the method of manufacture, environmental effects, and size to name a few. With a calculated endurance limit, a factor of safety can be calculated for those elements.

Model One Results

Model One was subjected to three different runs or scenarios. During Run One, the model was subjected to a steady 1.5 m/s (3 knot) current. During Run Two, the model was subjected to 0.05 m/s current and Sea State Five (SS5) waves. During Run Three, the model was subjected to a steady 1.5 m current and SS5. All currents and wave trains flowed in the positive 1 (x) direction

For Model One, the critical member analyzed is the main steel frame. The endurance limit for the steel in the structure was determined to be 67.2 MPa which is 16.8% of its tensile strength (400 MPa) or 26.9% of its yield strength.

Comparison of net-pen deformations

Figures 6, 8 and 10 depict the net-pens deformed shape near the end of their three runs. Figures 7, 9 and 11 graph the vertical motion of the main frame as a function of time. Nodes 1, 5, 9 and 13 are in the center of the right, bottom, left and top sides of the frame respectively.

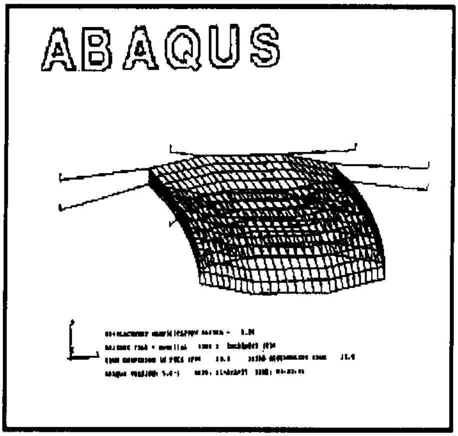

Figure 6. Run 1 Deformed Shape.

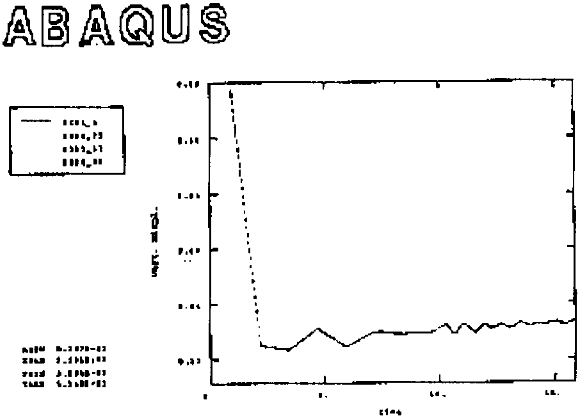

Figure 7. Vertical Displacements.

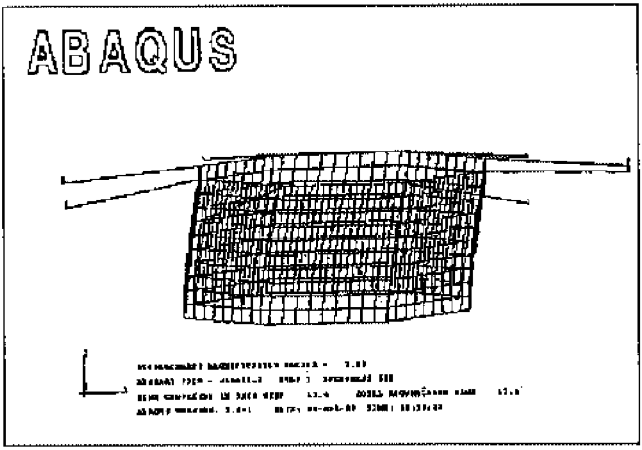

Figure 8. Run 2.

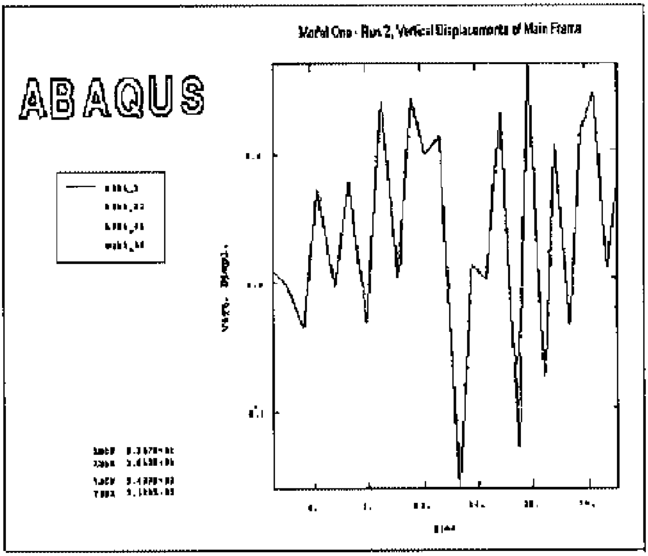

Figure 9. Vertical Displacements.

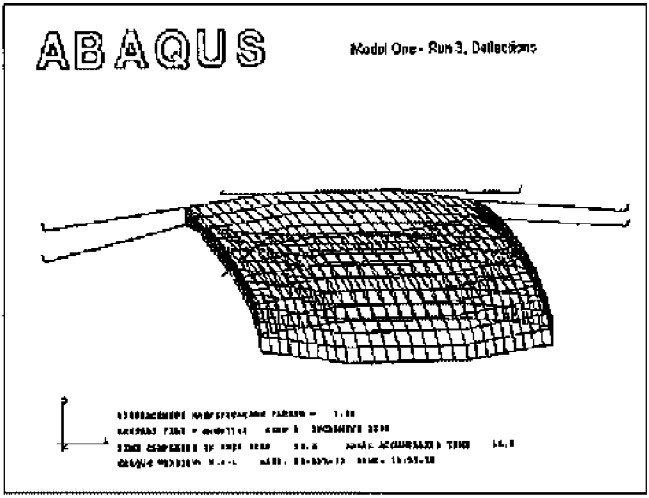

Figure 10. Run 3.

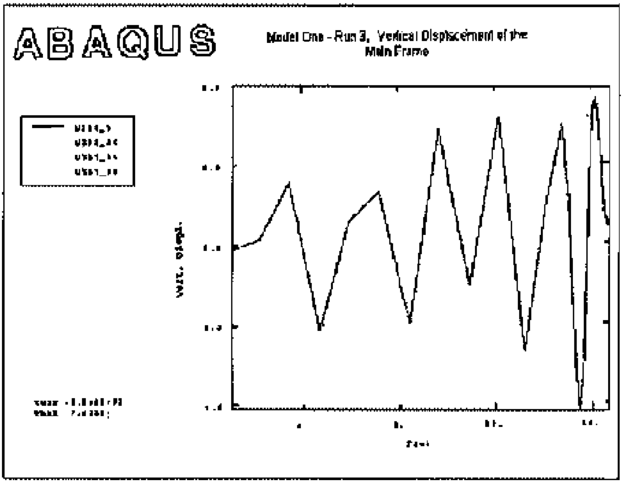

Figure 11. Vertical Displacements.

The loads are ramped up over the first two seconds. The strong current in Runs 1 and 3 cause a large deformation of the containment net even with the weighted net ring. Without it, the model fails due to Euler buckling in the net mesh when run with a 1.5 m/s current.

Net-Pen Stresses

Figures 12, 13 and 14 depict the s11 stresses in all the elements of the net-pen for each run.

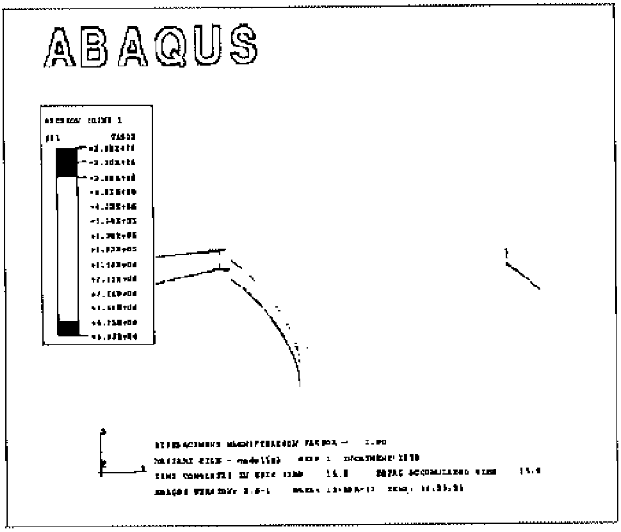

Figure 12. Run 1.

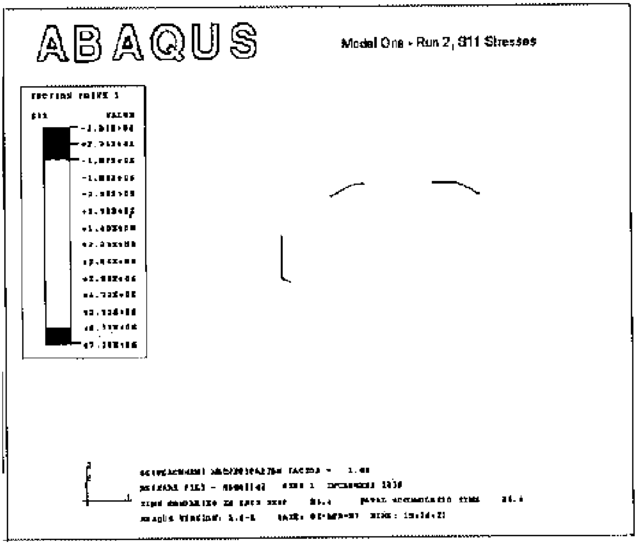

Figure 13. Run 2.

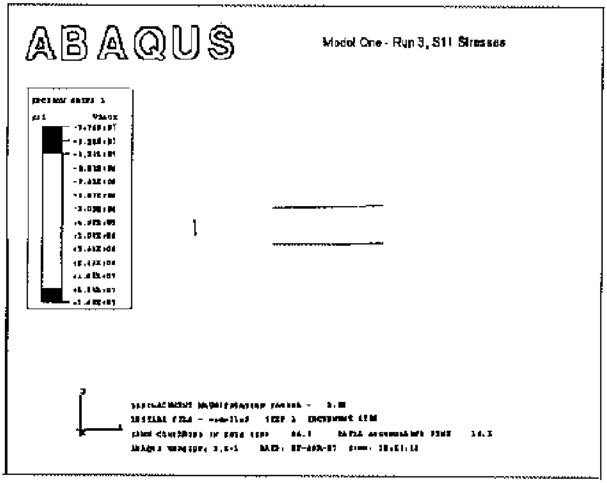

Figure 14. Run 3.

Since Run 1 is essentially a static problem, the maximum axial stress (σ11) in the main frame was found not to exceed 5.5 M Pa. This corresponds to safety factor greater than 10 based on the endurance limit. Figures 15, 17, graph the axial stress (σ11) at the four corners of the main frame as a function of time for Runs 2 and 3. The critical factor is the maximum stresses plotted. Figures 16 and 18 graph the corresponding inverted factor of safety based on the endurance limit of 67.2 MPa for A 36 steel.

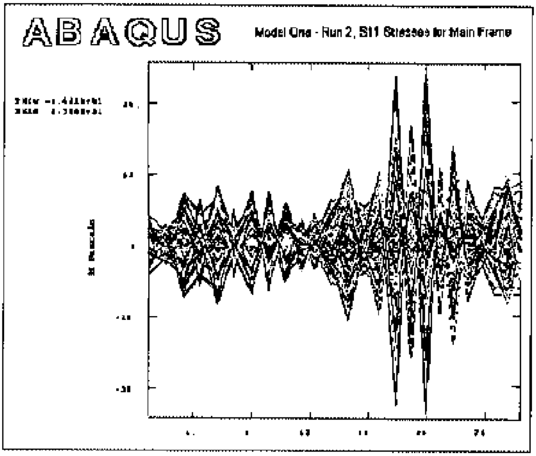

Figure 15. Run 2

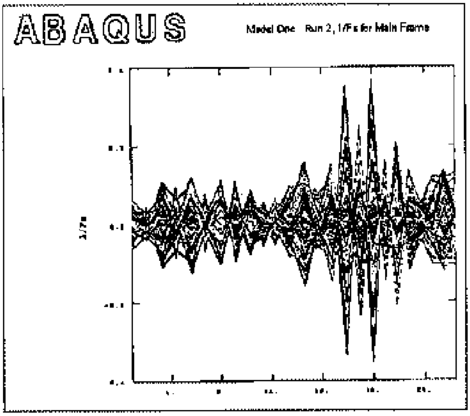

Figure 16.

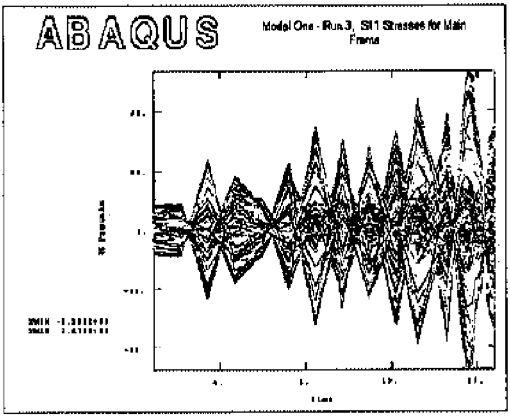

Figure 17. Run 3

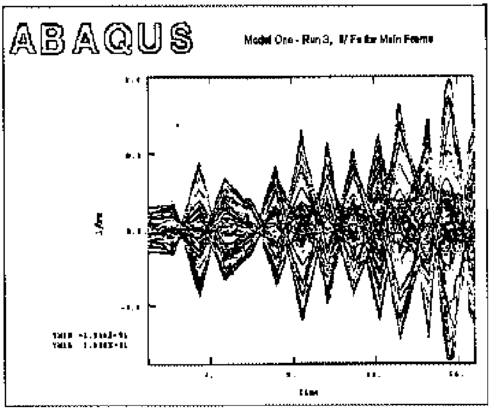

Figure 18.

Model Two

The PUP is designed for operations in both a surfaced and submerged mode. The primary objective of this analysis is to predict the maximum sea states the model can be operated at both the surface and submerged at 10 m. A secondary objective is to predict failure points and modes in the structure. This information will allow the developers to adjust the construction details to improve the survivability of the PUP.

Surface Mode

To find the members that were most likely to fail, the model was subjected to Sea State 5 in its surface mode. As expected, both the containment net support frame and the HDPE rings failed due to Euler buckling and plastic strain due to bending. The other members, piling, netting, lower ring, etc., are not critically loaded. The following results details the displacements and stresses of the support frame and HDPE rings for both operational modes. The model was subjected to decreasing sea states until the model ran well. In its present configuration, the maximum sea state that the PUP should be exposed while at the surface is Sea State 2 ($H \leq 0.5$ m, $\lambda \geq 3.5$ m). Exposed to SS2, the critically loaded members are the connectors between the upper frame and the HDPE rings and the lower frame. Figure 19 details the displacements of the PUP. Figure 20 portrays the $\sigma 11$ stresses for the entire frame.

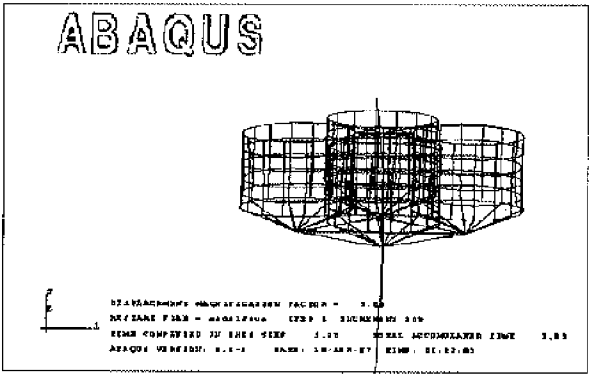

Figure 19. PUP Surface Mode.

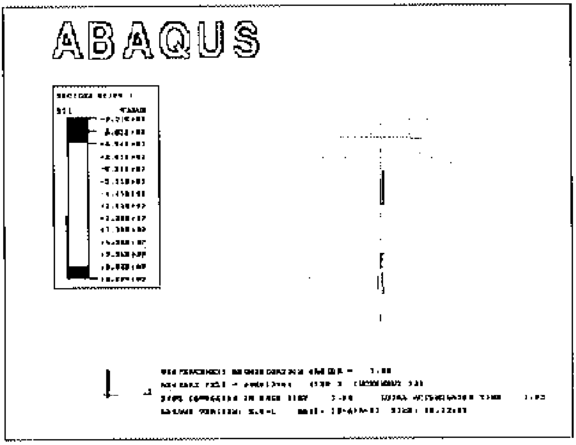

Figure 20. Frame Stresses.

The maximum stresses in both the net connectors and the lower frame exceeded the yield strength (250 M Pa) of the material as modeled. Adjusting the cross-sectional shape should reduce the stress levels in these members. Future work will concentrate on improving these elements.

Submerged Mode

The PUP was submerged to a depth of 10 m. A point mass of 2000 kg was added to the bottom of the frame to balance the buoyancy of the trawl floats. A spring was added between the pile and frame to keep the net-pen from sinking or surfacing. The frame is still allowed to slide along the piling. As modeled, the PUP performs well up to SS4 (H ≤ 1.8 m, λ ≥ 15.5 m). It is expected that improvements to the surface mode model will improve its performance when submerged.

Figure 21 details the displacements of the net-pen. Red depicts the model in its initial, undeformed shape. Figure 22 portrays the s11 stresses in the frame.

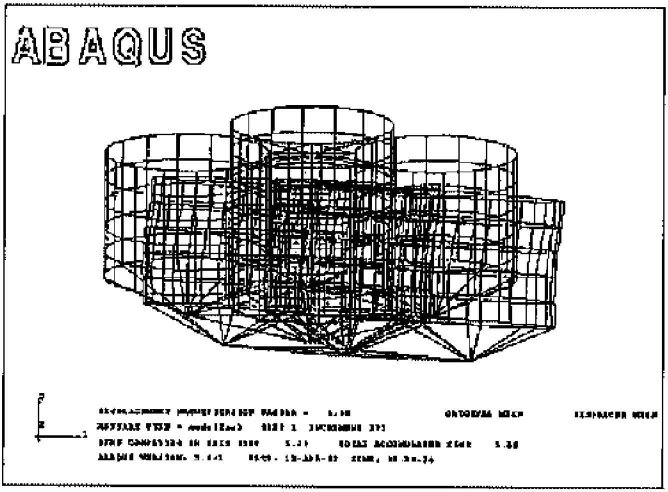

Figure 21. PUP submerged.

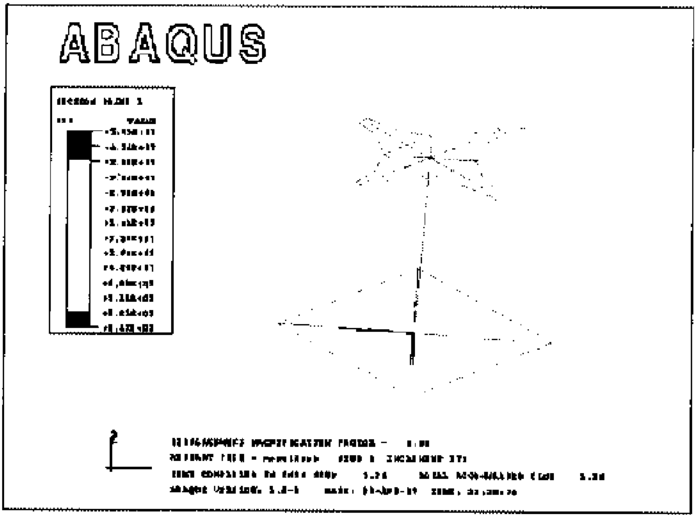

Figure 22. Frame Stresses.

Final Thoughts

An important aspect of this work that is not yet completed is to validate this technique with experimental results.

Individual parts of the models have been validated (e.g. the net mapping, and the structural response of the frame), but the response of the entire model needs to be validated. As funding becomes available, researchers at the University of Maine plan to complete this portion of this project.

With the validation completed, these models will start a library of FEA net-pen models. Additional models will be added to this library as needed. Aquaculture researchers, designers, and operators will have a useful tool to evaluate the performance and response of these designs under the applied conditions.

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The Effect of Currents and Waves on Several Classes of Offshore Sea Cages

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The primary characteristic of concern in sea cage design is that "water in the ocean moves." We don't want to belabor points we all understand, but the major water motions result from waves, tidal cycles, general ocean circulation, wind shear and storm surges. At any oceanic site, water will move due to one or more of these causes. This will always happen and it is not a question of if, but when, how often, and of what nature and magnitude?

Some sea farming takes place in areas of minimal water motion and these sites were initially the most sought after locations. Sea cage usage is based upon models thought to work well at these still water sites. However, now it is generally accepted that water motion is a benefit because it is needed to carry fresh oxygen to the fish and to distribute their waste products over an area broad enough for natural decomposition. When water moves, it is clean and free to the farmer and the environmental costs are very low because waste is reduced within the marine system. Within practical limits more water motion is better for sea farming (Ref. 1). As we go offshore, we have no choice but to accept that sea farming will take place in moving water, so we must accept the next truth, that the sea cages best serve their purpose if the motions and deformations of the cages are minimized or, at least, optimized. Accepting these facts, our primary design philosophy at OST can then be stated as follows:

1) We believe that the good health of the fish requires a stable and fixed growing volume. Consistent, repetitive, natural and predictable fish behavior patterns can only be established within sea cages of stable shape and volume.

2) We believe that the sea farmer is best served in his business and operation when the growing volume is fixed, definable and effective.
3) We believe that the further evolution of the sea farming industry, both inshore and offshore, requires, at least, a taut netting foundation upon which new equipment and techniques can be developed.
4) We believe that the future sea farming industry must have available cage designs which experience minimal motion, distortions and stresses caused by waves.
5) The industry must have these sea cages designed as a healthy and safe system integrated into the larger marine habitat.
6) Finally, these sea cages must be provided at a cost that promises an attractive return on investment.

The sea farming industry is daily exposed to "new cage" designs or "improved" cage designs which promise ocean performance. In order to make sense of this marketing and sales bombardment and to predict the performance of the many cage designs, it is necessary for someone to classify the different designs according to expected and achievable performance. Based upon the fish habitat requirements and engineering needs for a stable and well defined geometry, we have chosen to establish sea cage classifications based upon the structural means used to fix the growing volume. This approach is absolutely essential if we are to accurately assess our risks gauge the potentials and answer the tough questions being asked by the critical public.

We have defined four sea cage classes:

Class 1 gravity cages rely on buoyancy and weight to hold the cage shape and volume against externally applied forces. Figure 1 illustrates the typical configuration.

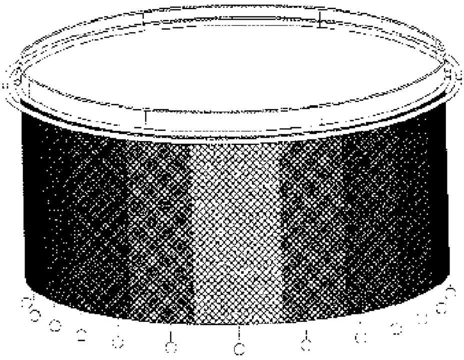


Figure 1. Class 1 Gravity Cage.

Both buoyancy and weight are forces resulting from gravity, thus the name. Gravity cages will not hold their shape or volume in the absence of gravitational accelerations, and furthermore, their enclosed volume is dependent upon the ratio of gravity forces to water motion forces. Most of today's commercial aquaculture uses this type of cage. Some of the more common class 1 gravity cages are the popular and much copied Polar Cirkle cage. Wavemaster, Bridgestone, Farm Ocean, Dunlop and any cages using suspended weight or buoyancy to provide volume are also gravity cages.

The Tension Leg Cage shown in Figure 2 illustrates the ideal shape and as deformed by a current. It is really an inverted version of the more typical gravity cages.

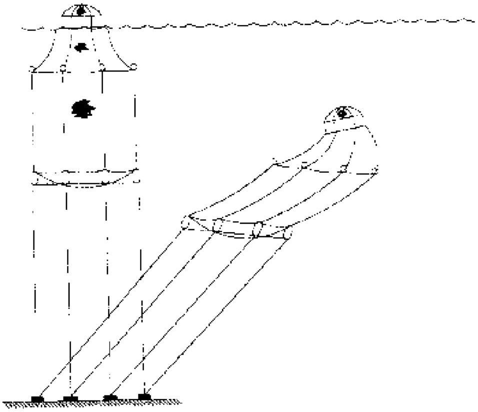


Figure 2. Class 1 Gravity Tension Leg Cage.

Class 2, Anchor Tensioned Cages such as Ocean Spar Sea Cage shown in Figure 3, rely on anchor tension to hold their shape. If these cages are placed in a zero gravity situation they will still retain their full shape and volume. The application of outside water forces to the netting enclosure will cause the anchor line tensions to increase which resists cage deformation.

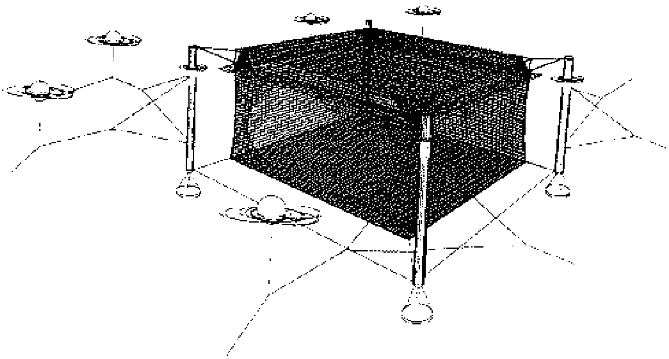


Figure 3. Class 2 Anchor Tensioned Sea Cage -- Ocean Spar.

However, they will not retain shape unless anchor tension is provided. This means that anchor tensioned cages need to be fixed at the site and, thus, they are stationary or immobile cages.

Class 3 sea cages are self tensioned and self supporting cages such as Sea Station, shown in Figure 4. These cages will hold their shape in the absence of gravity but will also do so without any anchor line tensions. The self tensioning structure resists net deformations.

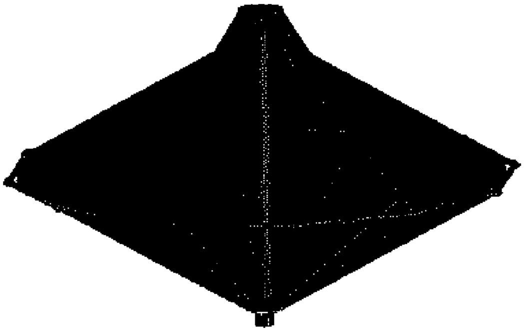


Figure 4. Class 3 Semi-Rigid Sea Station.

This class of cage is made entirely of beams and columns that are connected only by ropes and not by complex and rigid structural joints. Sea Station is an example of a class 3 sea cage where, floatation, stability and rigidity are provided by the spar buoy which in turn is connected to the rigid steel rim with ropes and netting.

The class 4 sea cages are characterized by rigid, self supporting structures made up of jointed beams, columns and trusses capable of withstanding compression, tension and bending loads. Figure 5 illustrates one possible configuration.

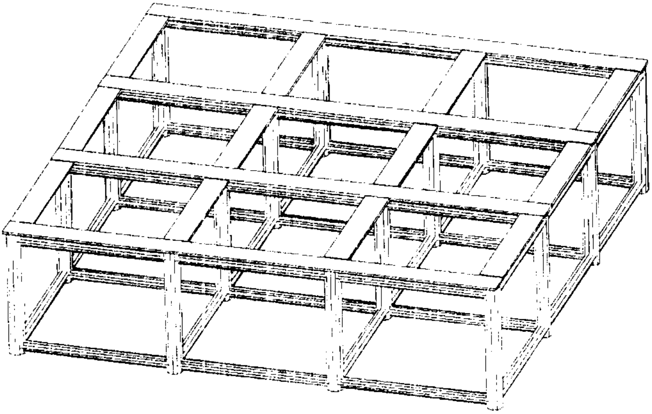


Figure 5. Class 4 Rigid Sea Cage.

They will retain shape in zero gravity and net deformations are resisted by internal structural forces. This class is characterized by several of the large barge structures experimented with in the past several years.

By defining these sea cage classes, we can evaluate performance based upon the class of sea cage. This simplifies the process of sea cage selection for particular sites. Identification of problems and solutions becomes easier, but most important of all, those involved in the industry are more capable of advancing the technology and profitability once general performance can be separated from the details presented by the differing designs within the same sea cage class. With this as our guide, we can now discuss the general behavior of each sea cage class in moving water.

General Performance in Currents

Currents cause the greatest loads on any of our sea cage classes and yet because netting is mostly made of holes, the drag forces need not be extreme for properly sized netting. The gravity cages are too compliant, and like a window curtain or a flag in a strong breeze, deform and flap in the water with the net result being a severe reduction in growing volume and some reduction in hydrodynamic drag. The deformations cause unpredictable, high loads on individual twines, with the resulting higher potential of failure. On the other hand, the sea cages class 2 through class 4 resist current deformations, but can experience greater drag forces as a result. The three higher class sea cages have a similar response to the currents, so these can be compared as a group against the gravity cage.

For a comparison, in moderate currents a typical sea cage net panel, normal to the current experiences a drag on the order of 2500 kg. The shape response of this net panel can be approximated by knowing the material elasticity, the drag force and the forces resisting deformations. Figure 6 shows an idealized cross section of a two dimensional net panel uniformly loaded to 42 kg/M2 and analyzed using a non linear finite element technique.

Here the collapse of a gravity net cross section is shown for different suspended weights and compared with the expected and observed deformation in the higher class cages, which are minimal. The volume efficiency of the gravity cages is considerably less than that of the higher class cages. Without taking into account three dimensional deformations, the total volumetric efficiency of the gravity cage can be estimated by the depth efficiency percentages shown at the bottom of each section. The maximum tensions in the individual twines are also illustrated in this figure and shown at mid sections. In each of the gravity net panels a buoyancy force, shown by the

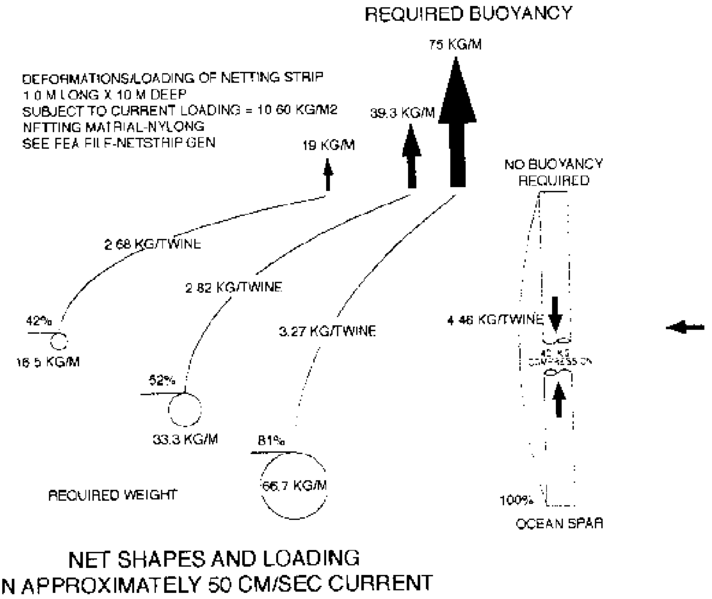
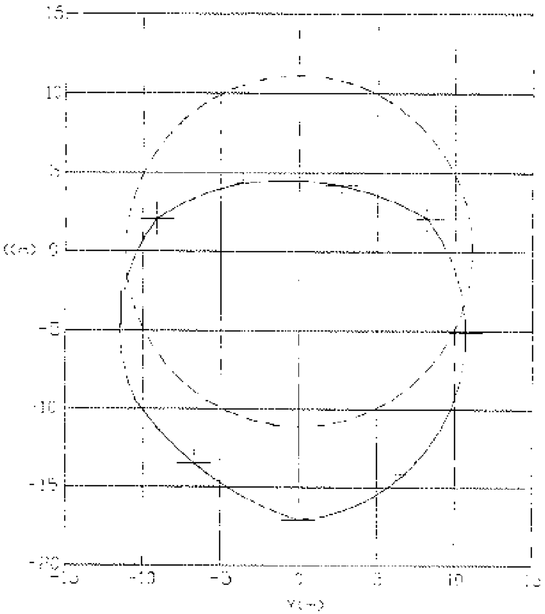


Figure 6. Netting Cross Sections.

vertical arrows, is needed to oppose the suspended weights and the net section drag. In order to get an approximation of the weight and buoyancy required for an entire cage, the values given need be multiplied by the length of the cage in meters. There are few gravity cages in existence that have the weight and buoyancy required to give depth efficiencies greater than the 42% shown in the figure. Add to this the fact that most oceanic sites will at some time experience higher currents than 50 cm/ sec. and it is easy to see why gravity cages have little future in the ocean.

In general, the higher class cages exhibit predictable and well distributed netting stresses when compared to gravity cages. The floating collar structures used with gravity cages are usually flexible or hinged, so they move with the waves' surface. The strong currents can deform the waterplane area of these cages and compound the deformations of the netting enclosing the fish. Figure 7 is taken from reference 1 showing deformation in a moderate 50 cm/sec current.



FLOAT DEFORMATION/OFFSET IN CURRENT
D. H. SLAATTELID 1990
ENGINEERING FOR OFFSHORE
FISH FARMING

Figure 7. Deformation of Gravity Cage Float Circle.

This causes a very complex, 3-dimensional net deformation with severe netting stress points causing high loads on individual twines. A proof of this fact is seen by the steady increase of twine sizes used for the gravity cages and the increasing complexity of nets which employ double netting, twin nets, shock absorbers, more strengthening ropes, more floats, etc. For gravity cages, this attempt to compensate for deformations by increasing net strength is a spiral, eventually closing to failure. The nets deform in the current and then break. The response is to build heavier and more complex nets which require more weights and more floats to stabilize volume, they then cause higher drag and more deformation, which requires heavier nets, etc.

Our experiences with Ocean Spar and Sea Station are showing that lighter nets with higher safety factors can be used for the job offshore. As an example, Sea Station uses twines of 1 mm diameter while Gravity cages in the same conditions use twine as heavy as 3.17 mm diameter. Gravity cages off the coast of Ireland have evolved in complexity and material sizes so that a single 12,000 cubic meter sea cage weighs 4.5 to 5.0 tons. Whereas a 15,500 cubic meter cage made of 100 % Spectra fiber for Ocean Spar weighs 0.90 tons. Based upon the weight only, the complexity of operation with the Ocean Spar net is greatly reduced over that of the gravity cage.

Sea Cage Submergence — Risk Reduction

A risk reducing behavior of sea cages is their automatic submergence as flow rates increase above a given threshold. Both Ocean Spar Sea cages and Sea Station sea cages are rigged to take advantage of this behavior as illustrated in Figure 8.

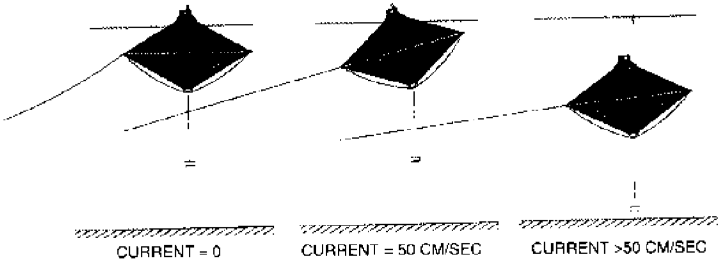


Figure 8. Automatic Submergence of Sea Station.

For example, a sea station can be buoyancy adjusted so that it normally floats on the surface for currents up to 50 cm/sec. Any storm driven currents above this value cause it to automatically sink. This can be an excellent strategy for putting the fish out of harms way until a storm has passed and requires no human intervention. Fish cannot escape because in both Ocean Spar and Sea Station sea cages the top netting is the same as the sides and bottom and completely sealed. The sinking behavior is difficult to achieve with gravity cages that are surface oriented. One of their major selling points is their compliance with the water's surface. This requires significant reserve buoyancy and low structural rigidity. This is confirmed by the use of hinged platforms in the case of Wave Master cages, flexible Polyethylene pipe with Polar Cirkles, or flexible rubber pipe used in the Bridgestone cages. Flexibility and reserve buoyancy work against automatic submergence. Excess reserve buoyancy requires high drag loads to cause submergence and low structural rigidity means the floating structure will easily bend (in the vertical direction) once it is submerged. Of the gravity cages, only the Tension Leg Cage easily exhibits this automatic sinking property, but in higher currents, anchoring loads and deformations become extremely high.

Motion in a Seaway — Risk Reduction

The criteria of minimizing sea cage motion in a sea way also reduces risk of failure. Our approach has been to use structures with low reserve buoyancy compared to the mass of the system. This puts the sea cage mostly underwater where wave induced water motions are quickly attenuated with depth. Both Ocean Spar Cages and Sea Station cages exhibit excellent performance in a sea way while floating on the surface. The low waterplane area of the spar buoys means that motion inducing forces remain minimal. Short period waves pass through without causing sea cage or fish motions, while both sea cages become wave surface followers for large period waves. For long period waves the surface following characteristic means relative motions between fish and cage are minimized and nearly zero. The relatively high drag of the netting enclosure damps any resonant response that might be expected.

The typical gravity cage floats on the surface and shock loading in the netting and ropes of the sea cage transfer continually between surface float and suspended weights. If it happens that waves are superimposed on the cages floating in currents, it is obvious that the gravity cages will experience very high additional loading on the twines. Because the net deformations are extreme, the high loads can and will occur anywhere in the net. The result is that the entire net must be made heavier to compensate for this. This is part of the explanation for the increasing complexity seen in the offshore gravity cage nets being used in the salmon industry.

The higher class cages will be relatively unaffected by combined waves and currents since the top and bottom of the net panel, being connected to rigid vertical structures will move in phase. Being rigidly connected to the supporting structure, the stresses in the netting vary gradually and are very predictable. Thus the high stress areas of the fish enclosure can be reinforced and supported without increasing the strength and weight of the entire net. This explains why the higher class cages can have nets that are much lighter and yet significantly more reliable than gravity cage designs. And all of this at nearly 100% volumetric efficiency.

Another strategy for reducing the effects of moving water is to allow the cages to drift with the current. Figure 9 illustrates this point. In the case of the class 1, 3 and 4 cage systems, the drag forces are non existent because the velocity between cage and water is reduced to zero. Although there are no current attempts to use this technique the advantages of it are worth discussing.

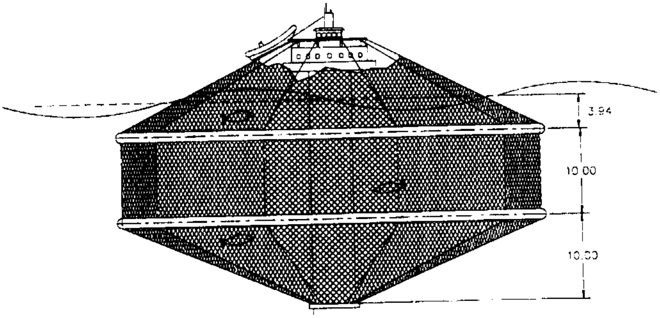


Figure 9. Sea Station-Ocean Drifter (25,000 cubic meters volume).

This strategy is not available to the class 2 anchor tensioned systems because they are not self supporting without anchors. For the class 3 Sea Station, the only induced motions are then from its response to waves, which tend to be very low or negligible. Although this strategy sounds idealistic, there are areas, such as the Straits of Juan de Fuca, where the water motion cycles will allow this tactic and will keep the sea cages within a bounded area. In this case, divers could work the system 24 hours per day because current is no longer a factor, and waves do not affect the cage. In the version shown in the drawing, it is possible to have a simple diver lock out door well beneath the water surface to make diving even easier. Fish waste would be distributed over a large area for natural decomposition and the fish would experience only minimal water motions. The structural design would be simplified because the water motion forces will be greatly reduced when compared to systems that are anchored. The behavior of the model Sea Station has been investigated under this free drifting mode and it is technically achievable with present technology.

Where Do We Go From Here?

We must concentrate on the class 2 and the class 3 sea cage designs because gravity cages do not meet any of our basic design criteria when applied in opened water. Gravity cage deformations in currents are the culprit. If we insist on taking Class 1 gravity cages to oceanic sites, their performance deficiencies will be compounded and the development of the industry will be greatly hindered. These are strong words, but they can be supported by theory, experience and the growing evidence of operational and environmental problems expressed daily in our publications. We believe the present stagnant state of development in the sea farming industry is a direct result of gravity cage application to sea farming. We believe that every problem confronting the gravity cage industry can be solved by using the higher class sea cages (reference 2). For example, some fish health issues and high stress levels, feed dispersion inefficiencies, operational inefficiencies and predation by marine mammals can all be traced directly to gravity cage enclosures. And think about this, what other animal besides farmed fish are raised in gravity cages that continually change shape, trapping the creatures in folds of netting, as the growing volumes approach near zero? Can we say that we are treating our final product well?

Since water simulates an anti-gravity environment, stability must be provided by structural rigidity or membrane tensions in the netting enclosure. For an example, without a stable and firm foundation, the development of machines, instrumentation and techniques for improving sea farming is greatly hindered. Class 2 through class 4 cages provide this stable base for sea farming evolution. We need a better understanding of the advantages of each cage class and its potential application. To encourage investment and development, risks must be evaluated based on the higher class sea cages and not on gravity cages. After studying the sea cage designs for nearly 10 years, I have come to the conclusion that gravity cages have no place in the ocean, and there is a growing body of evidence that they are even a poor cage class to use at sheltered water sites.

Summation

After attending almost every offshore sea farming conference since 1989, we have decided it is necessary to stand up and talk down to the gravity cage mentality, it is the wrong technology for the application. The ocean does not grant wishes, it doesn't tolerate the unfit. I would like to end with an analogy describing the gravity cage fixation of our industry.

Imagine that in front of us lies a large pile of rocks—perhaps 10 tons. We ask that each one of you go out to find a vehicle that can haul these rocks away. We will bet that all of you will look for a truck and that none of you come back with a passenger car to do the job. The passenger car represents the class 1 vehicle and the trucks, higher class vehicles. Yes, we can haul the rocks with the passenger car, but not very well. And yes, we can all cite situations were gravity cages have withstood the raging wind, wave and current, but statistically they are bound to fail. And yes, we can modify the passenger car to do the job a bit better, but normal performance of the vehicle and the sea cages must be matched to the job if statistically low failure rates and efficient, profitable operations are our goals. We all know each vehicle class and its capabilities with hardly a second thought. That is where we have to be in our understanding of sea cages if offshore sea farming is to become an industry in our lifetime. And higher class sea cages must be applied in the sheltered water aquaculture industry if its problems are to be solved and the challenge of continuing lower salmon prices are to be met. If this sounds too good to be true, it is not. It is the reality of the situation. Question us, challenge us, the industry needs to address these issues.

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Considerations for Longline Culture Systems Design: Scallops production

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Introduction

Mollusk culture in cages suspended in the water began in Japan with the oyster (*Crassostrea gigas*) 300 years ago, but only in the middle of this century did the Japanese develop a special culture structure where the main characteristic is to give an artificial environment to grow sessile organisms in a vertical water column. This is a great advance in the optimization of the production per unit of surface area. These structures belong to the general class of culture systems known as longline systems, and they are used commonly for scallops and oyster commercial culture, with some modifications in several countries, but all inspired in the Japanese system (Dupouy, 1983; Imai, 1977; Illanes & Akaboshi, 1985; Barnabe, 1991).

To design and dimension the longline system, it is necessary to know the depth of placement, the current speed, the longline flow exposure area, the respective drag coefficients, and an estimate of the fouling growth on the system (Merino, 1996).

In this work the basic physics and operational concepts for design, dimensioning and installation of a commercial longline for scallop production will be discussed.

Longline Systems and Structures

The spatial disposition of the longline in the water column could be totally immersed or at the surface. The immersed longline is used in unprotected culture areas and in areas with a considerable fouling biomass, because wave and fouling effects are minor under the water surface. The surface longline generally is used in protected areas with a low fouling biomass.

This general rule could reduce investment and operations cost in a commercial mollusk culture (Merino, 1996).

In the "longline culture system," three subsystems can be found: the mooring-anchor system, the floatation system, and the growing system, each of them are assembled from structures like ropes, buoys, pearl-nets, etc. (Figure 1).

The mooring-anchor system is used to stabilize the system against the effects of dynamic stresses, both vertical and horizontal, to which the longline is continually being subjected within the marine environment.

The floatation system is used to maintain suspension of the culture system, and is usually composed of different kinds of plastic buoys, or other manufactured materials, with varying sizes and capacities.

The growing system is used to grow the mollusk in captivity, and one of several growth structures is used, depending on the step of the culture and also on the selected species. In scallop and oyster cultures, pearl-net, lanterns, bags, ear-hangers, and other basket systems are generally used.

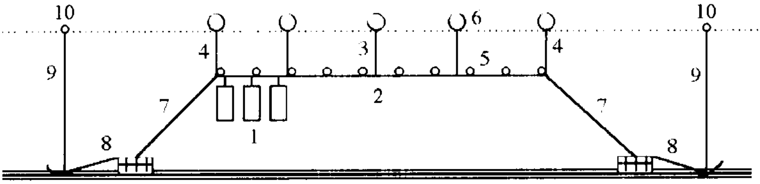

Figure 1. Typical Chilean aquaculture longline facility setup. 1) culture units, 2) main line, 3) buoy rope, 4) first buoy rope, 5) floats, 6) buoy, 7) mooring line, 8) anchor system, 9) anchor rope, 10) anchor buoy.

Knowing the Environmental Forces

The currents, waves, wind, system weight and management operations are the main variables that determine the dimensions and the magnitude of the stress that acts upon the longline system's structures.

Marine currents make horizontal tension a maximum in each of the extreme ends of the longline, and they are quantified through the hydrodynamic resistance of the longline's structures. The magnitude of this force depends on the current speed and the exposure area of the individual structures. Waves make horizontal and vertical tensions, and both are maximum at the water surface, and are progressively lessened under the surface. Winds also provide a horizontal tension, and its magnitude depends on the wind speed and exposure area of the surface structures. Finally, the system weight (animals, fouling, ropes, etc.) provides gravitational forces, and they can be compensated through the addition of floats during the system design.

Operational management requires the longline to be lifted to the boat for seeding, material changes, or harvest, and also when it is necessary to move or relocate the anchor and mooring systems.

Design Principles

The primary design challenge is to identify and evaluate the forces that are present on and in the longline, to determine the strength needed for the longline's structure to resist the natural forces and to reduce the culture labor risk. With sufficient technical data it is possible to size a longline for a specific goal and the specific environmental conditions of the culture area. This paper will show what is needed to specify a commercial longline system to grow mollusks.

Buoyancy force

In accord with the Archimedes Principle, all bodes, either totally or partially immersed in a fluid of density (δ) experience an upwards force commonly referred to as buoyancy force, similar in magnitude to the weight of the liquid volume displaced by the body.

Floatation or the gravity force on an immersed body

Floatation is a concept directly related to the buoyancy force, for the floatation of a body will depend on the balance that exists between the buoyancy force (upwards force) and the body weight (downwards force). Thus, it is possible to obtain the other force, a result of the addition of both forces, which is named floatation. Consequently, for any body:

Floatation = Dry body weight * $[1 - (\delta_{fluid}/\delta_{body})]$ (1)

δ_{fluid} = fluid density (Kg/m^3)

δ_{body} = body density (Kg/m^3)

Resistance force

To maintain an object in equilibrium in a moving fluid, there must be applied to the body a force of equal magnitude and opposite in direction to the resultant of the forces exerted by the fluid particles over it. This force, which will maintain the body in static equilibrium, is called "fluid resistance or drag" (R), and it is a function of the speed of the fluid (v), mass fluid density (δ), fluid viscosity (μ) and by the body geometry and surface roughness. The last two elements can be represented by a drag coefficient (Cd) and the projected body area (A), upon a plane normal to the direction of the flow. Thus the fluid resistance is given by:

$$R = {}^{1}/_{2}\, Cd\, A\, \delta\, v^2 \qquad (2)$$

These data are determined by observation and experiment (empirical data), not on theory, and upon the evaluation of the body resistance in a fluid. Generally the Cd value depends on the body size and of the Reynold's number (Re). Knowing the Reynold's number and the coefficient of drag (Cd), it is possible to obtain the respective resistance coefficient for a given body geometry and body cross sectional area from the numerous and widely published empirical tables.

Longline Rope Sizing

To size the structural longline ropes, the following should be considered:

- Evaluation of tensions in the mooring line
- Safety factor
- Characteristics of the materials used

Mooring line:

The recommended length for preliminary design is:

$n = j * h$ (4)

n = mooring-anchor rope length (m)

j = constant ($3.0 < j < 5.5$)

h = placement depth (m)

It should be noted that for a high length/depth ratio, the natural vertical changes acting on the anchor system are minimal, but at the same time the relative cost for this system is high due to the need for more rope.

Considerating the forces on the extreme ends of the main line and the diagonal configuration that will be adopted by the mooring-anchor rope subject to those forces, the tension will be:

$T_{m-a} = (T_h^2 + T_v^2)^{0.5}$ (5)

T_{m-a} = mooring line rope maximum tension (N)

T_h = maximum horizontal tension in the main line (N)

T_v = maximum vertical tension in the main line (N)

Once the maximum tension at the mooring line rope is determined, it is possible to determine the rope diameter (d), using the tension value for an approximate safety factor:

$d = (T_{max} * F_s)^{0,5} / C_r$ (6)

where,

d = rope diameter (mm)

T_{max} or T_{m-a} = maximum tension in the rope (N)

F_s = safety factor

C_r = resistance constant (N/mm^2)

Main line:

The main line's length is determined by the desired production level and the site characteristics. The following are the most important factors (Merino, 1996):

- Production level: This is in function of the investment available, supply of seeds, market demand, marine characteristic of the aquaculture site, etc.

- Productivity: The productivity of the aquatic environment will determine the maximum stocking level; from this one can establish an optimum culture density.
- Economics: Usually the ropes are used completely from anchor to anchor, so it is important not to introduce into the longline any element that could be the cause of structural failure during the period of operation.
- Design aspects: some design parameters, like the separation between each growing culture unit, determine the main line length and factor directly in the stocking density of the culture system.

Also to quantify the forces acting over the main line, it is possible to solve the problem by using coordinates at the one end of the main line:

$$T_h = R_h + F_h + T_o \qquad (7)$$

T_h = Horizontal force at the main-line end (N)

R_h = Hydrodynamic resistance of the main line and culture units (N)

F_h = Horizontal force due to dynamic forces (N) (waves, winds)

T_o = Horizontal force due to gravitational forces (N) (rope weight, biofouling weight)

Buoy ropes:

For the determination of the buoy rope diameter it is necessary to know the working tension to which they will be submitted. First it is required to calculate the immersed weight that should be lifted by the flotation main-line system.

a) Main-line total weight calculus ($W_{\text{main line}}$). The immersed total weight of the main-line system should be calculated from the immersed weights sum of each structural component (PSi). Then, from the equation (1) results:

$$W_{\text{main line}} = \sum PSi \qquad (8)$$

b) Main line weight per unit length calculation (w). The main-line weight ($W_{main\ line}$) per unit length is simply the W divided by the main-line length (s). Knowing this, it is possible to know how many buoys per unit length will be needed to maintain the main line at the surface. The following equation gives the longline lineal weight:

$$w = W_{longline} / s \qquad [kg/m] \qquad (9)$$

c) Buoy rope diameter calculation: Assuming that the adopted configuration by the main line, between two buoys, is like a catenary, it is possible to utilize the catenary expression to determine the tension in the line. Once a maximum is determined, a rope diameter can be chosen, and an adequate safety factor incorporated, using a methodology that is similar to that used in other portions of the longline systems (Equation 6).

Anchor Rope:

Although one might think that the anchor rope could be smaller than the main line, the working characteristics of the system require this rope diameter to be similar to that of the main-line rope. The reason is that during installation and relocation operations of the system, the anchor rope is used for tensioning the main line. Using this diameter, it is possible to get its length using the catenary principles.

Buoy Sizing

The buoy volume can be easily determined by the following equation:

$$V_b = [W / [(\delta_{sw} - \delta_b) * g]] * F_s \qquad (10)$$

V_b = Buoy volume (m^3)

W = Weight to lift per buoy (N)

δ_{sw} = Seawater density (1,025 Kg/m^3)

δ_b = Buoy material density (Kg/m^3)

g = Gravity acceleration (9. 8 m/s^2)

F_s = Safety factor

Anchor System Sizing

During operation, the main factors that generate hydrodynamic resistance are the growing units. In effect pearl-nets and lantern-nets produce a wall-like effect against water flow, and that creates a tension in the system that will be resisted by the mooring-line rope to the anchor system.

Design and sizing of the anchor system must also consider the bottom conditions of the place where the longline system will be located. The slope, substrate type and its sheer strength, are very important in determining the anchor system design characteristic.

The anchor volume could be determined by the following equation:

$$V_{anchor} = W_{dry} / \delta_{anchor} * g \qquad (11)$$

V_{anchor} = anchor volume (m^3)

W_{dry} = anchor dry weight (N)

δ_{anchor} = density of anchor material (Kg/m^3)

g = gravity acceleration ($9{,}8\ m/s^2$)

The dry weight anchor should be determined using equation 1.

The following equation describes the immersed weight in relation with the respective forces:

$$W_{sub} = (T_{m\text{-}a} * \cos \phi / \mu) + T_{m\text{-}a} * \sin \phi \qquad (12)$$

W_{sub} = immersed anchor weight (N)

$T_{m\text{-}a}$ = mooring line rope tension (N)

μ = drag coefficient

ϕ = mooring line rope angle

To decide the kind of anchor that is necessary for a specific place, it is possible, from a technical viewpoint to make a pre-selection based upon the concept of a "fixing coefficient" (K). K is the relation between "fixing force" (H) and the anchor dry weight (W), given by:

$$K = H / W_{dry} \qquad (13)$$

Table 1 shows several anchor and substrate types with their respective K value.

Table 1. Fixing coefficient (K) from different anchor and substrate types.

Anchor type	Sand substrate	Mud substrate
Stockless	$4.4 < K < 16.0$	$2.0 < K < 7.5$
Mushroom	$2.0 < K < 2.5$	5.0
Danforth	$14.6 < K < 21.0$	$7.1 < K < 8.5$
Stato	$20.0 < K < 35.0$	$15.0 < K < 22.0$
Boss	$30.0 < K < 55.0$	$22.0 < K < 35.0$

Rodriguez, 1996.

Beveridge (1987) also states that it can be shown that K depends upon the angle between the anchor and the seawater surface, and thus the ratio between water depth and line length, and also with the nature of the substrate (Table 2).

Table 2. The fixing coefficient (K) of sandbag anchors on different substrates and varying mooring cable length: water depth ratios (l:d).

Substrate l:d	1	2	3	4	5
Sand	0.19	0.53	0.63	0.70	0.74
Sandy mud	0.10	0.32	0.36	0.36	0.62
Mud	0.05	0.23	0.27	0.35	0.41

Beveridge, 1987.

Conclusion

The geometry and the spatial configuration of a longline culture system depend on the oceanographic and meteorologic site conditions, the depth of the main line below the surface, and the type of longline that depends on the operating approaches and procedures. Of these, the oceanographic and meteorologic site conditions are probably most important. If they are incompletely understood, the probability of failure is high, or the initial cost may be unacceptably high.

In this paper, means have been formulated to calculate or estimate the forces are acting upon the long-line system. Once they are evaluated, it is then possible to determine the strength that must be built into the long-line's structures by to resist the natural forces and to reduce the risk to laborers during culture. During the design stage it is also necessary to consider the projected levels of biofouling on systems components and the effects of age and sun damage. Biofouling on netting is particularly important for it increases environmental loading over the entire long-line system by added weight and drag but it also reduces water circulation in the lantern-nets and pearl-nets and this could kill the mollusks.

Finally, a word of caution. Always consider adequate safety factors, for this gives you an additional tolerance in your system design and to some degree compensates for unanticipated loading events or even unexpectedly high production.

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Optimisation of Southern Bluefin Tuna Resource in Semi-Open Ocean Farming, Boston Bay, South Australia, Using Numerical Simulation

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Abstract

Environment Carrying Capacity (ECC) of Boston Bay, South Australia was developed to optimise farming of the southern bluefin tuna resource. Existing and newly developed numerical simulation techniques, in conjunction with mean oceanographic, meteorologic and farm management data were used to derive spatially averaged peak annual levels of dissolved nitrogen and phytoplankton as a function of tuna feed. Simulations were conducted for annual (360 days) production levels (500-5,000 tonnes) and included allowance for uptake of nitrogenous material by sediments. Based on Australian and New Zealand Environment and Conservation Council recommendations for NO_3-N (neglecting sediment uptake), the mean value of ECC for Boston Bay was, mean 1,750 tonnes, range 1,300-2,400 tonnes. Corresponding simulations allowing 33% sediment uptake of waste derived products yielded an ECC, mean = 2,600 tonnes, range 2,000-3,400 tonnes.

Background

Southern bluefin tuna (*Thunnus maccoyii*) are caught in the waters of the Great Australian Bight and are transferred to cages in the protected waters of Boston Bay, South Australia, Figure 1. They are nurtured and grown until they reach a marketable condition. The tuna industry in Port Lincoln has

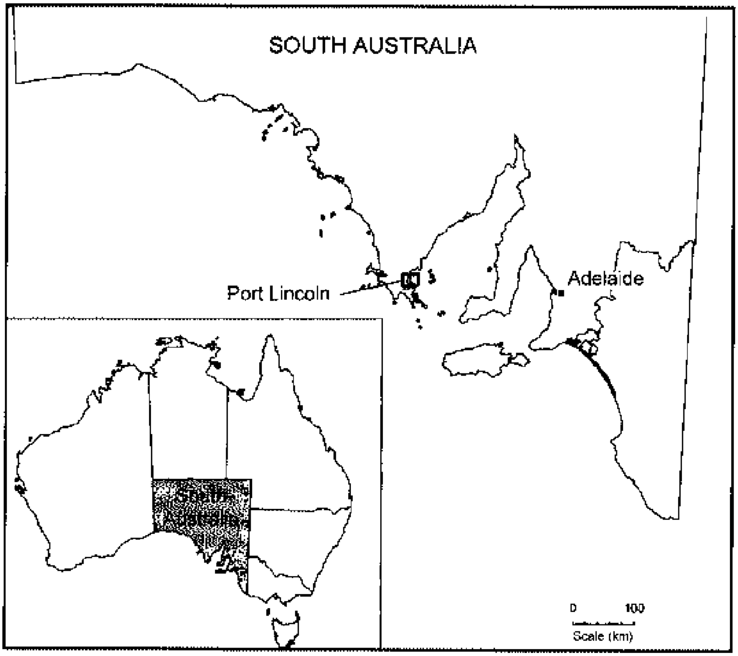


Figure 1. Location of the study area.

grown from traditional canning to a highly value added commodity. The first experimental tuna farm was established in Boston Bay in 1990 under a tripartite agreement between the Australian Tuna Boat Owners Association, the Japanese Overseas Fisheries Cooperative Foundation and the South Australian Government. Earnings from the industry have risen from about $4 million in 1990 to around $40 million in 1994. Farm sites are located in Boston Bay and surrounding area, Figure 2. Each site is allocated 126,000 m^3 of water at a stocking density of up to $4kgm^{-3}$.

This is equivalent to 10 cages, each holding up to 50 tonnes of tuna per site. The tuna holding cages are made of high density polyethylene plastic floating collars 30-40 metres in diameter from which two nets are suspended. The inner net, which contains the tuna, has sides which drop to a maximum depth of 10 metres. The outer net is used to keep predators away, such as seals and sharks. About 4-9 months is required

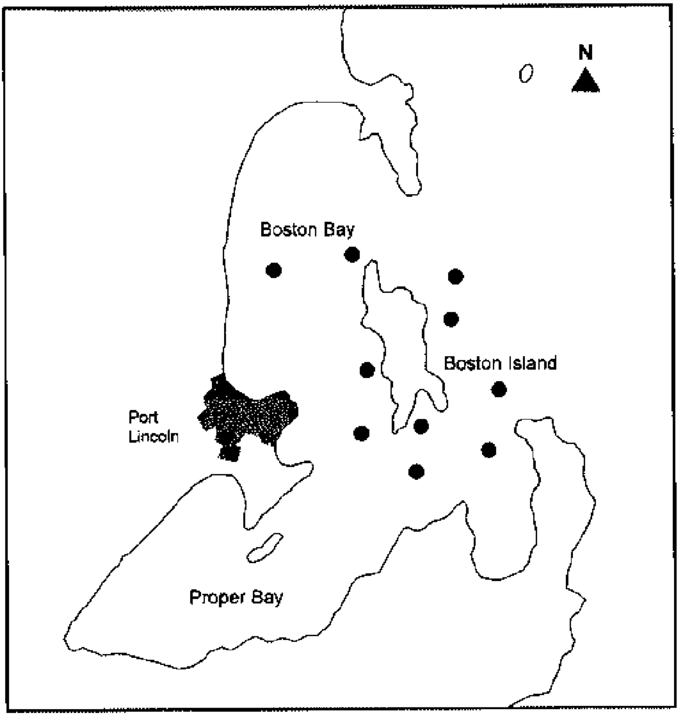


Figure 2. Boston Bay region showing approximate location of tuna leases (1994).

for the tuna to reach a marketable size of about 30 kg, after which they are harvested almost on a daily basis. The main market for the tuna is the Tsukiji Fish Market in Tokyo, Japan. (PISA, 1996)

The tuna are fed daily mainly on a diet of pilchards, mackerel and a supplementary vitamin powder. Pilchards have a high water content and about 17 tonnes of pilchards are required to produce about one tonne of tuna. This at the extreme end of commercial feed conversion and marks one of the major expenses associated with tuna farming. Research is currently ongoing into developing artificial feeds for tuna. This should allow for a much more efficient food conversion ratio of about 5:1. (PISA, 1996). Sea-cage farming involves stocking densities and feeding rates in excess of what occurs in the natural environment which generates large quantities of waste. Uneaten food and faecal material is deposited on the sea floor which leads to nutrient enrichment of the sea floor and the water column. Gowen et al (1988). This has two implications. Firstly, there is a need to maintain the environment under the cages in a healthy environment for the fish thus ensuring productivity of the farms and secondly to address the long term viability of the marine environment on a regional level.

Based on salmonoid farming the primary source of dissolved nitrogenous material associated with fish farming is due to fish feed waste and faeces. The following division of fish food has been suggested. Approximately, 10-20% of feed sinks directly to the sea bed, 80%-90% is consumed by fish which is apportioned as follows, 25% is retained by fish, 65% excreted as urine, 10% excreted as solids, Gowen and Bradbury (1987). As a first approximation, 80% of the feed may be considered as waste material of which approximately 3% is converted to nitrogenous compounds such as organic particulate nitrogen in sediments which can break down and be slowly released into the water and dissolved inorganic nitrogen (mostly nitrate, NO_3-N; and ammonia NH_3-N).

Despite much debate and proliferation of coastal zone policies and water quality guidelines throughout the world a simple and effective definition of carrying capacity of a coastal region, particularly in relation to aquaculture application, has not yet evolved. Terms such as carrying capacity, assimilative capacity, initially much supported, have not been translated into practical and meaningful definitions that can be applied across a broad spectrum of marine systems. Effective management of coastal resources requires agreement on intended use and type of "acceptable" water quality values. (Lord et al, 1994)

A possible definition suitable for aquaculture may be derived from the concept of sustainable development proposed by Pillay (1996) and defined at the Den Bosch Conference in 1991 (FAO/Netherlands 1991). Sustainable development was defined as "the management and conservation of the natural resource base and orientation of the technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for the present and future generations. Such development conserves land, water, plant and animal resources; is environmentally non-degrading, technically appropriate, economically viable and socially acceptable."

The term "environmental carrying capacity" is advanced as an appropriate interpretation of the above concept and is defined as "maximisation of tuna biomass in Boston Bay without exceeding recommended water quality guidelines for Boston Bay." The water quality parameters used in this case are a suite of environmental values (dissolved nitrogen and phytoplankton) proposed by the Australian and New Zealand Environment and Conservation Council (ANZECC) for specific classes of the marine environment.

For coastal waters, ANZECC, (1992) guidelines recommended NO_3-N and phytoplankton (chlorophyll-a) levels between 10-60 mgm^{-3} and less than 1 mgm^{-3} respectively. For estuarine and embayment cases the corresponding levels for NO_3-N and phytoplankton were 10-100 mgm^{-3} and 1-10 mgm^{-3} respectively. Boston Bay can be considered to be intermediate between these classifications. The presence of Boston Island tends to make Boston Bay a semi-estuarine system, however the relatively unrestricted exchange of the bay with the open sea suggested a coastal regime.

The approach taken in this investigation was based on the use of computer modelling techniques to calculate spatially averaged dissolved nitrogen and phytoplankton concentrations with respect to ambient levels in Boston Bay. Computation was made for different tuna stocking levels. The resultant levels of dissolved nitrogen and phytoplankton levels were considered in relation to ANZECC (1992) recommended levels to derive environmentally acceptable tuna production levels.

Numerical models in aquaculture – recent applications

Falconer and Hartnett (1993) used deterministic mathematical models for farm optimisation. The models predicted tidal currents and solute levels. Refined mathematical models for predicting tidal current, biochemical oxygen demand (BOD) and nitrogen levels for a proposed fish-farm configuration in a bay off the Eire coastline were examined. The models accurately predicted field-measured velocities at two sites within the bay and further predicted BOD and nitrogen levels which were known to affect adversely the hydro-ecology of the bay. Silvert et al. (1990) modelled the feeding, growth and metabolism of cultured salmonoids. Modelling package BSIM was used to simulate critical ecological processes that take place within, around and beneath a sea cage filled with salmon (Salmo salar). The derived model, SITE, was tested in the L'Etang Inlet of New Brunswick (Canada), an area of expanding salmon farming. The behaviour of the model was consistent with available field data. Kishi et al. (1991) applied a numerical model to calculate tidal and wind induced currents, spatial distribution of dissolved oxygen and distribution of deposits from mariculture of fish.

Turrell and Munro (1988) studied the dispersal of wastes from a fish farm using a two box model of a hypothetical fjordic sea loch typical of some Scottish west coast fish farm sites. Within the range of production (70-100 tonnes per annum) of fish, the release of ammonia was not considered to add significantly to existing ammonia levels in the loch. Petrusevics (1992) used a two dimensional depth integrated model which included diffusion simulation to examine nutrient distributions associated with a number of tuna pontoons in Boston Bay. The model permitted pontoons to be treated as point sources of nutrients. Nutrient loadings and pontoon location could be varied to demonstrate expected nutrient levels in the bay for variable tuna stocking levels.

Numerical models provide useful tools which can be used to estimate various processes and outcomes. However, irrespective of the complexity of a model, a model is an idealised and simplified representation of the environment and, at the best, produce estimates whose accuracy is a function of the quality of data used in the model and how well the model simulates known processes. In the case of Boston Bay, approximations of physical and biological processes were made to derive water quality levels resulting from tuna farm activity. The resultant levels were compared to broadly defined water quality criterion to provide an estimate of the "environmental carrying capacity." Southern bluefin tuna fish farming in Australia is relatively new and there was limited information which could be drawn upon to address various aspects related to the carrying capacity issue in Boston Bay. There was no readily available numerical model which could be applied and it was necessary to develop new modelling techniques.

The Physical Environment of Boston Bay

Boston Bay is a shallow, maximum depth of about 16-17 metres, north-south aligned bay approximately 12 km long and about 5 km wide. Boston Island, located centrally in the bay, is about 5 km long and about 2 km wide. Exchange between Boston Bay and Spencer Gulf occurs mainly through the northern channel which is about 4 km wide. Boston Bay is physically connected to the relatively shallower Proper Bay. Figure 2.

Winds

The summer dominant wind direction in the morning and afternoon is south-east (12.5%) and south (12%) with a relatively large (18%) contribution of easterlies in the afternoon due to the local sea breeze. The majority (75%) of the winds are gentle breezes (<18 kmh^{-1}). During the winter, the prevailing winds are from the west (18%), north-west (11%) and north (11%). The winds are gentle breezes (<18 kmh^{-1}) for about 78% of the time. Winds up to Force 8 (63-74 kmh^{-1} on the Beaufort wind scale) occur in the area. Approximately 93% of Force 8 or greater winds are north-westerlies while 7% are north-easterlies. The largest number (79%) of Force 8 winds occurred in the spring, 14% in the summer and 7% in the winter.

Wave regime

Wave conditions are mostly locally wind generated. Long period waves from the southern ocean do not generally penetrate into Boston Bay except during extreme storms across the southern continental shelf. Under Force 8 wind speeds and for the following wind directions the significant wave height and wave period are: south-westerly/north-westerly, 1.46 m, 4.7 secs; north-easterly, 2.1 m, 5.7 secs.

Currents

Current speeds in Boston Bay are highly spatially variable (Petrusevics et al, 1993). Currents between Boston Island and the mainland are the weakest. In this region majority (91%) of current speeds are less than 5 cms^{-1}. Major (33%) direction of flow in this region is in a south-westerly direction. The currents on the eastern side of Boston Island are stronger, in this region the majority (42%) of current speeds are in the range 2.5-5.0 cms^{-1}. The dominant (27%) direction of the currents is south-westerly. The strongest currents are experienced in the channel south of Boston Island where majority (65%) of current speeds are in the range 2-10 cms^{-1}. The major direction of flow is west south-west (32%) and east north-east (29%).

The effect of wind on currents

Large non-tidal residuals, as high 50%, have been reported in current records, VIMS (1992). Stevens and Noye (1995) reported that from numerical simulation of depth averaged currents in Boston Bay, wind did not have an important effect on currents in the region. Using dimensional analysis, Petrusevics (1996) showed that, for mean tidal and wind conditions, water elevation has at least three orders of magnitude greater effect on currents than wind stress. However, with decreasing tidal amplitude and increasing wind speed the effect of the wind becomes more important. In Boston Bay, this may occur during storms, and periods of "dodge" tide, a local phenomena when tidal elevations remain constant for a period of about one day every two weeks.

Temperature-salinity properties

Typical mean mid winter temperature and salinity values are 13°C and 35.75 ppt respectively. Corresponding values for late summer are about 20°C and 36.70 ppt (Petrusevics et al. 1993)

Methodology

Modelling considerations

The approach consisted of linking numerical techniques reported by Pridmore and Rutherford (1992) to simulate dissolved nitrogen and phytoplankton levels in Big Glory Bay, New Zealand, to a two dimensional depth integrated model, Bye (1977).

Throughout the year, Boston Bay is well mixed, vertically and laterally (Petrusevics et al, 1993). Further, based on mass transport calculations the major exchange between the combined Boston Bay-Proper Bay system and Spencer Gulf occurs through the northern passage (40%) and southern passage (60%) and only about 14% transport occurs between the southern portion of Boston Bay and the southern channel. This means that the southern channel serves to connect mainly Proper Bay with Spencer Gulf and the main exchange between Boston Bay and Spencer Gulf is through the northern channel. Water circulation patterns under typical seasonal tidal and wind conditions confirm mass transport estimates. A region of divergence can be noted in the southern region of Boston Bay, Figure 3, hence Boston Bay may be considered as a separate hydrodynamic unit. Nutrient loading to the system was assumed to be due to feed waste and excreted material from the fish in cages, Figure 4, and was dependent on stocking levels which varied throughout the year, Table 1.

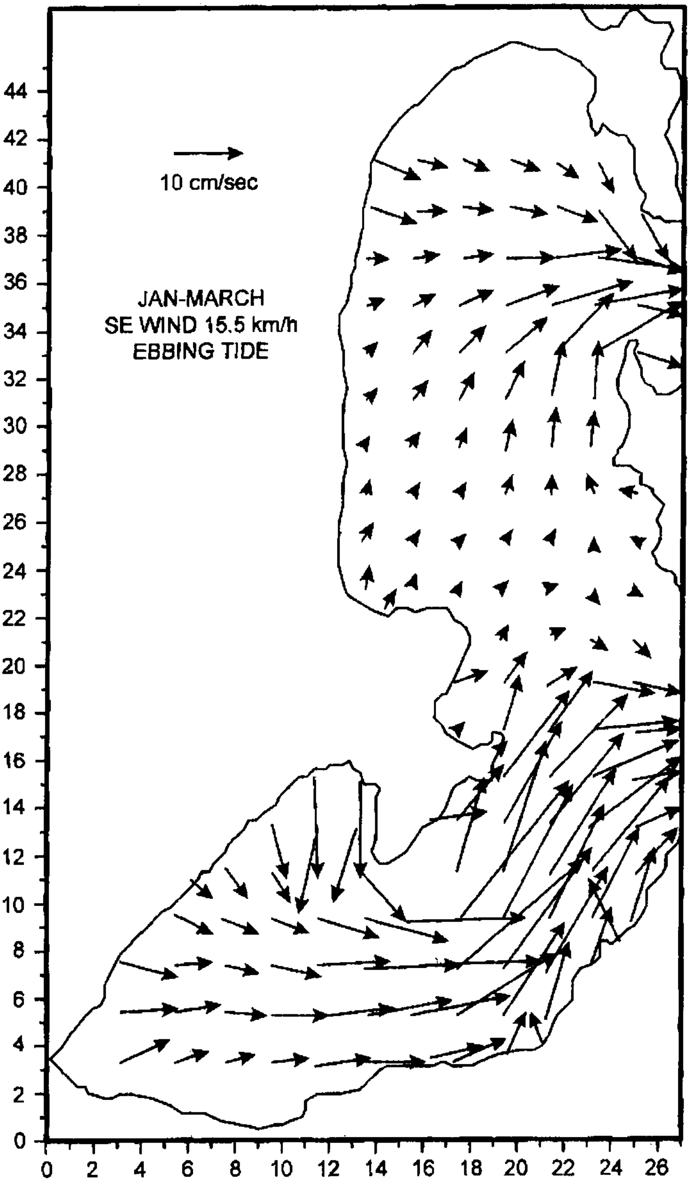


Figure 3. Peak ebbing tidal currents. Note region of divergence at row 22.

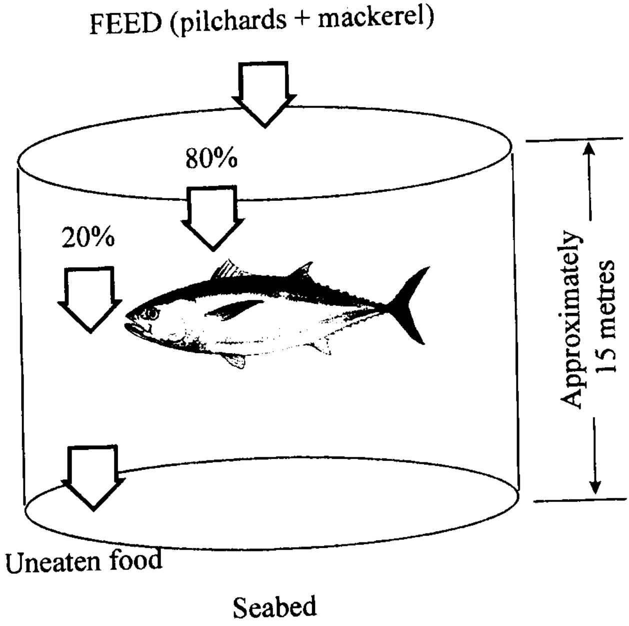


Figure 4. Schematic representation of tuna farm.

TABLE 1. Tuna farming informing

Month	Fish In %	Total Fish In %	Fish Out %	Total Fish Out %	Food Consumed (%Body Wt/Day)
JANUARY	10	10	0	0	10
FEBRUARY	25	35	2.5	2.5	10
MARCH	40	75	5.0	7.5	9
APRIL	25	100	7.5	15	8
MAY			10.0	25	7
JUNE			10.0	35	6
JULY			15.0	50	4
AUGUST			15.0	65	3
SEPT.			15.0	80	3
OCTOBER			15.0	95	8
NOVEMBER			5.0	100	0

Computation of dissolved nitrogen levels

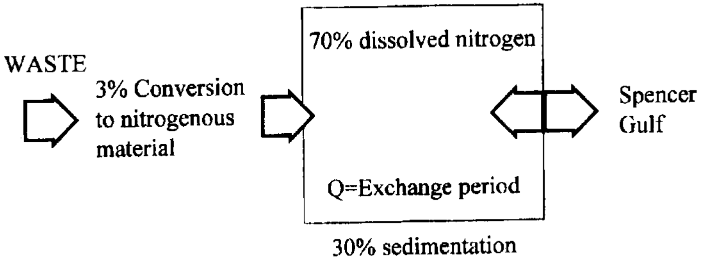
Simulations of spatially averaged dissolved nitrogen were made for sediment uptake and no-uptake cases. A ratio of 2:1 of dissolved to sediment based nitrogen was assumed. This corresponded to approximately 33% being taken up by the sediments which is in agreement with observations on sediment uptake reported by Cheshire et al (1996).

The steps involved in computation of dissolved nitrogen followed the method outlined by Pridmore and Rutherford (1992).

The simplified mass balance model is, $V\ dN/dt = I - QN + QN_0$; the steady value is given by $N = N_0 + I/Q$ and the time dependent solution by $N(t) = + (N(t_0) - N_0)\exp(-Q/V(t-t_0) + I/Q(1-\exp(-Q/V(t-t_0))$ where N and N_0 represent average concentration of dissolved nitrogen levels in Boston Bay and Spencer Gulf respectively; V is the volume of Boston Bay. I is the nitrogen input into Boston Bay due to tuna feed waste and Q is the net exchange between Boston Bay and Spencer Gulf. Figure 5. In the absence of a relationship between dissolved nitrogen and phytoplankton for Boston Bay, the value for ambient nitrogen level N_0 was obtained using the regression between nitrogen (N) and chlorophyll-a reported by Pridmore and Rutherford (1992), Chlorophyll-a =0.0867(N)-0.250.

Chlorophyll-a levels reported for Boston Bay from surveys conducted during 1991 and 1992 by the South Australian Research Development Institute (SARDI pers comm) are highly variable. Values ranged between 0.17 and 1.26 mgm^{-3}. For purposes of this investigation a value of 0.5 mgm^{-3} was used. The corresponding level of nitrogen was = 8.68 mgm^{-3}. These values are in reasonable agreement with values reported for dissolved nitrogen and chlorophyll-a for the Marmion Marine Park, Western Australia (13-23 mgm^{-3} and 0.4-1.2 mgm^{-3}) and Cockburn Sound, Western Australia for dissolved nitrogen of 5-11 mgm^{-3} (ANZECC, 1992).

The nitrogen input to Boston Bay (I) was obtained by use of the relationship; nitrogenous compound value = tuna feed x



$$V\,dN/dT = I - QN + QN_O$$

V = Volume of Boston Bay
I = Nitrogen input to bay
N, N_O = dissolved nitrogen levels in Boston Bay, Spencer Gulf

Figure 5. Schematic representation of processes at bay level.

0.024, which is based on the assumption that 80% of food is converted into waste matter and about 3% of waste matter is converted into nitrogenous compounds, Gowen and McLusky (1988).

Computation of phytoplankton level

The approach used for calculating phytoplankton levels followed that outlined in Pridmore and Rutherford (1992).

$dB/dt = D(b-B) + uB$ where B and b are the spatially averaged phytoplankton concentrations in Boston Bay and Spencer Gulf. D=Q/V, Q=exchange period of Boston Bay, V= volume of Boston Bay and u is the specific growth rate of phytoplankton which is expressed as $u=u_{max}\ ((K-B)/K)$ where K is the maximum phytoplankton concentration that can exist in a given embayment and is linked to dissolved nitrogen (N) level through the relation $K=0.086(N) - 0.25$.

The computation framework

The software program to perform the above calculations runs as a DOS program and consists of separate modules. Module FLOWC (after Bye, 1993) was used to calculate mass transport and flushing period of Boston Bay for mean monthly tidal amplitude and most frequently occurring wind speed. The module FARM calculated dissolved nitrogen and phytoplankton levels. Figure 6.

The program allows the user to input tidal data, wind data, ambient dissolved nitrogen and phytoplankton levels (in this case, dissolved nitrogen = 8.68 mgm^{-3}, phytoplankton = 0.5 mgm^{-3}), annual stocking levels (500-5,000 tonnes), feed levels (Table 1), feed waste, feed waste to nitrogenous material conversion factor and percentage nitrogenous material uptake by the sediments. The output, consists of *spatially averaged* dissolved nitrogen and phytoplankton values. These data were compared with recommended ANZECC (1992) guidelines for dissolved nitrogen and phytoplankton to derive a mean and range of production levels in Boston Bay.

Results and Discussion

The Exchange Period

The mean exchange period was derived from mass

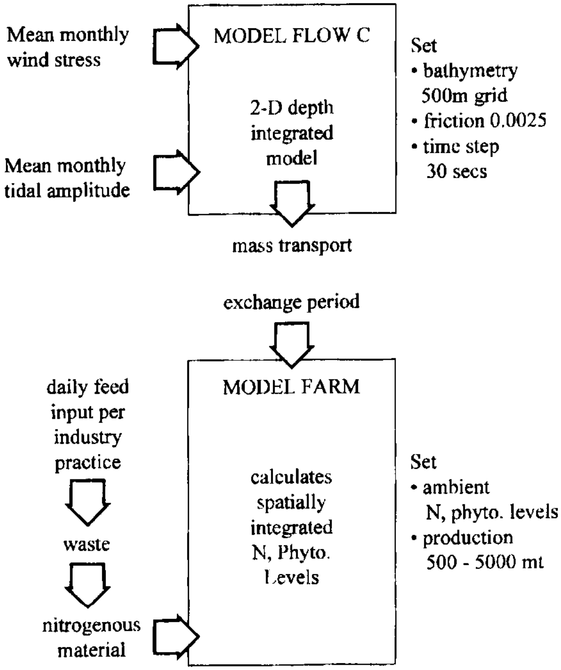


Figure 6. Model structure.

transport calculations across a section in the northern channel. The exchange period throughout the year varied between about seven and nine days.

Nitrogen input to Boston Bay

The amount of nitrogen released into Boston Bay varied throughout the year in proportion to the feeding regime. Figure 7a corresponds to a production level of 600 tonnes. The nitrogen level peaked in April.

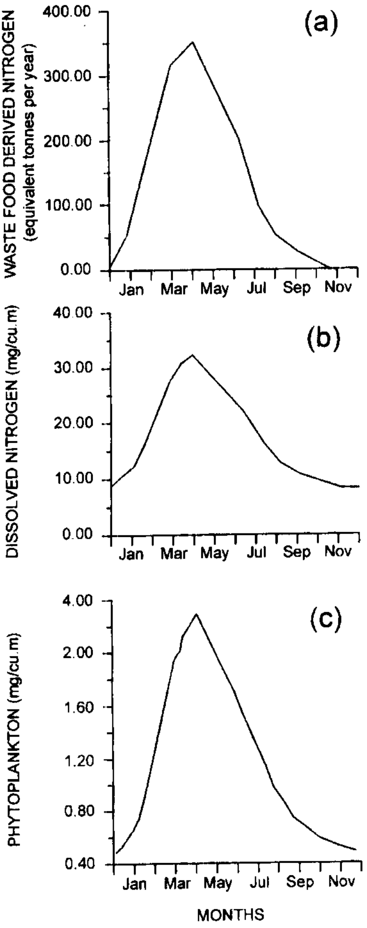


Figure 7. (a) Nitrogen input to Boston Bay, (b) Dissolved nitrogen as NO_3-N, (c) phytoplankton as chlorophyll-a.

Dissolved nitrogen/phytoplankton levels

Peak dissolved nitrogen and phytoplankton concentrations in Boston Bay followed closely the levels of nitrogen input, Figure 7 b and c. For example, for production = 600 tonnes and waste to nitrogenous conversion factor = 0.024, the corresponding concentrations were about 35 mgm^{-3} and 2.4 mgm^{-3} respectively relative to ambient levels of 8.7 mgm^{-3} and 0.5 mgm^{-3}. Simulations were carried out for cases where: (1) all nitrogenous compounds due to feed waste material were dissolved and (2) approximately 33% of nitrogenous material being taken up by sediments. Simulations corresponding to bay production levels between 500 and 5,000 tonnes per annum were conducted over a period of 360 days.

Boston Bay the bay was treated as an intermediate case between an embayment and coastal waters. Water quality guidelines for NO_3-N and chlorophyll-a (ANZECC,1992) were used to derive the environmental carrying capacity of Boston Bay. The results corresponding to dissolved nitrogen only and 33% uptake by sediments is shown Figure 8. The case for phytoplankton can be represented similarly.

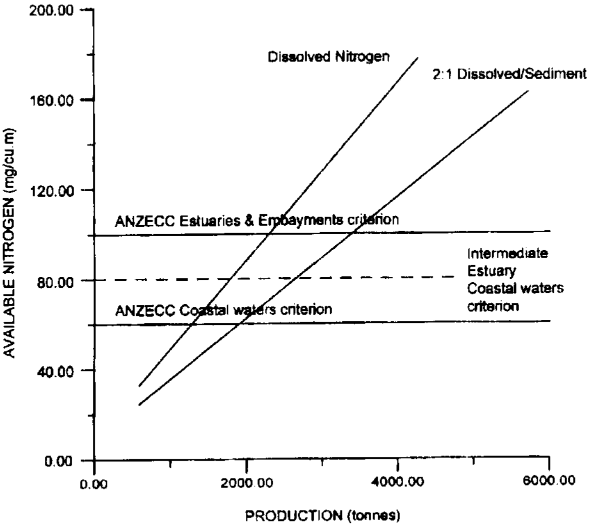


Figure 8. Estimate of sustainable fish production corresponding to 33% sediment uptake.

The outcomes were, no sediment uptake; NO_3-N criterion, mean ECC=1,750 tonnes, range 1,300-2,400 tonnes. Chlorophyll-a criterion, mean ECC=1,600 tonnes. For a 33% sediment uptake; NO_3-N criterion, mean ECC=2,600 tonnes, range 2,000-3,400 tonnes.

Residual levels

Dissolved nitrogen and phytoplankton at the end of 360 day simulation period, after all fish were removed, showed an increase above ambient levels. For example, for an annual production level of about 1,700 tonnes, the residual values for dissolved nitrogen and phytoplankton were about 8.95 mgm^{-3} and 0.52 mgm^{-3} which represented an increase of about 2.9% and 4% per annum respectively with respect to ambient levels. Residual dissolved nitrogen and phytoplankton levels fell when stocking levels were reduced to zero by end of October, rather than November. The extra time was sufficient, from a numerical simulation point of view, for the bay to recover to near ambient levels.

The study provided one possible way of quantification of the environmental carrying capacity of Boston Bay using numerical models based on mean or bulk oceanographic processes in Boston Bay. Several aspects of the technique could benefit from further investigations. The validity of model outcomes will be provided by data collected by other programs presently on-going and planned for Boston Bay.

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Demonstration of Open-Ocean Aquaculture of Groundfish

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Introduction

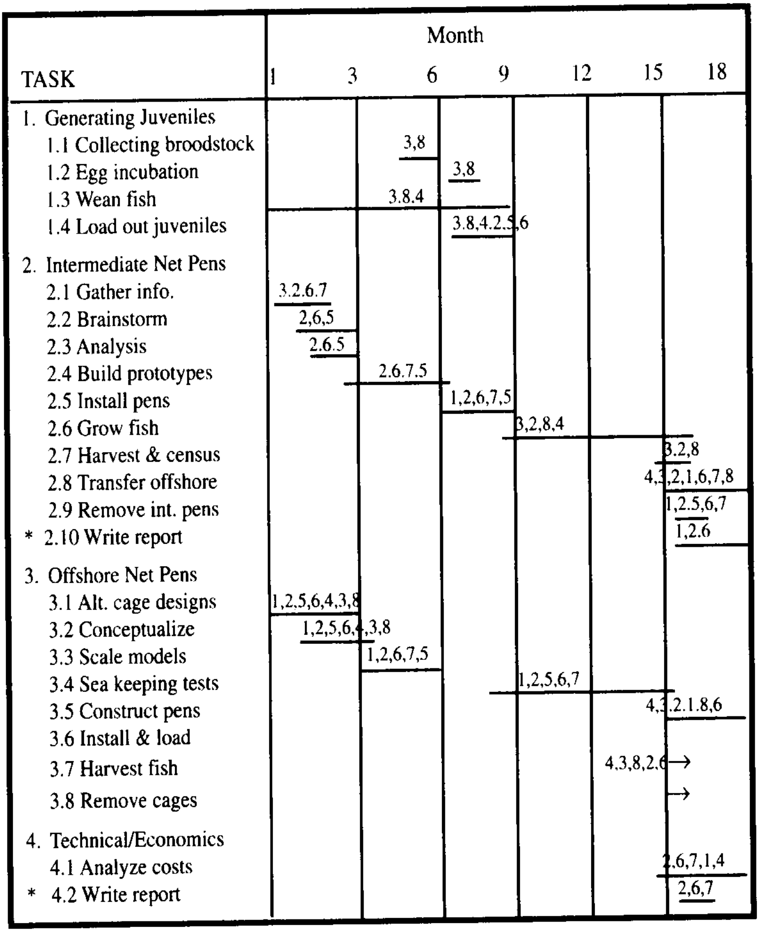
This work has been sponsored by the National Marine Fisheries of the National Oceanic and Atmospheric Administration, United States Department of Commerce; with contributions in-kind by the University of New Hampshire, the New Hampshire State Port Authority, the Portsmouth Fishermen's Cooperative, the Portsmouth Yacht Club, the Wentworth Marina, and the Cornell/UNH Shoals Marine Laboratory on Appledore Island. The work reported on herein was programmed from December 1995 through July 1, 1996 in the original proposal, but it was extended until December 1996 without additional funds to facilitate additional work during the summer and to write the final report.

The original purpose and scope of this project was much more ambitious than was ultimately possible under the conditions that existed. The goal was to demonstrate, by doing, the technical economic feasibility of open-ocean codfish aquaculture using submersible net-pens. This goal called for parallel biological and engineering efforts.

On the biology side, the objective was to hatch and grow out a large number of juvenile cod by the Fall of 1995, so that they could be placed in cages anchored in vacated marina areas along the coast. They were to be grown during the winter with regular feeding to achieve 3/4 lb-1 lb size by April, 1996.

While the cod were being grown, the engineering aspects of the project called for designing and constructing two different submersible, open-ocean prototype cage systems by April 1996. At this time, the biological and engineering aspects of the project were to join together with the engineers installing the two different prototype systems in the open-ocean and the cages loaded with juvenile cod for grow out during the period April 1996 through August 1996. Because of the nature of the one time funding program which supported this project, New Hampshire commercial fishermen were to be employed along with their vessels for feeding the fish and servicing these pens. When the fish were harvested, they were to be measured and the results recorded so that a theoretical market price could be established for the technical economic evaluation. These proposed efforts and the timing of them are recorded in a bar chart shown as Figure 1.

Unfortunately, all of the American hatchery operations for growing juvenile cod were unsuccessful during the spring and summer of 1995; so no codfish were available for carrying out this demonstration project. In an effort to salvage at least part of the project and demonstrate the technical feasibility of the submersible open-ocean cages which were being developed by the summer of 1995, several hundred wild cod were captured in February, 1996, and held for use in the following spring. However, the purpose and scope of the project had been considerably reduced, and became focused on the technical aspects with no hope of achieving an economic measurement of the feasibility of cod farming in the open-ocean.



* Indicates deliverables

Figure 1. Work Plan-tasks and Schedules.

Figure 2. Buoyant Cage (12' D x 10' H) used in both the Yankee and PUP Submersible Cage Systems. Note the 400 # weight ring at bottom which helps tension the net against penetration by preditors when it is on the surface and in its submerged mode of operation near the bottom.

Modified Purpose and Scope

The new purpose and scope which arose out of the roadblocks which were encountered with raising codfish, was reduced to demonstrating only the technical feasibility of open-ocean aquaculture of codfish using submersible net-pens; i.e.:

Start open-ocean systems design process - Spring 1995.
Run decompression tests on codfish - Summer 1995.
Catch codfish and fingerling/juveniles - Fall 1996.

Grow fingerlings in coastal cages in marinas - Winter 1995-96.
Tank test models of prototype cage designs - Summer and Fall 1995.
Review open-ocean pen designs with local fishermen - Fall 1996.
Select best two designs and build large prototype systems - Winter 1995-96.
Install two different prototype systems in the open-ocean - April 1996.
Load and grow out cod juveniles in these ocean systems - April-September 1996.
Use N.H. commercial fishing vessels to feed and service the fish during this period.
Harvest fish from both ocean pen systems by Fall 1996.
Record results and do technical evaluation of this project.
Recover and store cages and write up the final report - by December 1996.

By the Summer of 1995, we had not only been unable to obtain a large number of cod fingerlings with which to demonstrate grow out feasibility, we had also encountered large questions concerning the ability of cod to be raised and lowered from the depths we were considering for the submersible cages without decompression damage. Therefore, we conducted a field test using a small special submersible cage to determine the tolerance of fingerling cod to decompression from a depth of 90 ft. The results of those tests were reported upon in the Proceedings of the First Open-Ocean Aquaculture Conference in Portland, Maine. While the cod demonstrated a certain amount of shock from the decompression, it was determined that it was possible to raise and lower them from the bottom without causing permanent damage. This was a very important finding which had not been sufficiently examined and accounted for prior to the start of this project. With this important finding, the final design criteria for the open-ocean cage systems were established as follows:

1. System can be serviced by commercial fishing vessels less than 60 ft. long.
2. System must be safe and simple to submerge the net-pens below the wave action.
3. System must be predator safe (seals) at all depths.
4. System must be capable of being submerged and raised again to feed the fish using commercial fishing vessels with only a two man crew.
5. The lifting capacity of the servicing fishing vessels will be less than 1,000 lbs.
6. The prototype net-pen sizes must be representative of a full-scale commercial system.
7. System must be capable of being operated and serviced in sea states less than state 4.
8. The net-pen system can be used on the surface during calm seas.
9. Ocean installation of these systems may require special large-scale equipment and special vessels which are not those of the commercial fishermen.
10. The prototype systems must be capable of surviving 3-5 years of hard use.

During the late Spring, Summer and Fall of 1995, these criteria were used to develop a number of options, most of which were rejected. However, scale models were built of two of the gravity systems which were developed and these were transported to the Heriott-Watt University facility in Edinburgh, Scotland where tank tests under different wave conditions were conducted during August 1995. These tests were reported at the

First International Open-Ocean Aquaculture Conference held in Portland, Maine, in the Spring of 1996 (2).

Following these tank tests, the various candidate systems were reviewed in a formal evening session with 19 different commercial fishermen. This review was arranged by Roland Barnaby of the University of New Hampshire and was carried out to inform the commercial fishing industry in the area of our progress and also to gain their inputs into the operating limitations that we would face working with them.

An important outgrowth of this review was the idea of a pull-up pen system built around a spar buoy which would fix the location rather than having the cage be able to float around on the surface independent of any mooring. This idea evolved into the second final cage system design; so we ended up with the Yankee and PUP (pull-up pen) systems as those selected to be built and used in this demonstration project.

The Yankee System

This is a gravity system which relies on dead weight to hold down a buoyant cage near the bottom. This simple Yankee system was designed so that the cage would have permanent floatation on the top and weight at the bottom. This approach creates a tension in the net providing an effective barrier against the intrusion of predators trying to get at the fish inside. The Yankee Cage was designed such that it would float to the surface on its own when the anchor was lifted by the fishing boat pulling on the anchor tether line. The cage is a 12 ft. diameter, 10 ft. deep, net cylinder which has positive buoyancy of 750 lbs., which is supplied by a group of 8 in. trawler floats placed in nylon reinforced PVC plastic sleeves which run around the top of the cage as shown in Figure 2. Figure 2 is a photo of a cage suspended from the top in the assembly area of the University of New Hampshire's Ocean Engineering Building. The three plastic rings which hold the cage open are made from 3 in. diameter HDP tubing, which has been bent into

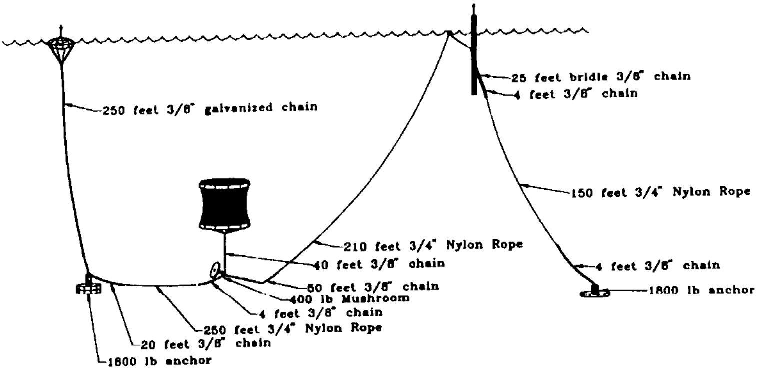


Figure 3. The open ocean Yankee single submersible cage system.

12 ft. diameter circles which are welded together at the ends. The walls of these plastic rings have been perforated to assure they fill with water when they are submerged and there is no pressure differential to crush them. The rings do not figure in the buoyancy calculations because high density polyethylene tends to be neutrally buoyant. In order to maintain tension in the size of the cylindrical pen, a 400 ft. ring, made of 3 in. steel flat stock is secured to the bottom ring of the net-pen (see Figure 3) and used as a mooring ring for holding the pen to the bottom with the chain bridled to a 400 lb. anchor. As a result of this design, each of these pens has a 350 lb. net buoyancy with 750 lbs. tension in the net side.

There are three main components to the Yankee System, as shown in Figure 3. First, there is a 6 ft. x 3 ft. oblate ellipsoid aluminum buoy on the left which serves as a marker for the entire Yankee layout. This buoy has a radar screen and strobe light mounted on top and is moored by 3/4" nylon line with a 3/8" chain leader ends to guard against chaffing. The anchor at the bottom of this marker buoy weighs 1,400 lbs. (2 railroad wheels) to insure that this highly buoyant marker did not shift its anchor during severe wave action. This oblate ellipsoid buoy and its anchor also serve as a safety anchor for the Yankee System. A tagline runs from its anchor to the anchor on the submerged Yankee Cage. This line can be an emergency pick-up line in case the regular pick-up line is lost. The liftable mushroom anchor on the Yankee Cage weighs 400 lbs. and is secured to the cage with 40 ft. of 3/4" chain. This makes the total system approximately 300 lbs. negative when it is submerged. A second line runs from the Yankee Cage anchor to a 20 ft. spar buoy, which is secured as a spatial locator of the cage. This spar buoy was also constructed of high density polyethylene.

It is 8 in. in diameter and 20 ft. long. It is weighted at one end by inserting a 4 in. steel I-beam, 5 ft. long into the hollow of the spar buoy and holding it with a pin. Above this I-beam, the buoy is sealed so the remaining 6 ft. of the buoy is complete buoyancy. This spar buoy served as a locator for the cage, and it assured that the Yankee pickup line stayed sufficiently away from the cage on the bottom to allow for lifting that did not permit the cage to run into the pick-up vessel.

The scheme was for the surface vessel to come to the spar buoy, take off the pick-up line, place in on a winch reel lift the anchor and bring the submerged cage to the surface where its anchor could be buoyed off. The surface vessel was then free to service the cage and feed the fish. When this job was completed, the cage was put back on-line between the oblate ellipsoid aluminum buoy and the spar buoy, and then lowered to the bottom.

The cage dimensions are such that it has approximately 1,000 cu. ft. of capacity and can therefore hold approximately 1,000 lbs. of codfish at harvest time (1 cu. ft./1 lb. of fish). Zippers, approximately 3 ft. long, were installed in the top of the cage where they could be pulled open for food to be thrown in to the cage from the top. As the project progressed, however, it became apparent that a long net sleeve was needed that could be brought to the side of the boat so that food could be put down the sleeve and into the cage. It proved very awkward to operate at the surface level of the cage from the side of a 50 ft. fishing boat. However, the fishermen were unwilling to get on the cage and it had not been designed to accept their weight. This is something that should be guarded against in the future because it is necessary to be able to get on cages to do this work.

All lifting lines on the Yankee System are 3/4 in. nylon with chain leaders to allow for chaffing at the end connections. The mesh of the cage is 2 in. nylon netting and it was cut and secured by a professional netmaker, so that all net surfaces were straight and fared and there were no wrinkles for a predator to grab hold through the sides or the top of the cage.

The Pull-Up Pen System

The PUP or pull-up pen system shown in Figure 4 in skeletal form is the second of the two prototype systems which were designed, built and tested in this project. The PUP system

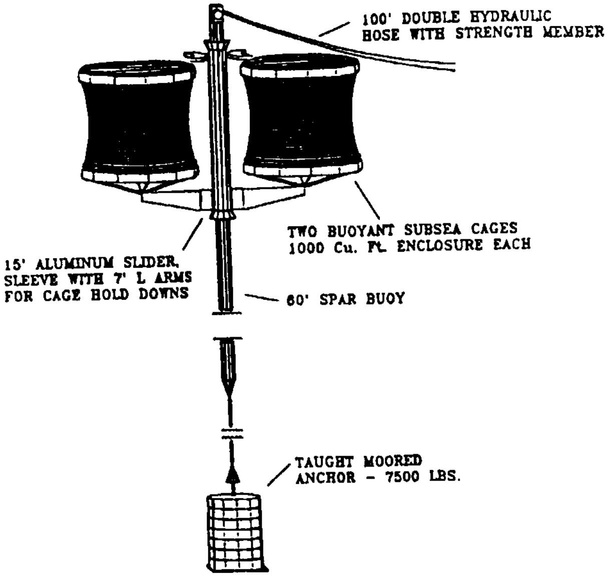


Figure 4. "PUP"-a submersible pull-up-pen system centered on a taught spar-type buoy with either hydraulic or air lift.

is made up of four major structural components: the spar buoy, the sliding aluminum sleeve with its arms which hold the cages, the buoyant cages, which are identical to those used on the Yankee system, and the anchor and chain which hold the buoyant spar buoy to the ocean floor. These four structural components are pointed out in Figure 4. The PUP spar buoy is 60 ft. long and has an 18 in. outside diameter (OD). It is constructed from two 40 ft. lengths of 18 in. OD x 15 in. ID high density polyethylene (HDP) cylinders which are welded together. The bottom 20 ft. is then sawed off the bottom cylinder. The upper 53 ft. of the of the remaining 60 ft. of cylinder is hollow and filled with air with both ends sealed by polyethylene welding. The bottom 7 ft. of this long tube is filled with high density concrete (190 lbs/cu ft.), which is a mixture of metal plugs together with concrete mix and a small amount of sand aggregate. A rod and ring system is used together with a bottom metal cone which has been embedded in the concrete and cemented in place with crossrods to hold it.

This metal cone and rod shown at the bottom of the spar buoy shown in Figure 5, is the mooring point for the anchor chain. The ends of the 53 ft. air cylinder are both welded shut prior to the attachment of the weighted end. This welding was done by a subcontracting company with special machinery for that particular purpose.

The second component, the aluminum sleeve, is shown in Figure 6 and has an overall 15 ft. length and is 2 ft. in outside diameter. The two arms attached to this sleeve are 7 ft. long and are removable so the system can be transported easily without this added dimension. The two arms are to hold the two pens when the system is installed and they assume the configuration shown in Figure 4.

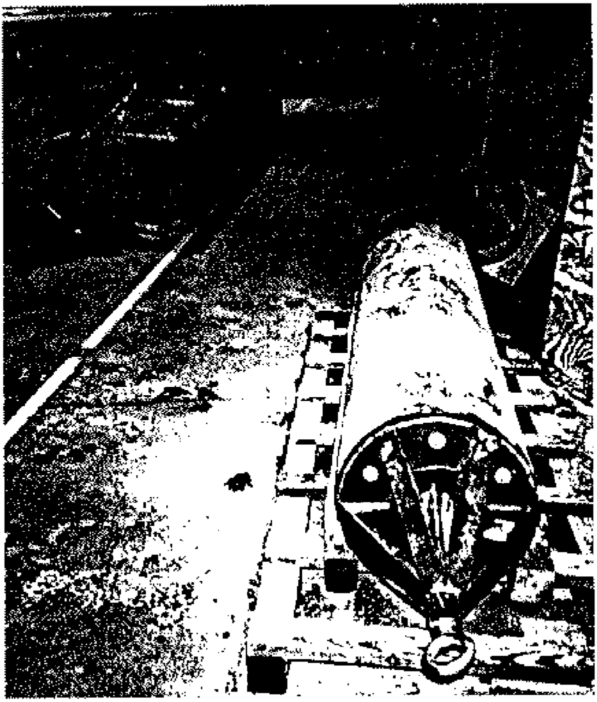


Figure 5. PUP spar, 18" x 60' L, showing the mooring end with cone to assure smooth sliding from the mooring chain up the spar. Note weld seam 7' from end marking end of concrete ballast chamber in air filled spar.

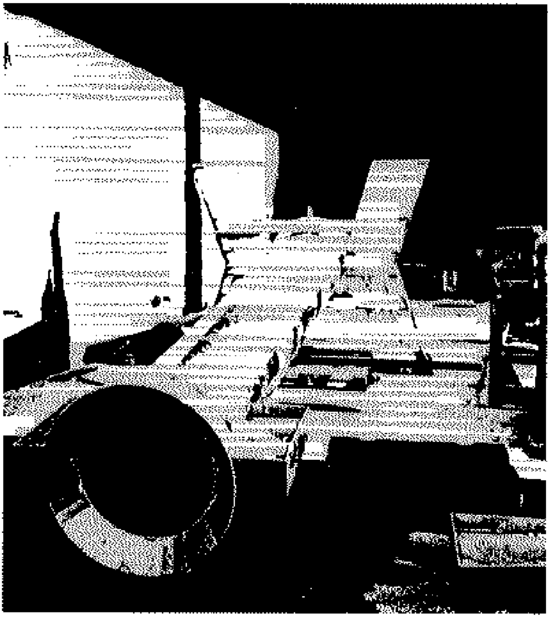


Figure 6. PUP slider, bottom end closest to camera. The 20" ID x 15' sleeve has two Al arms attached to the stubs at the bottom which hold the two floating net pens from below. Platforms at top end allow service people to stand on the PUP for net or winch repair.

In addition to the spar buoy and the aluminum slider, there are the two net cages of exactly the same dimension and construction as the cage used for the Yankee system which was described earlier in this section. The photo in Figure 3 shows that cage. Four of these cages were constructed, but only three of them were used; the fourth was held for standby. These cages are constructed exactly as was the one used for the Yankee system and they end up having the same net buoyancy so that when they are held down near the bottom and under the water, the cage netting is in approximately 700 lbs. tension which gives it the sufficient resistence for withstanding predator attacks.

We had originally expected to construct 5,000 cu ft. cages for this demonstration project, but even 2,500 cu. ft. cages proved to be too large for the type of logistical support that we could muster for this project.

However, because we were expecting to work on these systems with 40-50 ft. fishing boats, it was decided that these smaller, 1,000 cu ft. cages, were more appropriate because small fishing boats would be unable to handle larger ones, if they were to try to deal with them with such things as trying to tow them in the water.

Subsequently, it has become apparent that vessels installing cage systems will have to be much larger than those that service them if open-ocean aquaculture is to be successful. The installation process is too difficult and demanding for any cage system which one would expect to be able to hold up in open-ocean conditions.

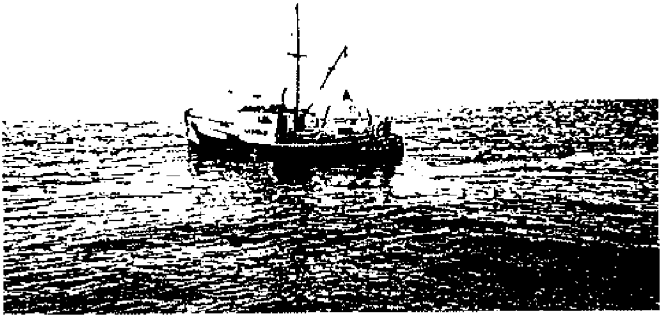


Figure 7. Yankee cage floats on surface behind service vessel which has lifted its anchor to surface and buoyed it off; so that vessel can tend the cage and feed the fish through zippered top.

Figure 8. Completed PUP with hydraulic winch in place, and the two cages winched to the surface ready for the service vessel to move in and feed the fish.

Systems' Installation

Both the Yankee and PUP systems were eventually installed at a location one mile south and east of the Isles of Shoals, which are located approximately seven miles off the mouth of the Piscataqua River from the New Hampshire and Maine coastlines. The high tide depth was 170 ft.

After several false starts, the Yankee system was installed in mid-April 1996, as per design as shown in the previous skeletal sketch of this system. Although this system was installed in mid-April, we were unable to put fish in it for nearly a month because it turned out that the cage had been improperly assembled. The floatation had not been secured to the bottom of the cage so that it permitted the top of the cage to float a few inches under the surface of the water. This might have allowed the fish to escape when they were being fed through the zipper openings in the top of the cage. In addition, very inclimate weather interfered extensively with trying to fix this cage. Each time we had the installation vessel reserved for this project, the seas were so rough we were unable to use it. On the other hand, when the weather was attractive, we did not have the UNH Gulf Challenger reserved and other people were using it. No other available vessel was suitable for lifting and handling the cages at the time, so we simply had to wait.

This operational delay resulted in our having to remove our fish holding cage from the Wentworth Marina and put the small cod in tubs in the UNH Coastal Lab because of our being unable to take the fish out to the open-ocean cages. The Marina had been promised that we would vacate the slips we were using by April 15 and we honored that commitment. With all of the delays and problems, the Yankee system was not installed and operational until May 5, 1996, just a few days before the First International Open-Ocean Aquaculture Conference, which was held in Portland, Maine. We had hoped to demonstrate this Yankee cage system to the visitors at that conference on Saturday, May 11, when 45 of them came to New Hampshire for this demonstration. Unfortunately, bad weather again prevented us from showing the cage operations at sea; however, our visitors were able to come to the UNH Ocean Engineering Center where they were given a presentation and were able to see one of the cages up close, as well as pieces and parts of the PUP system which had not yet been installed.

Fish were installed in the Yankee system on Friday, May 24, after we had run a series of demonstrations of raising and lowering the cage with both service provider fishing vessels which were participating in this experiment. Figure 7 shows the Yankee cage on the surface behind one of the service fishing vessels which had lifted its anchor.

Just before terminating the Yankee sea trials in early August, 1996, an airlift was installed with buoyancy of less than 400 lbs. just below the cage and above the 400 lb. anchor. When the airlift was filled with air from a scuba bottle, transmitted through a hose to the bottom, the cage floated to the surface. This air assisted system was much easier to handle with the airlift since it relieved the fisherman from having to deal directly with the mushroom anchor. However, questions remain about the ascent speed, because too rapid rise may adversely affect the swim bladders of the fish. This problem is being investigated by researchers at the University of New Hampshire using a hyperbaric research chamber.

The PUP system was successfully installed on Friday, June 14, 1997. Its installation went according to plan and the buoy ended up only a few feet from the predicted location with 8 ft. of freeboard, exactly as predicted for the tide conditions which existed at the time of installation. The spar buoy rose straight up except for a slight tilt due to the running current at the time. Figure 8 shows a picture of the completed PUP system with its hydraulic winch in place and the two cages winched to the surface ready for the service vessel to move in and feed the fish.

Operations and Servicing of the Cages

The Capture, Pen Holding and Feeding of Small Wild Cod in an Effort to Provide the Necessary Candidate Fish for Open-Ocean Operations

As already noted, too few cod juveniles were produced in 1995 to supply the net-pen experiment scheduled for 1996. For this reason, a local commercial fisherman was contracted in February 1996 to catch a number of juvenile cod which would be used in the tests of our prototype pen systems. Fishing began in the first week of April. All fish were kept alive onboard the vessel, and the daily catch of small cod were delivered to a temporary holding pen located at the Wentworth Marina located in New Castle, NH. Over the course of seven days of fishing, approximately 800 juvenile cod were caught and returned to the temporary holding pen. Mean size of these fish was 19.2 cm total length and 64.8 g wet weight. Fish were fed daily on a diet of minced herring.

As the experimental pens were not ready to receive the fish, the fish were moved in late April to tanks at the UNH Coastal Marine Laboratory. Feeding at the laboratory was identical to that in the temporary holding pen.

The first experimental pen (Yankee System) was ready to receive fish in late May, and a total of 146 of the largest fish were moved from tanks in the laboratory to the net pen at this time. Mean size at stocking was 24.0 cm total length and 135 g wet weight (Figure 9). The remainder of the fish continued to be held in the laboratory.

Two local commercial fishermen were contracted to feed the fish in the experimental net pen. Feeding (diced frozen herring) occurred twice per week. On one occasion, a zipper in the top of the submersible pen was inadvertently damaged, and the pen was submerged with the zipper open. Observations the following week indicated that most of the fish had escaped through the opening, and that only about a dozen fish remained.

The second experimental pen (PUP System) was ready to receive fish in late June. Approximately 250 fish were moved

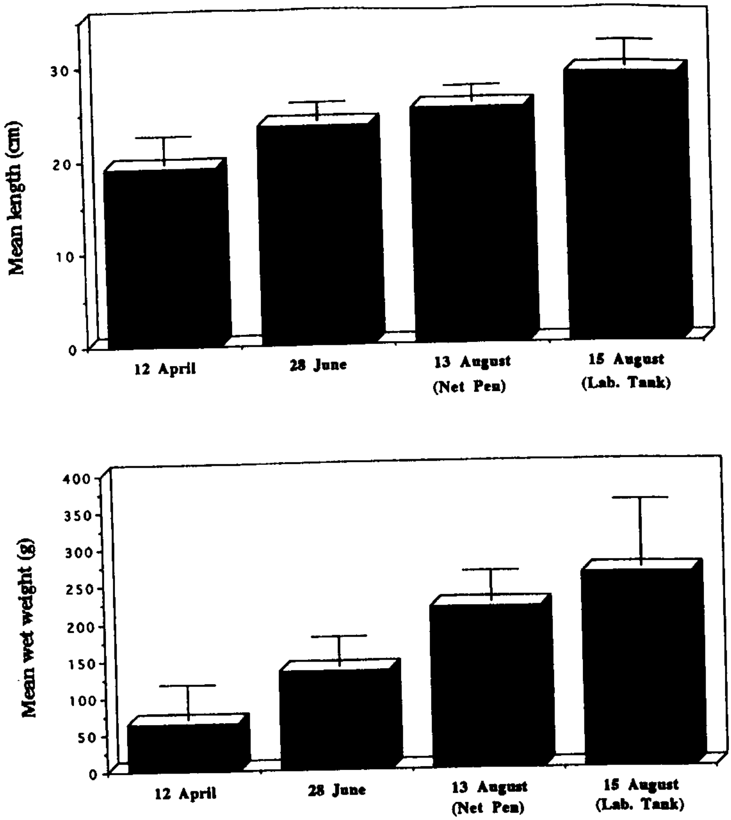


Figure 9. Mean length and weights of cod upon capture (April), stocking into pens (June), and at termination of the experiment (August).

from the laboratory to the net pens on June 29, 1996. These were divided about equally between the PUP System and the Yankee System, which was restocked at this time. Mean size of these fish at stocking was 23.5 cm total length and 133 g wet weight. Fifty fish were retained in the laboratory to serve as pseudo-controls for growth comparisons. Fish in the Yankee System were fed twice per week (minced frozen herring) throughout the experiment. Fish in the PUP System were fed only once before the hydraulic system failed and needed repair. This was accomplished in about a week, and the fish were fed twice per week throughout the remainder of the experiment.

Fish in the PUP system were released in the first week of August. As the fish were only in this system a short time, and as their feeding was interrupted for a brief period, no data were collected from these fish at the termination of the study. Fish from the Yankee System were removed on August 13, 1996. Of the approximately 75 fish that were stocked into this system, 52 (about 69%) were recovered. There was no evidence that the missing fish had died in the net pen, and it is probable that some individuals had escaped by swimming through the meshes. Mean size at termination of the experiment, which lasted for 46 days, was 25.2 cm total length and 217.5 g wet weight (Figure 9). Thus, on average, fish in the net pen grew 1.7 cm in length and added 74.5 g in weight. While the increase in length was small (7.2%), the dramatic increase in weight (56.0%) is an indication that the fish adapted well to the cage. The degree to which these final results may have been biased by the escapement of small, thin fish is unknown however. When the net pen was raised to the surface for the last time, the ascent was rapid (2 minutes) because the pen had been modified with an air-lift system. After several minutes at the surface, most of the fish were observed to be floating ventral side upward, and it was clear that the fish had swimbladder problems that resulted from their being decompressed too rapidly. An attempt was made to return these fish to the laboratory for further study, but all died within 24 hours. This observation indicates that the fish were capable of surviving during the experiment because their rapid decompression, as they were brought to the surface for feeding, was quickly (within 10-15 minutes) followed by recompression as the pen was once again lowered to depth. When this recompression did not occur at the termination of the experiment, the fish died.

Two days after the fish were removed from the Yankee System, a random sample of 43 fish that had been held in laboratory tanks were weighed and measured. Sizes of these pseudo-control fish were compared to those held in the experimental net pen. Mean size of fish held in the laboratory was 29.0 cm total length and 261.4 g wet weight. These sizes represent a growth in length of 5.5 cm (23% increase), and a growth in weight of 128.4 g (96% increase). Thus fish held in the laboratory grew more rapidly than those held in the experimental pens, and were significantly longer and heavier (Mann-Whitney Test, $P<0.002$) than fish that had been held in the experimental pen.

Results from the 1995 and 1996 net-pen experiments differed. In 1995, there was no difference in size between fish held in the small, decompression test, submersible pen and those held in the laboratory (1).

There was no obvious mortality. In 1996, however, fish held in the pen were significantly smaller than those held in the laboratory, and there was high mortality of the fish when they were removed from the pen. There are several possible reasons for these observed differences. First, experimental fish used in the two years were different sizes, and this may have had some effect on the outcome. Second, the experiments done in the two years were done during different months. Third, the net-pens used in the two years were quite different in design. Fourth, different individuals cared for the net-pen fish in the two experiments, and this may have had some effect. Last, there were more fish used in 1996 than in 1995, and this increased sample size almost certainly increased statistical power. These differences make comparisons of the data from the two years difficult to impossible. Clearly more research will be needed before the efficacy of using submersible net-pens to raise cod can be determined.

A report on the early portion of this cod performance research was presented at the Open-Ocean Aquaculture Conference held in Portland, Maine, in May 1996 (2).

Interaction With the Commercial Fishermen and Other Members of the Fishing Community

The commercial fishing industry in New Hampshire played an integral part in this project from the very beginning. Before the proposal was even submitted, the principal investigators met with several industry leaders, including the President of the New Hampshire Commercial Fishermen's Association, the Director of the Portsmouth Fishermen's Cooperative and the Director of the New Hampshire State Port Authority. In the Fall of 1995, a meeting was held with commercial fishermen to outline the goals of the project and to get their input. Both lobster and groundfish fishermen from Hampton Harbor, Rye Harbor and Portsmouth were present. The purpose of this meeting was to get support from the industry, educate them on the design and operational aspects of the project and its prototype net-pens, identify individuals from the industry who want to play an active role in the project and get their input on the best locations to put the pens. The meeting was a great success. Two of the participants turned out to be active participants in the project.

During the duration of the project, many meetings were held with fishermen, fishing cooperatives, marine operators, decision makers, the New Hampshire State Port Authority, the New Hampshire State Fish and Game Department and members of the news media. There was a conscious effort by all involved to make this project as open and visible as possible.

Of special mention should be the good working relationship which developed with the yacht clubs, the marinas and the New Hampshire State Port Authority. The fishpens were placed in a marina during the off season and the Yacht Club offered its winter mooring space. The Port Authority used their cranes to load and unload the pens, mooring equipment and the buoys and anchors at their facilities. This collaboration proved to be invaluable to the project.

Conclusions and Recommendations

The project team successfully designed, constructed, installed and ocean tested two different prototype submersible systems holding small live codfish. The cages were successfully raised to the surface, the fish were fed and the cages returned to the bottom at least twice weekly for several weeks. The project was terminated in August 1996 when the funding level called for it to be terminated, but not before it had made significant strides towards proving the technical feasibility of operating submersible cages in the open-ocean.

There are modifications necessary for both systems to assure their successful operation during heavier sea conditions than were experienced during the few summer months that this project operated. Both systems were successfully tended by New Hampshire commercial fishermen using their own small boats which was one of the key objectives of this project.

As noted earlier, the title of this project might better have been "The Exploration of Open-Ocean Finfish Aquaculture Using Submersible Cages — A Technical Feasibility Study." The reasons for saying this are because of the state-of-the-art of cod hatchery production, the intermediate holding and grow out of hatchery production and the knowledge of cage economics and fish physiology as affected by submerging cages, are all not sufficiently advanced to permit such an economic feasibility demonstration yet. We conclude this because during the course of this project we experienced many missing steps in trying to demonstrate the feasibility of growing codfish in open-ocean cages:

1. The cod hatchery operators in North America were unable to produce even 100 fingerlings for this project in time for the planned 1995 grow out from small fingerlings to possibly 3/4 lb. underlings by April, 1996. The hatcheries are still not ready to supply more than 10,000 or 20,000 small cod for such a demonstration project. This limitation applies to most ocean finfish excluding salmon and possibly fluke or flounder.

2. Even if the fingerlings were available, there are as yet few assured places to hold them after they reach 20-30 gm weights. Unless there is an ability to grow them out to a larger size in mass numbers, this would mean that they would have to be put offshore at this weight with all of the attendant problems of net size and fouling of nets, etc. Also, they would have to be

kept on station and fed all winter in order to grow out to marketable weight, and that is a major challenge for open-ocean work in New England.

3. Submersible pens which can be dropped below the higher significant wave forces when they occur, require fish decompression when raised to the surface or near the surface for either feeding or net cleaning. We found no reliable data in the literature concerning finfish decompression tolerance; this seems to be the case for both groundfish and flatfish. Our experience from this project indicates that most fish should not be subjected to any sort of regular decompression/compression cycling, even though our wild cod seemed to have a high survival rate for the period that we operated our cages.

4. It is desirable to have pelletized feed which will lend itself to mechanized feeding at depths in most cases. We could not attempt such mechanized feeding because we had to use wild fish, which do not adapt to pellets, and required natural food such as herring chunks.

Therefore, the major contributions of this project have been in the area of open-ocean cage design, construction, installation and operation. Both of the cage systems which were designed for this project were successfully operated while holding fish which survived the operations. Neither of the two cage systems which were demonstrated by this project, has sufficient volume to offer even the remotest possibility of economic, as well as technical, feasibility. On the other hand, the size cages and systems used was sufficient to demonstrate strong technical feasibility; this allowing for the fact that several modifications are recommended before advancing with either one of these systems to a larger size.

5. The Yankee cage system proved to be simple in concept, but not so simple to operate. Once on the surface, the cage was free to move about and offered the potential of entangling any adjacent cage moorings or marker buoys as it moved off station with the wind, tide and sea directions. Having the cage so free to move on the surface made it difficult

to return it to its original bottom location in other than flat calm waters.

6. We recommend the following modifications to the Yankee System:

a. The anchor lifting line be run through a pulley on the spar buoy marker so that the lifting vessel can pull from the spar buoy, and therefore assure that it is not over the cage when it rises to the surface. This arrangement will also keep the cage secured by two fixed lines, one to the anchor of the oblate ellipsoid marker buoy and the other to the spar marker buoy. This arrangement will make it possible to lower the cage back to approximately it's same location even when the winds and tides are running strong.

b. Increase the cage size to at least 6,000 cu ft (30' D x 20' H), and set up the layout so that there are at least two cages, one on either side of the oblate ellipsoid or similar large marker buoy. This much system capacity, duplicated several times, will probably be necessary to have an economic, as well as technically feasible system using the Yankee approach.

c. Increasing the size of the cages will require increasing the size of the anchor holding the cage to the bottom. This will require adding an air ballast system that displaces much of the anchor weight prior to its being lifted by the attending vessel. How to install this airlift system with a hose to the surface which will not entangle when you are lifting the cage with a winch after the air ballast is inserted, has not been completely worked out at this point.

However, the system worked in a test with the airhose being run up to the 20' spar buoy. In this arrangement, the heavy airhose did not entangle the lifting line when the lightened system was pulled up to the surface.

A sketch showing these recommended modifications is shown in Figure 10.

7. With modification, the PUP System offers excellent potential for either a fixed moored submersible cage system or

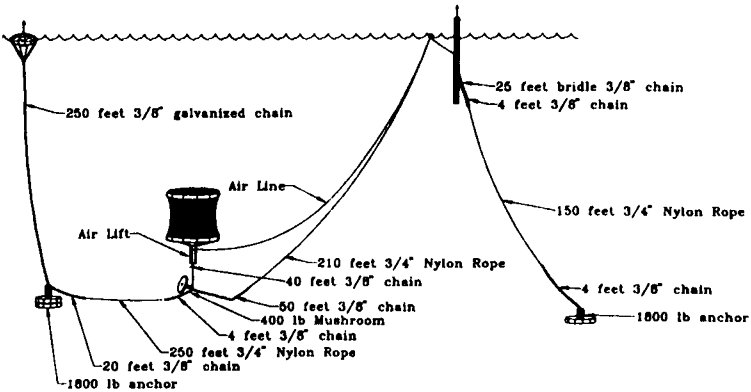


Figure 10. Enlarged Yankee Cage System with air ballast tank above the anchor and compressed air line to surface where it is attached to spar buoy. Service vessel with scuba air tank can ballast tank, thereby reducing anchoring weight; so lightened anchor can be lifted slowly.

a free floating submersible cage system for very deep water, where cage moorings would be expensive, even if feasible. The modifications that we recommend be made are:

a. Replace the hydraulic sleeve lifting system with an airlift, using a concentric air chamber around the lifting sleeve (see Figure 11).

b. Increase the individual cage size on the PUP to at least 6,000 cu ft (30 D x 20 H), and use four cages with four arms on the elevator sleeve instead of the two as in Figure 11.

c. At the same time that you increase the cage size, you would need to increase the sleeve length and the spar buoy length to accommodate these larger cages. Possibly a 100' spar and 30' sleeve?

d. Place walkways in between the four cages that run from the center spar to the exterior of the cage. Supply these walkways with inflatable ballast tanks under the ends of each walkway which would only be blown on the surface and flooded before the cages were submerged by blowing the main lifting chamber on the sleeve.

e. Plan to hold the four nets at 30 ft. below the surface almost all the time by suspending them from lines from the top

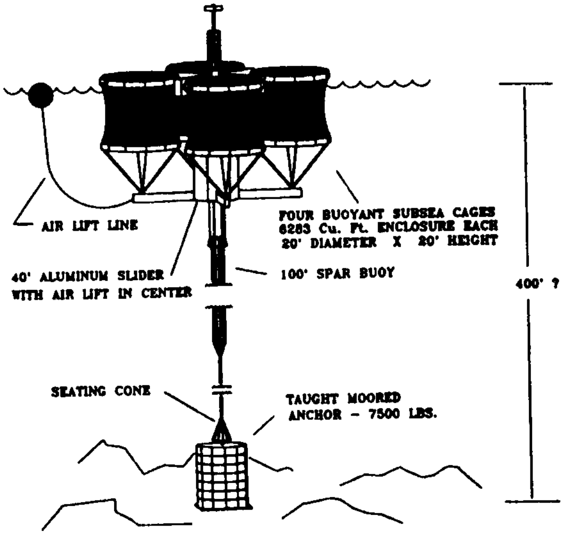


Figure 11. Modified PUP Net Pen System with centralized air lift replacing hydraulic winch, and four vs. two net pens which are enlarged. System would have to be anchored in deeper water than original, and air chamber volume tuned for proper pen ascent speed.

of the buoy, and feed the fish through net tubes from the surface to the top of each of the net-pens. This will not expose the net-pens to being runover by incidental vessels looking at the spar buoy and would also make them less vulnerable to theft and vandalism. Only when heavy seas were predicted would the cages be lowered to the bottom of the mooring system via a dropline from the bottom of the spar to a sufficient depth where there would be a stop for the cage sleeve. This would be similar to the cone arrangement that we had at the top of the anchor on the PUP system we operated last summer.

Any further development of open-ocean submersible cage systems for aquaculture should be done with the expectation that it will be another two years or more before the biological aspects of developing candidate ground fish for a valid technical/economic demonstration of the feasibility of open-ocean aquaculture will be possible. One could mistakenly conclude that the project we have just completed was premature in light of the many problems which developed which demonstrated a lack of necessary biological knowledge to carry through to the goal. However, that kind of conclusion would be a major mistake.

This exploratory project has served to focus future effort on problems which must be solved before a true technical and economic demonstration can be attempted. In the meantime, there is a great deal to be done in each of the three critical areas: hatchery operations, intermediate grow out and finally, open-ocean cage design and operation. The fact that these three areas will be developing separately, and without necessarily leading to an immediate solution, should not take away from their equal importance, and the need to continue the pace of research and development in all three of these areas simultaneously.

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Biology of Candidate Species

The White Seabass (*Atractoscion nobilis*) as a Candidate Species for Open Ocean Culture: A Review Based on Four Years of Culture in Nearshore Cages

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Introduction

The feasibility of culturing and releasing juvenile marine fish, with the goal of enhancing depleted wild stocks in southern California, has been investigated since 1984. The research is directed by the California Department of Fish & Game (CDF&G) as part of the Ocean Resources Enhancement and Hatchery Program (OREHP). Revenues to support research are accrued from the sale of sport and commercial marine fishing stamps to fishermen south of Point Arguello, California.

Early OREHP research included developing the culture technology (i.e. spawning induction, larval rearing, nutrition, disease prevention) for the program's primary target species, white seabass (*Atractoscion nobilis*). Much of this work was conducted at an experimental hatchery on Mission Bay, in San Diego, California. In 1991, OREHP researchers and volunteers from the Ventura Chapter of United Anglers began a pilot program to investigate the feasibility of using cage systems to cost-effectively extend the growout phase of hatchery-reared white seabass. Based on the success of those initial efforts, the United Anglers began to recruit other individuals to develop additional growout facilities that are now being constructed in different locations in southern California.

The primary goal of the volunteer-based, growout program is to maximize the potential of the OREHP by releasing large, healthy juvenile fish in a cost-effective and environmentally protective manner. Additional goals of the growout program include increasing the geographic range of fish releases and increasing public awareness toward conservation issues.

This paper summarizes the experiences of the OREHP volunteer program in designing, siting and permitting cage systems, and the process of culturing white seabass in these cages.

Historical Perspective

Currently, volunteers from ten growout facilities are culturing white seabass for stock enhancement (Figure 1) in southern California. A total of nearly 80,000 white seabass have been successfully cultured, tagged and released from these facilities. The annual contribution of fish released from each facility is illustrated in Figure 2.

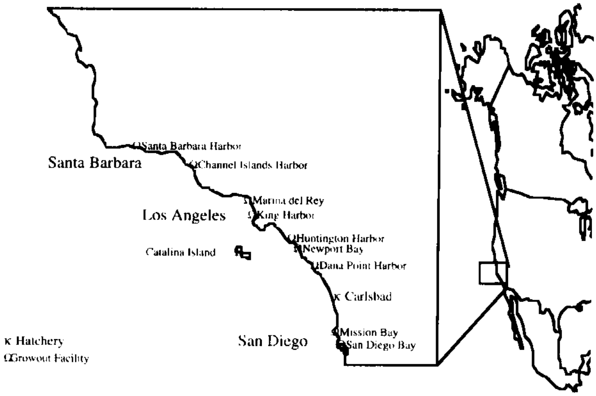

Figure 1. Site map showing locations of satellite growout facilities and the main hatchery.

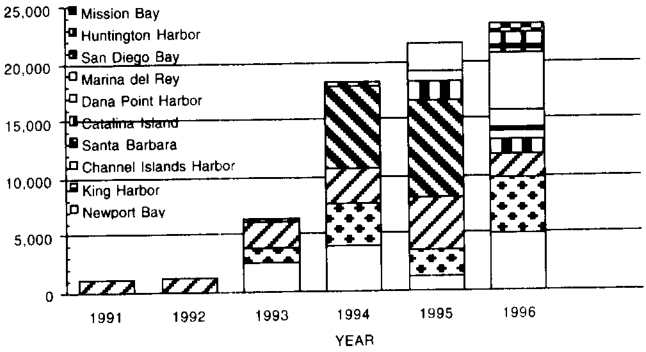

Figure 2. Summary of annual contributions of tagged fish released by each growout facility.

Siting and Permitting

Nine of the 10 growout facilities are situated along the southern California mainland and one is located on an inhabited offshore island (Figure 1). The growout program and its associated release area encompasses over 200 miles of coastline from San Diego to Santa Barbara, California. Catalina Island is approximately 22 nautical miles from the mainland at its closest point. White seabass occur naturally throughout this range.

All of the cages are located in fully protected embayments with the exception of the Santa Barbara facility. Although fully exposed, the operation of this cage is regulated by mooring restrictions for the area and must be removed from the water between October and May each year. The depth of water at each site varies (1-10 m), as do the tidal characteristics associated with each.

Site selection for volunteer-based white seabass growout facilities is based on a number of factors. On a broad level, these factors include the range of the OREHP funding base, proximity to volunteer support groups, and areas where white seabass are known to occur. On a local level, sites are targeted that are already permitted for mooring or docking of vessels. This is done to minimize time delays and costs associated with obtaining additional permits and approvals. Among these preferred areas, specific sites are selected in areas believed to have good water quality and exchange. Accessibility is also a factor in the site selection process.

The permitting requirements for development in the coastal zone of California is a very involved process. The complexity of this process can be attributed largely to the overlap of authority that exists among local, regional and federal regulatory agencies. In addition, mariculture is so new to southern California that many hours are spent educating agency officials at each level. Because of these factors, permitting requirements experienced by OREHP participants are often site and project specific. A list of permits, approvals and supporting documents that are required by growout facility operators is presented in Table 1.

Table 1. List of supporting documents, approvals and permits required by each facility prior to construction.

	Form of Approval	
AGENCY	Verbal/Letter	Permit
California Coastal Commission		**a**
California Department of Fish and Game	**a**	
Regional Water Quality Control Board		**b**
State Lands Commission	**b**	
County Parks Department	**b**	
Army Corps of Engineers		**a**
City Planning Department	**b**	**b**
Harbor Master/Water Director	**b**	
Marina Lessor	**b**	
OTHER SUPPORTING DOCUMENTS		
Building plans		
Site photographs		
Site maps		
OREHP fact sheet		
Club organization description and documents		
Proof of Insurance		

Key:		
	a	required by all sites
	b	required by some sites

Design and Construction

Currently, there are two cage designs being used to culture white seabass. The first is a traditional design where the cage is moored in open water or alongside a dock and a net bag is used to contain the fish. The bag is supported by a rigid frame, protected by thick netting or rigid mesh, and buoyed by pontoons. The second design consists of a semi-submerged, fiberglass raceway that is affixed to a pier or floating dock (Figure 3). In this design, the raceway serves not only to contain the fish, but also as a predator barrier. General design specifications for existing cage facilities are listed in Table 2.

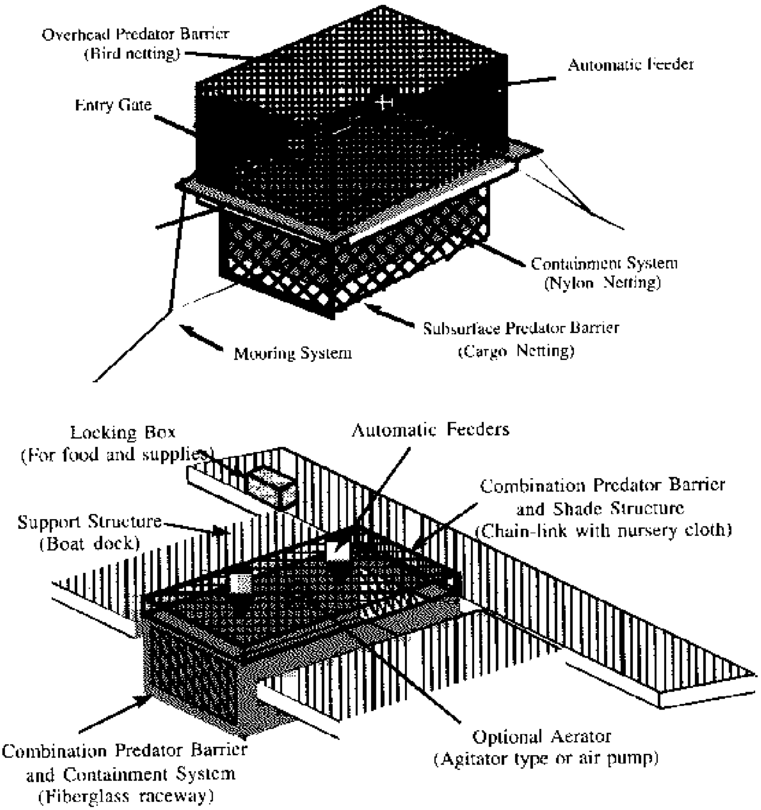

Figure 3. Two typical designs used by volunteers to culture white seabass. Net pen design (top) and floating raceway design (bottom).

Table 2. Design summary for growout facilities operated by volunteers and participating in white seabass stocking program. Active systems are those currently in use. Subunits refer to individual containment areas.

Site	System Type	Access	Active (y/n)	Subunit Numbers (#)	Subunit Volume (cubic m)	Total Culture Vol (cubic m)
Catalina Island	Raceway	Land	n	1	10	10
	Raceway	Boat	y	4	13	51
Channel Islands Harbor	Net	Dock	y	3	65	196
	Raceway	Dock	n	1	29	29
Dana Point Harbor	Net	Dock	y	3	8	24
Huntington Harbor	Raceway	Dock	y	1	14	14
King Harbor	Raceway	Dock	y	1	16	16
Marina del Rey	Raceway	Dock	y	1	14	14
Mission Bay	Net	Dock	y	2	14	29
Newport Bay	Net	Boat	n	4	51	203
	Raceway	Boat	y	4	13	51
San Diego Bay	Raceway	Dock	y	1	14	14
Santa Barbara	Net	Boat	n	3	33	98
	Net	Boat	y	1	113	113

Because neither the net cage or submerged raceway designs has been standardized and differences in water quality exist among sites, it is difficult to identify the more efficient system of the two. From a fish production standpoint, there is no evidence suggesting improved growth or survival of the white seabass in one system or the other. Net systems offer greater freedom for water exchange because water can move through the cage mesh from any direction. Because of their solid walls, submerged raceways may require mechanical devices such as pumps or aerators to exchange water. These devices require electrical power which increases operating costs. In addition to cost concerns, the operator must consider the catastrophic losses that could result from a power failure. Feeding levels are generally easier to monitor in submerged raceway systems because uneaten food remains visible on the bottom of the raceway and does not fall through to the sea floor as readily as in a net cage design. However, if raceways are not cleaned daily, excess food will have the negative impact of decreasing water quality in the system. If a vacuum system is available, excess food and detritus can readily be removed from the raceway. Different opinions currently exist on the maintenance requirements of each system with regard to the amount of cleaning required to maintain high water quality standards and sufficient water exchange. The most popular feature of raceways is the smooth texture of the fiberglass walls that can easily be scrubbed to remove algae and encrusting organisms. Because submerged raceways are so rigid, they are better suited for protected waterways, including embayments. This siting restriction may impose an additional limitation on the overall size of a given system. Similarly, since most of the raceways are currently produced from a common mold, there are a limited number of configurations and later modifications (i.e. to increase depth) are difficult. Itemized cost data are not yet available for comparisons between the two system designs.

Culture Operations

Juvenile white seabass are tagged internally in the cheek muscle with a coded wire tag[1] prior to delivery. Fish are typically stocked into growout facilities at a size of 75 mm (5.0 g). Stocking densities vary and are still being evaluated in order to maximize production levels. However, a density of 210 fish/m^3 appears to be safe for most systems regardless of the time of year they are stocked. Fish are fed a high protein (approx. 55%) diet in the form of a sinking pellet[2]. A variety of feeding techniques and schedules are employed, but generally, automatic feeders are set to feed during 2-3 periods from dawn to dusk. Maintenance schedules also vary considerably among growout facilities. Some volunteer groups schedule site visits every other day or as frequently as three times per day to clean and inspect feeders, nets, and circulators. Dive inspections are scheduled periodically to check and clean nets and mooring systems.

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[1] Manufactured and distributed by Northwest Marine Technologies, Inc. Shaw Island, Washington.

[2] Marine Grower Diet - manufactured and distributed by Moore-Clark, Vancouver, BC.

Growth rates of juvenile white seabass range from approximately 0.4 mm per day during the winter (12-15°C) to as high as 1.8 mm per day during the summer (22-26°C). Harvesting (for release) is done when the fish reach approximately 200 mm (80 g). To date, the maximum harvest density is 26 kg/m^3. Prior to release, all fish are counted and inspected by a certified Fish Pathologist from the California Department of Fish and Game. Survival rates vary among facilities and among groups cultured at the same facility during different times of year. However, survival typically exceeds 80% during the 3-6 month growout phase.

Factors that negatively impact white seabass health are often attributed to either the siting, design or operation of the growout facility. Siting problems include proximity to bait receivers, the contents of which may serve as a source for pathogens; proximity to thermal effluent from power plants, which may result in supersaturated water conditions; and siting in water that is too shallow, which may lead to high turbidity or supersaturated water. Problems attributed to system design include electrolysis of window panels, which may lead to escapement of fish or entry by predators; restricted water exchange caused by solid wall panels, which may lead to poor water quality; and depth limitations imposed by rigid systems, which may limit hydrostatic compensation by the fish. Other problems related to system design include malfunctioning feeders or water circulation systems. Operational procedures connected to health problems include stress caused by delivery, inadequate feeding ration, and extremes in water quality-especially temperature.

Discussion

The OREHP has demonstrated that white seabass, a highly prized food fish, can be cultured successfully in land-based systems. Hundreds of volunteers from the recreational fishing community, across a 200 mile range, have been involved in an effort to cost-effectively culture and release white seabass to a larger release size. These groups have successfully constructed and supported small-scale cage systems in protected coastal areas. Since 1991, nearly 80,000 juvenile white seabass have been released by these volunteers. The infrastructure established to support this program includes technical staff from private and state organizations, and a Procedures Manual written to assist volunteers in designing, permitting, constructing and operating a growout facility. This same infrastructure could readily be adapted to commercial interests, including redirecting the efforts of commercial fishermen toward mariculture, once the marketability of smaller, cultured white seabass has been determined. A commercial demonstration project is currently planned to accomplish this.

Experimental work conducted in land-based raceways, combined with data collected at volunteer-based growout facilities, suggests that biologically, white seabass is a viable species for commercial culture. Sufficient water exchange and good water quality consistently result in high survival, fast growth and healthy fish. White seabass held in land-based raceways have grown to 1.0 kg in 17 months.

In order to meet OREHP's stocking goals (>350,000 fish per year), and to support future commercial needs, larger cages are now required. Nearshore areas, especially embayments, are unsuited for this expansion due to user conflicts and view issues, space limitations and poor water quality. Unless a more pro-active, user-friendly regulatory process is established supporting open-ocean aquaculture, expansion of OREHP will be limited.

Acknowledgements

This work was conducted as part of the Ocean Resources Enhancement and Hatchery Program, under the guidance of the Advisory Panel and the California Department of Fish and Game. Much of the data reported in this paper was collected by members of the growout facilities and represents thousands of hours of volunteer work. Our sincere thanks to these dedicated individuals.

Candidate Species of the Pacific: The Hawaiian Fisheries Development Project

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One of the major constraints to mariculture in the United States is limited access to high-quality water resources. Coastal zone development is limited by competing interests, such as urban development and recreation. High land costs and regulatory constraints limit the economic feasibility of certain pond or nearshore systems, and water quality is often affected. It has been and will continue to be increasingly difficult to justify locating growout systems nearshore.

Use of offshore cage systems circumvents many of the environmental and regulatory problems associated with growout of marine finfish species. Engineering aspects have rapidly advanced to the point that demonstration trials can proceed, and several cage designs either currently exist in the marketplace or are being refined. However, bottlenecks exist in the lack of reliable hatchery techniques for mass production of fingerlings for targeted species and the absence of established marine finfish hatcheries for seedstock production. In fact, the majority of seed for marine finfish growout operations worldwide is captured from the wild. Techniques for maintaining and spawning broodstock and raising larvae are not well established for the most marketable of U.S. marine finfish species.

There has yet to be a concerted effort to develop a multi-species concept for hatchery and growout development of marine finfish in the United States. Federal support has been granted largely to pursue solutions or alternatives in response to regional problems that have affected the commercial fishing industry. For instance, recent closures or severe restrictions on traditional fishing areas have provided incentive and interest in farming such marine species as cod, halibut, and other bottom fish. Maine has established a Groundfish Hatchery Study

Commission to examine the feasibility of developing a hatchery to produce cod larvae for stock replacement (USDA, 1994). This has mostly concentrated on development of techniques to raise fingerlings from eggs stripped from wild broodstock. In July of 1995, the federal government approved funding for 13 aquaculture projects, mostly in Massachusetts, as part of a $4.5 million aid package to the ailing fishing industry in New England. At least three operations are in the permitting and construction stages for both offshore and land-based production of summer flounder (*Paralichthys dentatus*) in Massachusetts, New York, and Rhode Island (Spatz et al., 1996). In addition, haddock, halibut, cod and eel are being considered.

In 1995, a multi-year project was funded by the National Oceanic and Atmospheric Administration (NOAA) through the National Marine Fisheries Service (NMFS) to develop a multi-species, marine finfish hatchery concept for commercial-scale production of fingerlings for stock enhancement and farm production purposes. The project, titled "Hawaiian Fisheries Development (HFD)" systematically addresses development of hatchery technologies for species prioritized as having the greatest potential for aquaculture and stock enhancement in the Pacific, as well as for the ease of application of the technology to other, similar species in other regions of the country. The project targets development of standardized approaches to broodstock management, maturation and spawning, and larval and nursery rearing through comparative analysis of species. Development of the multi-species hatchery concept is based on the principle that diverse species exhibit fundamental biological commonalties that allow them to be mass cultured within the constraints of modern aquaculture techniques. The HFD project targets representative species from different ecological and environmental habitats including nearshore, offshore, and deepwater regions in Hawaii. Successive stages build upon commonalties of the previous stages, and incorporate only those aspects unique to the representative species of interest. In this respect, development through each successive stage occurs more rapidly and more efficiently. This also provides the rationale for rapid development of newly targeted species. Because targeted species represent a wide range of habitats, it is believed that the technology developed would be immediately applicable to a large number of species of economic importance not represented and in different regions of the country. Having determined the common factors to rearing different species, hatchery facilities could readily modify techniques and/or change species to target the most economically desirable product at any given time.

Does this approach work?

In 1995, the Oceanic Institute (OI) successfully completed a NMFS-funded project to develop commercial-scale hatchery and growout techniques for the dolphin fish or mahimahi (*Coryphaena hippurus*), a warm-water marine carnivore that inhabits pelagic, open-ocean regions within 20°C isotherms. This species is clearly one of the more difficult to master exhibiting very stringent environmental, physiological, and behavioral requirements.

Lessons learned during the phases of mahimahi research created a theoretical base for marine finfish culture in the western Pacific and set in motion the vision for the HFD project. It was envisioned that culture techniques for new species could be developed more rapidly if each was developed around a common technology. Confirmation was obtained when research was being conduced on the Pacific threadfin (*Polydactylus sexfilis*), a surf-zone species indigenous to Hawaiian waters. Research with mahimahi established ways to address aggressive behavior and cannibalism in the nursery (Kim et al., 1993) and the importance of fishmeal quality in diet development (Ostrowski et al., 1996a). The techniques were applied to the Pacific threadfin, rapidly advancing hatchery technology of this species (Ostrowski et al., 1996b).

The most dramatic example that the approach was viable was in transfer of nursery techniques (Figure 1). In mahimahi culture, a shallow water raceway design was used to greatly improve weaning onto pelleted feeds and overall survival

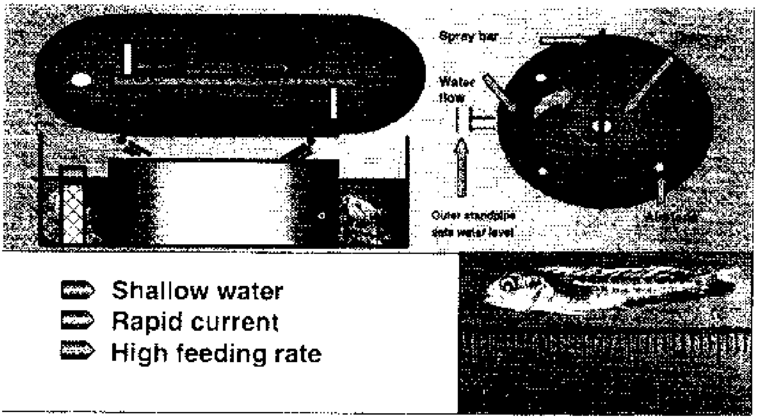

Figure 1. Shallow raceway designs for rearing and weaning mahimahi in the nursery.

during the nursery stage when juveniles (20-40 days of age) are highly aggressive. The shallow system coupled with high water current speeds and a better understanding of feeding rates provided lengthy contact time between pellets and fish to increase feeding opportunities, animation of pellets to induce strikes, and rapid swimming against the current to occupy and distract more aggressive individuals and provide a quick means of escape from attacks by change in direction. For Pacific threadfin, high cannibalism rates (yielding circa. 50% survival) in the nursery was identified as a key technological constraint to mass culture development. The shallow raceway developed for mahimahi was applied as well as satiation feeding rates and high quality diets. In just a few trials, the survival rate increased dramatically to upwards of 95% in experimental testing. It was also found that the animals were more uniform in size.

Currently, nursery survival averages 85% for large scale production of Pacific threadfin at OI. Pacific threadfin is expected to be one of the major aquacultured species in Hawaii in the near future and is one of the best candidates for offshore demonstration tests in the region. It is a popular food fish in Hawaii and has been well received in vertical fish tasting events in Philadelphia and San Fransisco (Deese, personal communication) that can be steamed whole or filleted. It is also of a family of fishes popular in Asia (Wong 1995). Farmers in Hawaii receive approximately \$6.00/lb in the round for 3/4 to 1 pound fish, which is achieved at 6-8 months of age. Techniques developed at OI have resulted in year-round egg production, survival rates of 25% from egg to larvae, 85% from larvae to stockable juvenile, and 95% in growout. Techniques have been developed for year-round spawning. Based on current seedstock production levels, commercial sales of this species in Hawaii will be 50% of the total finfish aquaculture production in the state by 1999.

Another nearshore species being investigated by the HFD project, and an excellent offshore candidate, is the bluefin trevally, *Caranx melampygus*, a reef-inhabiting representative of the large jack family (Figure 2). OI has cultured an F1 generation of this species and successfully grown them out. Using NMFS data for growth rates of the animals in the wild, it was determined that the cultured growth rate is approximately two times that in the wild. Market size is 500 grams and that can be reached at age 10-12 months. Sexual maturity is achieved earlier, but at a larger size than in the wild. It is a hardy species, adaptable to life in captivity, and amenable to

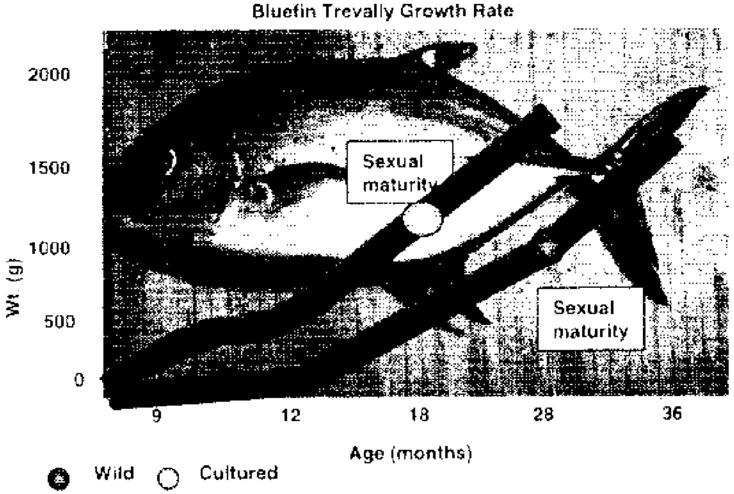

Figure 2. Bluefin trevally growth rates.

varied culture conditions. Flesh quality is high, particularly for raw (sashimi) product because of high levels of inter muscular fat.

Year-round spawning has also been achieved with this species (Figure 3). Egg production is high therefore fewer broodstock are needed for commercial production. Current research shows that they are multiple spawners and release multiple clutches of eggs during a spawning period.

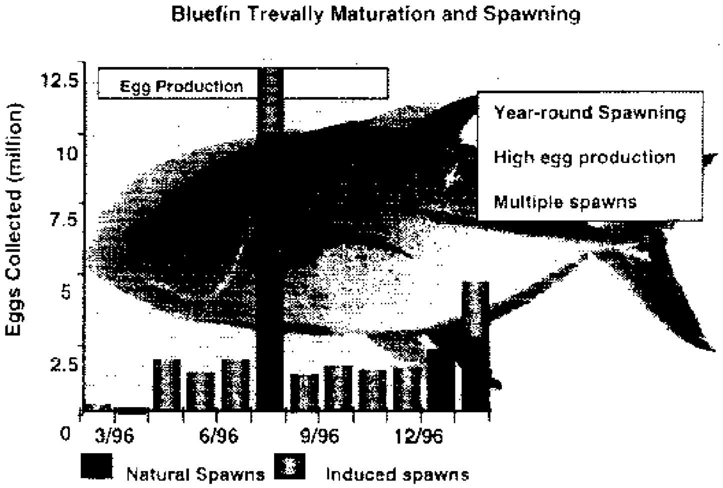

Figure 3. Bluefin trevally year-round spawning.

The next species identified for development is the greater amberjack, *Seriola dumerili*, another member of the large jack family, but a more transitional zone species that also inhabits deeper waters (Figure 4). The same species exists in the Gulf of Mexico. *Seriola dumerili* is considered a good candidate for intensive aquaculture because of its rapid growth rate (García Gómez, 1993; Greco et al., 1993; Porrelo et al., 1993), high commercial value (Greco et al., 1993; Porrello et al., 1993), adaptability to close confinements (Micale et al., 1993), and handling tolerance (Greco et al., 1993). Greater amberjack is intensively cultured in sea cages and/or tanks in the Mediterranean (Greco et al., 1993; García Gómez, 1993; Grau

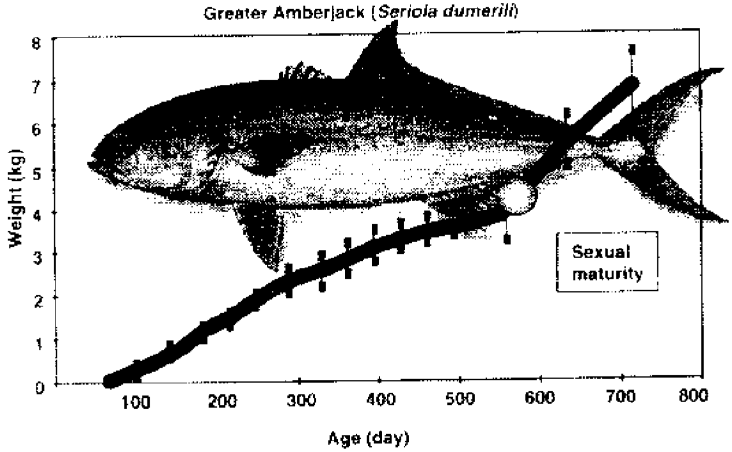

Figure 4. Greater amberjack growth and sexual maturation rates.

et al., 1993), Japan (Masuma et al., 1990; Tachihara et al., 1993), and Hong Kong (Wong 1995). However, hatchery production in one of the major stumbling blocks. Broodstock and hatchery techniques are currently being aggressively pursued in the Mediterranean (Grau et al., 1996), Japan (Tachihara et al., 1993) and Taiwan (Liao et al., 1995).

Work at OI has just begun on this species, but is showing promise. Greater amberjack grow as rapidly as mahimahi. In fact, mahimahi reach sexual maturity much earlier, so after a few months the growth rate of amberjack is actually better than a mixed population of mahimahi. Young juveniles captured in the wild have been fed on pelleted feeds at feed conversions of approximately 1.2. Vitellogenic eggs have been identified in females (6 kg) captured as young juveniles (circa. 20 gm) after less than two years in captivity. In Hawaii, commercial capture fisheries for both bluefin trevally and amberjack do not exist because of potential problems associated with ciguatera outbreaks in the region, and worms. Mariculture production of such species has clear potential.

Other species targeted, but yet to be investigated, are in the Etelinae subfamily of snappers. Snappers are considered a high-value food fish in many parts of the world; however, culture has been confined to the subfamily Lutjaninae (i.e., *Lutjanus* sp.) (Pooley 1987; Wong 1995). Snapper (*Lutjanus argentimaculatus, L. malabaricus, L. russelli*, and *L. johni*) are cultured in China, Hong Kong, Malaysia, the Philippines, Singapore, and Taiwan (Anonymous 1995). In 1994, cultured snapper production totaled 4,379 metric tons, with an estimated value of $21,832,000 (FAO, 1996). Culture of *Lutjanus campechanus*, popular in the Gulf of Mexico, is currently being addressed in the United States for stock enhancement purposes. The Hawaiian subfamily has been heavily over-fished, leading to introduction of legislation to impose strict regulations and some area closures.

Conclusion

It is evident that the commercial fishing industry in the United States will be unable to supply the rising domestic demand for fish and fisheries products in the near future. Stable catches and area closures have placed limits on supply and access to traditional fishing grounds, while lowered catch per unit effort and increased operating costs have placed severe economic pressures on fishermen. Concern for the inevitable domestic supply problem and the potential for development of a robust offshore mariculture industry has created a rising interest in marine finfish hatchery technology. The Oceanic Institute is committed to development of a multi-species approach toward hatchery development for production of fingerlings for stock enhancement and commercial growout. Bluefin trevally, greater amberjack, and the Etelinae subfamily of snappers are targeted. There is also great potential to demonstrate and develop offshore systems in the islands. Hawaii offers optimum conditions for offshore aquaculture with stable water temperatures, nearshore steep ocean drop-offs, and a strategic market location close to Asia and the greater seafood eating communities.

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Economics of
Open Ocean Aquaculture

Economics of Longline Technology in Offshore and Drift-Ice Environments: How to Make or Lose Money?

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Abstract

The expansion of marine aquaculture appears to be heading offshore, into the open ocean environment! Offshore longline culture operations are confronted with longer fetch, stronger winds, choppier seas and, additionally in some latitudes, to winter drift-ice conditions, which thus limit the number of available work days. For many northern temperate bivalves, two to five year production cycles are not uncommon. Submerged longline technologies are thus preferred for these environmental conditions. However, how do the advantages of unlimited space compare to smaller operations confined to protected nearshore embayments? The daily operations at offshore sites require extra travel time for human and material ressources, for maintenance and harvesting. Ultimately, it is the type of ship and its working capacity that become the factors that limit production or affect its cost. Although we expect higher production levels to bring in more revenues, once the volume of production exceeds a certain level, there is no more economy of scale, and profitability levels off. We examine the economics of duplication at different scales of production, and suggest alternative technologies that can be applied in order to reach new levels of economies of scale.

Introduction

No one should get involved in shellfish production if they don't plan on making a profit How many would not scoff at such an obvious statement! Yet, it is amazing how many operations don't really sit down to analyse how they will control the outflow of money once they're in production mode.

Just consider the high capital expenditure and start-up costs as the volume of production is increased. Before any substantial inflow of revenue, there is a need for sufficient working capital for the first three to five years of operation. Then, as more product is marketed, the necessary revenues are created from the mariculture production to stay afloat. Some ongoing operations may even be making a profit! Since the market decides on price structure, the likely choice for greater profit creation is to expand.

There are two ways to make a profit. The obvious one is to increase the volume output to increase revenues. This can be achieved by duplicating the scale of production several-fold through an increase in the number of boats, manpower and longlines at sea. The other more challenging way to make a profit, without too much additional investment, is to reduce operating expenses and decrease the cost per pound. This requires a clear understanding of the limiting factors governing the calendar of operations, such as the working capacity of the boats and equipment in use, the potential yield per longline, the number of available days to accomplish each production activity and the flow of manpower per activity. A slight improvement in any of these areas may produce substantial benefits, especially as the scale of production increases.

The best strategy, however, is to combine both methods to attain economies of scale. This occurs when the efficiency of a unit increases, as for example, in the case of a longline producing 3,000 lbs of mussels instead of 2,200 lbs, simply by increasing the vertical length of socks from 3 to 4 m; or by increasing the working capacity of a boat by mechanizing an operation or reducing the handling time between longlines.

Whatever the mariculture production, economies of scale can be achieved through comprehensive analyses of the operation.

Objectives

In this study, we examine the economics of duplication at different scales of production. Specifically, we look at economies of scale when using submerged longline techniques for mussel culture in offshore environments.

We also examine which factors most influence the cost of production, in order to determine whether the expanded mussel production will make or loose money!

Description of mussel production parameters and activities

The location of the study area is in Baie des Chaleurs, just on latitude 48 West and longitude 65 North, along the Quebec coast of the Gaspé Peninsula in 25 m of water. The peculiarity of this temperate region is that it is inaccessible between December and April due to drift-ice conditions and frozen harbours. During the rest of the year, gale force winds are not uncommon, so the producer must work within a 31-week calendar year to produce and market the mussels.

The province of Quebec produces mussels along three latitudinal clines, so that the production cycle increases with latitude, from two years in the Magdalen Islands to four years on the Lower North Shore. All lagoons and enclosed bays are subject to 1-2 meters of winter ice and are accessible by truck or snowmobile during winter harvest.

This mussel producer is looking at a conservative yet realistic three year production cycle between the time the collectors are installed and the last mussels are harvested off the socks, at about 50-55 mm in length. There are no offshore winter operations, no visits on site, and all surface buoys and markers must be removed, and the lines must be submerged to at least 10 meters depth to avoid being tangled in winter drift ice. The longlines remain unavailable for at least 20 weeks of the year.

The selection of single backbone submerged longlines is based on the type of boats available in most coastal fishing harbours. The lines are 150 meters long between the anchors, and 133 vertical mussel socks may be attached on each longline. Since the longlines are submerged 10 m below surface year-round to avoid second-set of spat and winter drift-ice, there is an unusable segment of about 12 meters, after the corner buoy, at each extremity of the longline where no mussel socks may be attached (see Bonardelli 1996).

The boats may be made of wood, but fiberglass is preferred because of the ease of cleaning, its handling among the longlines and its greater resistance to ice during the first freezing in the harbours. The length of the boats are 10-12 m, and the deck space is at least 3 by 5 meters, sufficient to support a one-ton crane and five to six large tote boxes. One side of the boat is geared with a hydraulic hauler near the cabin and a star-wheel near the stern (Figure 1).

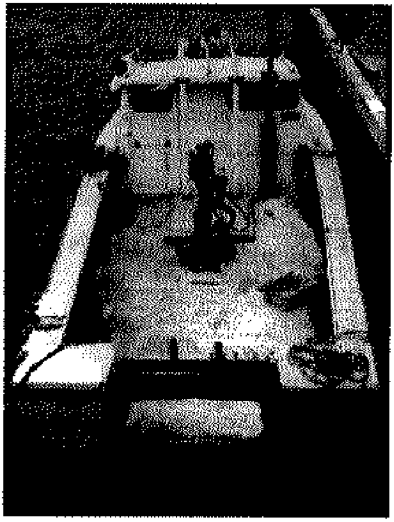


Figure 1.

Production volume 1997-2004

The projected production is to gradually attain a commercial volume of 1.25 million lbs of cultured blue mussels. This requires some 55,000 mussel socks to be installed annually from the fourth year on (Figure 2). Since this is a wise company, it realizes that it must increase production levels in parallel with the acquisition of a trained labour force and of the appropriate types of boats and longlines. Thus, the number of socks to install will increase gradually from 10,000 to 18,000 to 37,000 socks in the first three years of its start-up phase.

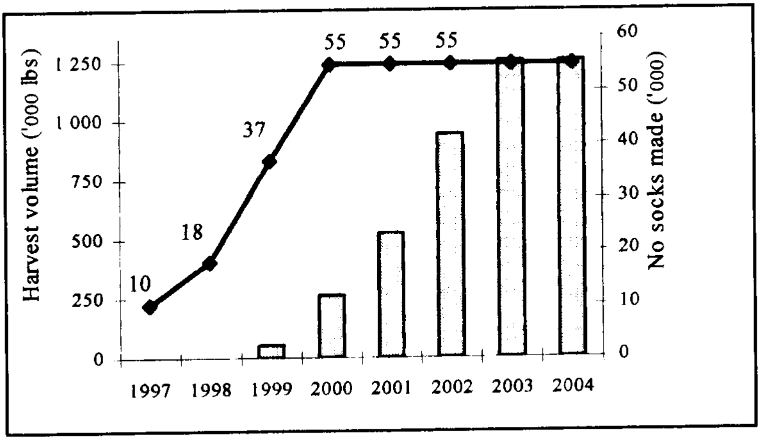


Figure 2.

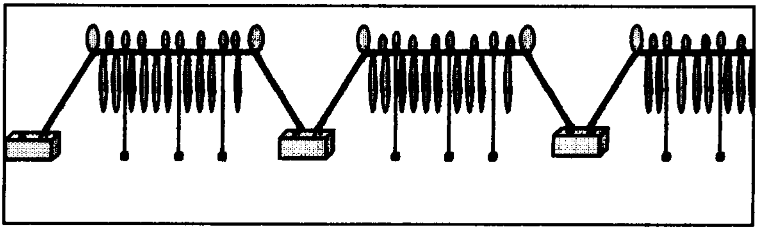
This strategy allows for management to also adapt to the initial shock of harvesting commercial mussels while volumes are still relatively small and make a move on the outside market. The latter not necessarily so evident in a competitive industry. Thus, by the second and third year of operation, harvest volumes will increase respectively from 60,000 to 250,000, to reach about 0.9 to 1.2 million lbs in the fifth and sixth year. By the seventh year, the company reaches a stable production level.

This theoretical development plan is the starting point for establishing the technical, biological and financial parameters of the operation.

Production parameters (true & tried)

The scale of production, the production cycle and the environmental conditions at the proposed culture site, will directly influence the type of equipment required and the complexity of each production activity. Site-specific conditions will determine the time frame that can be allotted within each activity.

In this study, the submerged longline can support 133 socks (3 m long) on 120 m single backbone. The distance between the anchors of the dynamic longline in 25 m water depth is about 150 m, such that each series consists of 10 longlines attached end to end for a total distance of 900 m. Thus, one series requires a string of eleven 2 Tm cement blocks.



The production cycle (sale of commercial size mussels from beginning to end of a cycle) is completed in three years, and it takes seven years to attain a stable production volume of 1.25 M. lbs. Because of winter ice, only 31 weeks are available to market the mussels. The maximum weekly volume is stabilized at 42,000 lbs.

The net market yield for a 3 m (10 ft) sock is 22.5 lb (10 kg)/sock. The price paid for this net product is established after the mussels have undergone several treatments by the wholesale processor. Specifically, the mussels are declumped and graded, then debyssed at the plant and bagged, which includes about 5% loss of mass for byssus and breakage that is removed at the inspection conveyor. The mass is further reduced anywhere from 5-12% for water loss during packaging and shipment to the buyer. This percentage fluctuates in relation to the reproductive condition of the mussels.

The additional percentage loss may seem elevated, but herein lies the onus on the producer to manage the density and growth of mussels on the socks to minimize the amount of wastage that the processor must handle. Generally, the wharf price paid to the producer is determined from the net paid market yield.

Production activities and annual timetable

The model of the economic analysis calculates the manpower required on the basis of the amount of time it takes to complete each of the production activities. Managerial experience establishes the daily working capacity for each production activity. As the volume of production increases, the number of work-days required per activity is recalculated within the allotted time frame (Table 1). The same method is used to determine the number of days that a boat or piece of machinery will operate based on their daily production capacity. This is important so as to know when another crew or another work boat must be added to accomplish the task as volume increases.

Table 1: Sequence of production activities of a mussel culture operation within an annual timetable of 31 weeks of operation on land and sea.

May	**June**	**July-September**	**October**	**November**
Floatation of submerged longlines	Spat collection	Assembly of new lines and upkeep of stock	Spat harvest and socking	Sinking of longlines for winter
25 d (5 wk)	10 d (2 wk)	70 d (12 wk+2 wk off)	25 d (5 wk)	25 d (5 wk)
Identify and float lines	Install collectors collectors	Upkeep of production in progress and spat	Declump and grade spat	Remove all surface buoys
Add buoys to backbone	Minimize flotation	Assemble, prepare and install new longlines	Install mussel socks at sea	Move buoys to backbone
Add surface buoys to longlines for identification	Maintain records of mussel growth	Maintain close watch on spat collector lines and remove surface debris hazards	Add correct floatation for longline tension	Monitor sock densities to upkeep stock assessment

These activities are based on a 5 day work week.

For a number of reasons other than drift-ice conditions in eastern Canada, a company may have to limit the time allotted to accomplish its production due to biological (fouling, spat transfer), environmental (temperature stress, storms or hurricanes) or technical (equipment delays) reasons. A successful operation should have the necessary planning tools to determine where, when and how it is to proceed.

Assumptions of Economic Analysis

We compared a small-scale commercial mussel operation that produces 450,000 lbs annually, to a production level three times the size, that will produce 1.25 million lbs. The expansion of the mussel farm looks interesting for the increase in volume of sales, but will it make money!

The small operation which amounts to harvesting a little over 14,500 lbs per week, will annually install aver 19,000 socks suspended onto 143 longlines, using two boats full time. The large operation plans to harvest over 42,000 lbs per week by suspending over 55,000 socks on 417 longlines, which will require eight boats working at peak capacity in some periods of the year.

Objectives of the economic analysis

We want to show if a mussel production using the single backbone submerged longline method is even more economical at greater production levels. Firstly, we analyse the production level for the projected 1.25 M. lbs operation, specifically:

- the type of investments & costs
- the working capital required
- the salaries & administrative costs

Once the analysis is completed for the 1.25 million lbs operation, we compare the cost / lb between the two production levels.

Cost of submerged longlines for 1.25 million lbs

After a period of seven years, some 1,400 lines are installed at a cost of $600 cdn each. The longlines, from anchor to anchor are made of 18 mm (3/4 inch) polyrope, include the installation of 2 mT cement blocks for anchors and are buoyed at each corner with 110 lbs floatation. Until a stable production level is reached, there is a progressive addition up to 72,000 plastic 30 cm compensation buoys (65/backbone at commercial harvest size). The total investment cost is $1.2 million.

Investments for boats

The fiberglass hull boats may range from 10 to 13 m and and operate with a three-person crew, women not excluded. The work boat must handle itself in open ocean conditions and travel at least 9 knots, be equipped with a crane and hydraulic hauler and starwheels for manipulation on the longlines. The individual cost is $100,000 ea.

The daily working capacity of boats depends on the type of operation and season. Production activities include floating lines, installing mussel collectors and socks, adjusting line tension and routine inspections. They may also be fitted to harvest mussels and sink lines before winter. The rate of purchase in the number of required boats depends on the selected level of annual production (Table 2). Until a boat's working capacity is surpassed, and in situations where a boat is only needed for two weeks, renting during peak periods should not be excluded! The total cost for eight boats after seven years is $800,000.

Table 2: Increase in number of boats purchased over a seven-year period.

	1997	1998	1999	2000	2001	2002	2003	2004
Purchase	2	-	1	2	2	1	-	-
Cumulative	2	2	3	5	7	8	8	8

Working capital requirements

Based on a three-year production cycle and the gradual increase in sales revenue, the investment needed to support the start-up costs of mussel culture for the first five years, as the volume of production is built up, amounts to $350,000.

Table 3: Working capital requirements for the first five years of production.

	1997	1998	1999	2000	2001	2002
Working capital	80 K	90 K	30 K	50 K	100 K	0

In the sixth year of production, sufficient revenue becomes available to support operating expenses.

Production activities and salaries

The daily capacity of a unit of workers within a production activity determines the total time it will take (cost) to complete an operation. Thus, we estimated the salary requirements until a stable level of production is reached in 2004, and compare this to the level for 1998 (Table 4). The total annual salaries reach $200,000 by 2003.

Table 4: Comparison of manpower requirements for the schedule of various production activities between 1998, when no harvesting occurs, and 2004, when production levels are stable and harvesting is continual.

	May	June	July-September	October	November
Production activity	Floating of submerged longlines	Spat collection	Assembly of new lines & upkeep	Spat harvest & socking	Sinking of longlines for winter
Schedule	25 d (5 wk)	10 d (2 wk)	70 d (14 wk)	25 d (5 wk)	25 d (5 wk)
1998	3	3	3	8	3
2003	15	6	3	21	15
Harvest	6	6	6	6	6
Total	21	12	9	27	21

Fixed annual expenses (before tax)

The administrative costs, including the maintenance (boats, longlines, lease fees) and other costs are	$ 175,000
Salaries	$ 200,000
Total fixed expenses	**$ 375,000**

Summary of costs after 7 yrs

Longlines & buoys	1,200,000
Boats	800,000
	$ 2 million
Working capital to support start-up costs	**$ 350,000**

Economic Outlook for 1.25 M lbs

In terms of the cost of production invested and the volume produced after seven years, whence there are no new investments, annual revenues of $700,000 (wharf price of $0.55/lb based on net volume) and an annual operating cost of $375,000; the resulting operating cost is $0.30/lb.

However, at a wharf price of $0.55/lb, there is only $0.25/lb left over to cover all the investments!

Do we make or lose money?

If an investor is expecting a 14% minimum return on his original investment of $2.35 million, this project expansion is clearly not profitable. The following reasons support the investors decision:

After waiting for a period of seven years to reach a stable production level of 1.25 million lbs, he must sell the company at $3.3 million (14% Internal Rate of Return), which is highly unlikely, or

Not sell, and wait 10 more years to realise a return on investment of 10% (instead of 14%)! Even then, this scenario assumes no re-investment.

Comparison with a 450,000 lb production (1/3 scale)

In terms of the cost of production invested to reach a stable volume, after a period of seven years only two boats are required at full capacity. Despite a relatively small annual revenue of $150,000, there is no difference in the operating costs of $ 0.30/lb.

Thus, although there are greater revenues in the proposed expansion, there is no economic advantage to increasing the volume of production.

Can we attain economies of scale?

This study demonstrates that there is no economy of scale between a 450,000 lbs production level using two boats, and a larger operation producing three times the volume (1.25 million lbs), which requires four times more boats (8). The discrepancy in number of boats is related to increased activity during peak periods, because of the fixed calendar of activities within 31 weeks. Rentals (1-2) could replace purchases during these periods.

Thus, if the same techniques are used to expand production from 450,000 to 1.25 million lbs, there is no advantage in duplicating the levels of production.

Are there alternative strategies?

Four critical factors affect the production costs:

1. Boat production capacity (the number of lines floated or units of socks attached per day)
2. Longline technology and its production capacity (the type and length of longline determines the number of socks that can be attached, which can affect the yield or volume produced
3. Labour (manpower performance on boats and on land for each production activity may affect costs, but efficiency is also gained as more days are spent doing the same task)

4. Production cycle (the turn-over rate of the longlines is critical and related to both the growth rate of the mussels and the period available to harvest lines).

If there is no possible way to change the duration of the production cycle, through better management and husbandry, then it is the production capacity of each activity that must increase. Either, it will be a short lived experience for the producer, or he considers alternative technologies to become more efficient.

A look at alternative strategies for offshore production systems!

There is little doubt that a long production cycle, combined with a shortened work season in northern climates makes for difficult operating conditions, but there are alternative strategies that can be explored. The objective is to increase production capacity and reduce operating costs. This can be achieved in several ways:

More socking units per longline

By increasing the length of the longline, more socks or droppers can be attached. The effect will be to reduce the overall number of longlines and the number of times a boat must switch lines in a day.

By adapting the double longline system, the yield per longline system can be tripled, but this requires greater capacity, more efficient (and more expensive $) workboats. This scale-up is only efficient beyond a certain production level, when the number of lines becomes too complex to manage.

Efficient offshore harvesting vessels

By investing in faster more efficient boats, travel time and labour costs may be greatly reduced, allotting more time to conduct actual production activities. This is critical for distant offshore sites.

By adapting integrated mechanised boats to reduce the number of manpower per boat and increase efficiency at sea, economies of scale can be achieved

....or much lower wage rates!!

- There is no price for qualified mariculture technicians and responsible captains that look after the expensive boats and longlines, that take care of the employees' safety and that have the dedication and know-how to manage the production. The producer must balance the wage-rate game with his projected goals for solid growth in the company.

Post script...

We applied the same assumptions as in this study to sites with shorter production cycles (2 yrs). The project is profitable!

Just imagine the results of this model with a two year cycle, if the production capacity is also increased through more efficient longline technologies and greater vessel capacity!

Discussion

The producer must properly evaluate the cost structure of his present operation. If he or she has the right tools to conduct some sensitivity analyses of the proposed modifications, be they technical or financial, then the decision-making process will be based on a solid framework, instead of trial and error judgment.

Serious consideration must be made to determine a comfortable level of expansion that meets the production capacity of his equipment and labour force. There comes a level of production where the sole proprietorship mariculture model falls apart — there just are not enough days in the week to accomplish the operations without trustworthy, reliable partners.

Practical Experiences in Off-Shore Cage Rearing, the Good, the Bad and the Ugly

Joseph McElwee
Dunlop Marine and Bonner Engineering
Galway, Ireland

The off-shore cage installations I refer to are the large flexible Dunlop and Bridgestone rubber cages that are in use in Ireland on a number of sites. At the last count there were circa 30 in operation, up to five miles out to sea. These are operating in wave action of up to 15 metres in height, and currents of 3-4 knots.

Open ocean aquaculture, is the rearing of fish in open hostile environmental conditions, in deep waters, with little to no protection from wind or wave action. These sites may exist only a few metres from the shoreline or conversely be many miles out to sea. Depending upon where the site is located, specialised equipment must be deployed with the confidence of not only allowing fish to grow, but also survive the conditions it will have to endure.

Locating an offshore site involves much research, integrating scientific, technological, biological, socio-economics and legislative issues, some of which are easy to find, and some which will cost money to find. The decision to build an offshore installation requires not only finance but also a dedicated team, the right equipment and the correct biological parameters that dictate all profits .... growth and performance of the stock.

The first commercial Salmon farm in Ireland was installed in a protected inshore site on the west coast in 1979. It was constructed of square wooden cages, held buoyant in the water with large blocks of polystyrene nailed, strapped or glued to the wooden beams. It became apparent quite soon that not only would the fish grow and earn money, but the choice of location would be of paramount importance as the structure and design of the proposed cages. From this initial trial period, in a space of three years at least 10 salmonid farms established themselves in these inner bays and an industry was born. In conjunction with this new development was the designing of new cages and associated ancillary equipment, which all portrayed the industry in a good light, and created employment and spin-off industries. The fish farmers and feed companies were all getting a better biological handle on all aspects of the life-cycle of the Salmon, and production methodology was getting better all the time.

However, as more inshore sites were used up, and the farms getting bigger, there were inevitable problems, first with diseases and then over-crowding of each bay. This occurred circa 1985-1986, and it was felt by both the relevant governmental bodies and the salmon growers themselves that it was time to examine the options. From this the concept of growing salmon in offshore installations was born.

Currently the closest offshore site is located at the foot of a cliff half a mile from the shore, and the farthest is five miles out to sea.

In order for us to develop these type of farms we had to examine a number of parameters, each in it's own way as important as the other. Due to the rapid developments in technology and cage design, especially the flexible cage, there was a way to construct a site, enable it to withstand the atrocious weather conditions it will have to endure and yet still be workable, accessible, and enable fish to perform.

Fish farming was now a big business, producing a quality product, but margins were getting tight. We had to look at bigger and better cages, and a way to develop them. Consequentially we decided to go farther from the shore, into completely exposed areas and try to grow the fish. As we did this many types of cage designs were looked at and experimented with, from steel to plastic and of course the flexible rubber cage of varying designs. All these cages had to perform in strong currents, high waves (10-15 metres), prevailing winds and still allow a platform to grow fish and work on. This was or is no easy task, as these cages are in extreme locations subject to the full rigours of the environment at all times with little respite.

Accordingly, to establish one of these farms, it costs a large amount of money in capital equipment and running costs. The site costs a lot to buy, maintain and service, with the ancillary equipment being specialised and expensive. The actual running costs of a farm offshore are daunting as compared to that of a successful inshore site, and one must always bear in mind the fluctuating price of fish in domestic and international markets, as this will also have a effect on costs and profit margins.

Whilst the costs are of major consideration, so too is the cage type to be deployed and the numbers of fish it can sustain. Will the numbers of fish realise profits, and does it take into account for higher than previously experienced mortalities?

Therefore setting up an offshore site is advantageous, as it:

1) Ensures better growing conditions, with deeper waters, strong currents and a vast water exchange, thus allowing for much improved biological growing conditions.
2) It's much more environmentally conscious, as being distant from the shore means out of sight, out of mind. Pollution issues are much more diluted in every way, and the marine fauna and flora are not impeded or adversely impacted in any detrimental manner.
3) Once assembled and moored correctly, the maintenance of these cages and the moorings are relatively cheap, and little needs to be done to keep them this way.
4) More space=more fish=bigger profit potential.

These type of offshore cage systems are now in use quite successfully in Ireland, and although inshore sites are proven, in the last 3-5 years the bigger sites have more than proved themselves and farms are generating good profits.

So just what is required in setting up a farm like this?

Whilst licensing and lack of adequate inshore sites swayed us to go further out to grow our fish, but also, to examine deeper more extreme potential sites around the coast. In addition to this we had to look at the straight practicabilities of local and experienced staff, an adequate infrastructure, and the help available in grant aid from relevant governmental agencies. Certain governmental agencies do provide financial aid in the form of grants to aquaculture industries setting up in peripheral areas, but as it would have it, many of the offshore sites had to be funded by themselves, as the huge initial start up costs may not qualify for grant aid! This is really just an indication of the huge financial resources one must be able to secure in order to start.

Accordingly, starting a site will entail some serious decisions. These include: physical location, navigational and fishermen's rights

- Prevailing winds and tidal conditions
- Water depth and quality
- Bottom type for moorings
- Wave action-strength and direction
- Accessibility by land (piers) and sea
- Availability of roads, infrastructure, ice-plants, etc
- Staff qualifications and availability/experience
- Disease status — any wild stocks/runs or rivers
- Site potential for further development
- P.R. issues/environmental issues
- Health and safety regulations and procedures
- Grant-aid and tax incentives and do bear in mind that whilst we cannot control the weather, we can prevent or limit its effects on the stock and equipment. The price of the fish however may not be in our hands, so each farm will have to factor this into its stock numbers, and allow a buffer zone for production.

Having looked at the practical/physical aspects of start up, let's examine everybody's favorite ... Financial considerations.

The cage design having been decided ... the cost of them.

- The costs of nets, ropes, chains, moorings, etc.

- The ancillary equipment ... boats, trucks, harvesting/ grading gear
- Staff
- Feeds
- Medication/vaccines
- Maintenance/repairs
- Licenses/P.R. and legal costs
- Smolt costs (if not supplied in-house)
- Net-washing and repair facilities
- Insurance fees

Thus it's of paramount importance to regulate all monies, and control spending on a week by week basis ... the reason for this is that if things will go wrong, they will! And it's costly when you're operating at this level.

Performance of Off-Shore Cages

The main feature must be its ability to survive the conditions its deployed in, and allow for the fish to grow. This may seem an obvious statement, but if it isn't achieved, not only will profits be down, but one is only throwing money away!

No matter what system one chooses, it must be durable, flexible, sturdy, non-corroding, hardy and workable/assessable to work on. The most important feature of the cages will be how they are moored. Care and consideration should be taken when mooring your cages, as the weather takes no prisoners, and I have been in the unfortunate position of seeing cages break free, and travel their own way, with valuable stock! We would regularly work on these cages in storm force 6-7. Whilst the cage manufacturers may have their own preferred systems for moorings, this will be dictated by a number of features:

- Sediment type
- Previous mooring experience
- Average weather conditions
- Actual Type of moorings to be used/cost
- The equipment available to set the moorings
- The depth of water

Again I must reiterate ... the moorings and how they are set will dictate whether or not your cages and ultimately, your stock, survive to fruition. It's worth spending decent money on them, and you'll get a good nights sleep knowing your cages are still there in the morning! This may seem a glib comment, but our experiences have left us this way, and it happens on a regular basis throughout the European industry.

Whilst there are a number of different types of anchoring types, such as blocks of specified weights, metal anchors, drill type anchors, helix anchors and tension anchors, they all have to fulfill the same role, and that's to keep the tension and stability/structure of the cages in all weather conditions. If they can't or don't do it, it's a disaster waiting to happen, and it will!

There are a number of features I would like to comment on with regards to the actual running of these cages. I am referring to the type of cage we in Ireland helped to pioneer for salmon farming. These are flexible rubber Dunlop and Bridgestone cages with four sides, with 15 m sides, six sided or hexagons with 16 m sides and the biggest form, the eight sided or octagon cage with sides of 16.5 m or a circumference of 132 m, with nets ranging in depth from 15-25 m, or circa 13,500 m in capacity. This is probably the most common type we use, and run at a stocking density of 15-20 kg/m, which enable us to harvest circa 250-300 tonnes per octagonal. They are moored in depths of 3,040 metres, with a combination of one tonne blocks and one tonne anchors at 16 per cage with 32 mm braided rope and 2.5 inch studded chain. The stanchions range in height from 1 m to 4 m on the surface tubes, and these hold the net and bird net in place taking the strain at all times.

We stock them with 150,000 40-60 gram smolts in March/April, delivering them by helicopter. Some farms then either move the cage to a inner bay in October, or thin out the cage, down to 80-90,000 fish for on-growing, from September onwards.

Disease/Treatments

Due to the enormous working surface area of these cages, monitoring of the stock must be of paramount importance, and a good observant biologist must be alert at all times. Daily vigilance of swimming and feeding behaviour will alert a good manager to a pending problem in the stock, which will have to be acted upon due to the large numbers involved.

Aside from disease diagnostic skills and identification, the actual physical aspect of treating these cages is enormous. Any viruses or bacterium can only be treated orally, incorporating the medicines in the feed. This of course poses it's own problems.

- Are all the fish getting the food/medication mix
- Is the dominance factor preventing even feeding
- Are the stock actually feeding in the first phase
- Is the antibiotic compatible with the feed
- The costs incurred in mixing and purchasing the medicines
- The wastage, and any detrimental effects on the sub-strata

These are only some of the considerations involved in disease/treatment area, but the key is to be vigilant at all times, and the golden rule is what appears on the surface, multiply it by three, and that's what happening in the depths of the cage.

The second method of treatment is by enclosure or bath method. This is near impossible in the large cages and is dependent on calm weather conditions. However we do use this method in the square cages for lice treatments, but with current legislation in progress, we are now experimenting with oral treatments, which are making things much easier, and we are having good success.

Bath treatments are not as successful due to:

- It produces high levels of stress in the stock
- Water volumetric calculations factors may be and are hard to get exact
- It is expensive and labour intensive
- The treatment may be ineffective
- Its hard to monitor the results

- 02 levels drop quickly and expensive oxygenation systems need to be used

Accordingly, the best method of treatment is prevention, and this can be achieved only by strict on-site vigilance, by all staff, at all times.

Feeding

It requires specific equipment to feed these large cages, due to the surface area and numbers of fish involved per cage. It also requires specialized boats to carry out this task. The most common method is by air/water cannon mounted on platforms in the boats. These machines are relatively cheap and easy to operate. Constant care and vigilance are required when feeding so as not to waste any food due to the prices, and not overfeed or more importantly underfeed the cage, as this achieves nothing either, and in fact the fish will damage themselves in the ensuing melee to get feed.

One must be careful and observe the fish in there feeding behaviour, as this will be the first indication of any problem in the stock. The amount of feed used should also be carefully monitored, as any wastage will be literally money thrown away, and we have achieved FCRs of 1:1.1 on some of these offshore sites. We have been able to monitor this using biomass scanners and end of harvest results.

Diving

Due to the nature of these locations and the need to know what's happening with the stock at all times, the requirement for divers has increased dramatically. This is due to the need for mooring work and mort removal as well as general cage and stock maintenance. The need for trained in-house divers is vital and safety regulations have changed in order to take this into account on all fish farming installations. Having a diver on site at all times is necessary from net changes through to mooring work.

Harvesting

Harvesting, while a most integral part of the operation, is expensive and labour intensive. Again, specialized equipment is required and this isn't cheap.

Large rafts, vacuum pumps and cranes are required either attached to boats or on separate rafts. Most harvests are bled and the bloodwater is treated at sea, so as the transmission of disease is kept to a minimum. The average harvest would be about 20-30 tonnes per day and this is iced on site, and bought directly to the packing plant, and accordingly onto the European market within 24 hours.

Ancillary Equipment

As the sites are in exposed areas or rough areas, the need for strong reliable and economic equipment is centre to the operation. At sea there should be working boats (half-decker type or plastic type), a boat with towing/crane and deck space facilities, sturdy rafts capable of large tonnage and possibly a barge for food storage.

At the land base, net washing and repair facilities, bin storage and ensiler space will be required. Offices, etc. may also be located here. These all take up space and the relative infrastructure will need to be there for them.

Legislation

This is a distinct parameter different in each country, and is often linked to the environmental aspect of current laws. Whilst it is in the fish farms best interest to have the cleanest and purest waters possible, it may be hard to access them or get a license to operate in these areas.

The problem we were facing in Ireland was an over population of inshore sites and not enough money to go offshore. As we developed these sites we were granted alternative fallowing sites, so as to break the up the longevity of production and any detrimental effects it may have on the bottom fauna and flora. So we now have a situation where some farms put there smolts into the offshore sites in March/ April and bring them back into the inshore sites in October, for controlled growth. This has resulted in many legal difficulties and delays due to the fact that the laws hadn't changed so as to keep up with the fast pace of development. At this particular moment, a new aquaculture bill is going through government, as many of the related laws went back to 1959 acts. This may not seem to be applicable to some of you, but if you are to develop, it's good that the legislation is prepared to adapt as is required as well. We have experienced delays in getting licenses, and if you are waiting for grant aid, it certainly can stifle you.

Accordingly, many new insertions incorporated into these acts will be referring to specific environmental aspects, such as proximity to the shore, pollution issues and the aesthetic aspect of site location. We have also had to tighten up on net quality, so as to prevent escapees, due to storm damage, which have caused great consternation and debate with angling bodies.

Conclusion

Salmon farming is a profitable business, carried out in a number of countries. There has been tremendous strides forward in all areas of biological and technological related areas, from better faster growing smolts to sturdy equipment able to work in the most adverse weather conditions. We are now able to venture farther out to sea, with the better, more advanced gear available, and the enhanced knowledge of new species, thereby allowing a diverse spread of different species to be grown. We (the industry), have proved that offshore cage farming is feasible, profitable and sustainable. There is new equipment being tried, developed and tested all the time, thus providing a range of options to any prospective buyers/setup situations.

Finally, to explain my chosen title,

The good – Well, that's easy. Its employment a challenge every day and a new industry worth developing.

The bad – This is the downside, working in atrocious weather, the risk financially of locating and operating in this environment, and the sheer logistics of it all.

The ugly – Having to try on a consistent basis to beat all the odds on a day-by-day basis.

However, it can and is successful, but be under no illusions, offshore cage farming is costly in the initial phases and it has to be done properly and economically, and there are experienced people out there to avail of.

The potential is as yet untapped though, and with a world attitude swinging towards the healthy perception of fish in diets, there is plenty of opportunity.

Integrated Fish Farming in the Mediterranean: Case Study of NIREUS, Chios Aquaculture S.A. in Greece

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Introduction

The marine fin-fish culture industry has grown rapidly during the last 10 years around the Mediterranean basin. It is characterized by the predominance of two species, seabream *Sparus aurata* and seabass, *Dicentrarchus labrax* representing 48% and 50% of total production respectively. The rest 2% includes several other species mainly of Sparid family (*Puntazzo puntazzo, Pagrus pagrus, Diplodus sargus, Mugil cephalus, Dentex dentex., Pagrus major,* etc.). This event can be attributed to the development of techniques for rearing larvae on live feeds (which is the most difficult part of the process) and to the strong financial assistance EU provided through consecutive regulations, covering up to 45% of the total investment. This was combined with an additional 10-30% of the total investment by supportive multi-annual guidance programs by the member States. Rearing the fish at sea has been done using cage technology developed by the salmon industry.

There have been some problems associated both with cage technology and with feeds not fully appropriate to these farmed species. Labour cost remains high due to the fish husbandry difficulties associated with seabream damage to the nets, and feeding efficiencies are still well behind those in the salmon industry.

Marine Finfish Production in Greece

Greece, one of the countries enjoying maximum EU support, was found at the forefront of this impressive growth due to the favorable geo-morphological and climatic conditions: extended coastline and abundance of inlets and sheltered bays; great number of small rocky islands standing firmly against waves; wind speeds rarely exceed 30-40 knots (force 8-9, moderate storms); water temperature for the most of the year within the optimal range for the fish growth (15-26 C).

In 1995 there were operating 190 on-growing units and 25 hatcheries around the country (Tables 1 and 2), all of them in the form of private businesses, while the two market leaders (NIREUS Group and SELONDA Group) are listed on the Athens Stock Exchange. The production reached 17,000 tons. The total space utilized reached 2,714,000 m^3 of which only 60,000 m^3 in pump-ashore tanks and the rest in floating cages. The estimated annual capacity is more than 30,000 tons. The main production is realized by the two leading groups representing around 43% and 30% of the total production of juveniles and marketable fish, respectively (Tables 3 and 4).

The current situation regarding the financial incentives from the side of the European Union is that grants are not available any more for seabream and seabass farming and the main reason is the saturation of the market. Subsidies are offered only to investments regarding the farming of new species. In addition, the five-year Sectoral Plan of the Ministry of Agriculture drastically limits the establishment of new mariculture units for seabream and seabass farming, focusing at a balance of supply and demand.

Marketing and Distribution

Greece is the main exporter of seabream and seabass in Europe (40% and 80% of the total production, respectively). Italy is the main market, for seabass in particular. According to the data of the Federation of the Greek Mariculturers in 1995, 915 of exports are absorbed by Italy (which attracts the attention of other mariculture producing countries), 4% Germany, 3% UK and the rest 2% other countries (France, Spain, Switzerland, etc.).

The very rapid growth in volume of fish produced has outstripped demand. Fish prices decreased by 53% (in ECU) in the local market over the last six years. The price drop was partially only compensated by a reduction of production cost. Product quality, consistency and reliability of supplies, processing as well as farming of other marine fish species with a higher value are considered priorities for developing the market of aquaculture products.

Cost Analysis

Production cost for fattening

Table 6 shows the elements which comprise the production cost for seabream and seabass farming at fattening stage.

The parameters which affect the production cost are:

1) economies of scale in the production process related to the size of the farm/enterprise and to the size of the site (i.e. to farm 700 tns at one site or divide the production into 2-3 different sites); critical elements to be evaluated are packaging unit within the farm, availability of boat with crane, automatic feeding system.
2) final sale weight of the product; from a certain weight and up the conversion rate increases, and this border is around 330 grs; the optimum size for highest profitability ratio is between 250-380 grs.
3) water temperature; one of the most important factors for achievement of the fastest growth at desirable sales weight; the culture period varies from 12 to 20 months for an average individual weight of 350 grs.
4) stocking season; the ideal period for stocking is May, and for harvesting is the next August-September; this combination has the shorter production cycle and the faster growth with low FCR but the disadvantage is that during the harvesting period the market price is at a low level due to increased supply, as all farmers try to organize their production in that way.

5) the quality of the fry Juveniles.
6) the quality and type of fish feed.
7) personnel; it has been assessed that the type productivity per worker ranges from 15 tns per person per year up to 40 tns per person per year which is much lower with that of the salmon industry (200 tns per person per year).

In general the Gross Profit Margin can reach up to 40%. Making a comparative analysis through time we shall identify a trend where the costs are increasing while the price is relatively decreasing. Referring to the biology of the species with reference to production costs, seabass formulates more advantages as there are many females among the total population compared to seabream which is composed of male fish exclusively.

The criteria which will indicate the success in the future of mariculture are:

- Shortening of production cycle
- Increasing of productivity
- Applicability of economies of scale
- Diversification to new species.

Production cost for hatcheries

Table 7 shows the elements which comprise the production cost for seabream and seabass fry. In general the production cost influenced by the size of the investment. This implies that solutions are targeted towards either industrial scale units or even to pocket hatcheries (small scale) which could sustain depreciation of 2-3 GDR per piece (juvenile), with a normal depreciation period of 10 years.

Case Study of NIREUS

NIREUS S.A. was established in 1988 on the island of Chios. Within five years the company became a fully integrated fish farming company operating a hatchery unit, a central storage and packaging plant and five cage farms with a production of 1,000 tons of market size fish and 10 million juveniles per year.

The rapid financial growth qualified the company to enter the Athens Stock Market in1995, and the increased liquidity allowed the completion within the same year of an ambitious program of acquisitions of other companies. This policy established NIREUS as a leading group in Europe with three hatcheries, 10 on-growing cage units, four packing stations and a turnover in 1995 of 40 million US dollars. The program was completed in 1996 with the establishment of a fish processing plant, comprising filleting, freezing and smoking.

The farming of seabass and seabream is carried out in floating cages in sheltered and semi-exposed sites with a minimum fetch of 10 and 50 miles, respectively. Initially, classic wooden cages were used with a high maintenance cost and a depreciation set at five years. Many reasons led to the development of a new cage technology. Among them the need to use larger volumes for cost effectiveness and the need to increase the life span of cages and their ability to withstand worse weather conditions. This tendency follows the evolution of cage technology for the salmon industry which reached an industrial level in terms of volume and automation of the culture systems.

Current cage technology comprises circular HDPE up to 60 m. circumference, 12 m depth, and square galvanized steel up to 15 x 15 x 12 m cages. Steel cages offer far better working conditions than any other cage type, and are more suited for new technology applications (feeders, graders). However, the circular HDPE cages are a lot cheaper and seem to be more suited for the wave type of the Greek seas, absorbing easily and uniformly the wave action. They have also a big life-span.

In the tendency to exploit more exposed sites, large steel and plastic cages are going to prove very useful, providing that the related husbandry problems are solved. However, for the time being seabream and seabass culture has not overcome the dependency on the small cages at least for the first stages of the ongrowing.

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Aquaculture In Hawai‘i - Past, Present and Future

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Background and Ancient History

Large-scale aquaculture activities in Hawai‘i date back at least 600 years. Students of Polynesian culture are often intrigued by the "highly stratified chiefdoms" that existed throughout Polynesia (references cited in Kikuchi, 1976). It has been rationalized that the development of such a highly defined social structure was, in part, the result of exercising control over the limited water resources throughout the various island groups. With regard to the evolution of the Hawaiian culture, a recurring theme is the development of an agricultural system consisting of a complex array of irrigation ditches engineered and constructed for the production of taro in wetland plots. Evolving from the wetland culture system was a uniquely Hawaiian innovation, the development of ponds for the specific purpose of sheltering and nurturing fish for consumption (Apple and Kikuchi, 1975; Kikuchi, 1976). Several types of fishponds (freshwater, brackish, and saltwater) were developed by the ancient Hawaiians to take advantage of the topographical conditions found in the Hawaiian Islands. These have been characterized by Wyban (1992) and Henry (1993). The origin of Hawaiian fishponds is believed to predate the 14th century A.D. (Kikuchi, 1976) and it is estimated that by the year 1800 there were approximately 360 ponds in existence in all of

Hawai'i (Apple and Kikuchi, 1975). Of particular interest are the fishponds along the coastal zones or *loko kuapā* (Figure 1). This was the dominate type of fishpond accounting for 59.5%, 39.3%, and 13.6% of the fishponds on the islands of Moloka'i, O'ahu, and Hawai'i, respectively (DHM Planners, Inc., 1989). The ponds varied in size from a fraction of a hectare to more than 10 hectares, with an average size of approximately four hectares. The *loko kuapā* was made by constructing a wall of stone on an existing reef, extending from the shoreline and enclosing a body of water. The large basaltic boulders and soil used for construction were carried from the land by hand to form walls about two meters wide. Some of the more massive walls are very impressive to this day and their construction must have involved thousands of workers. Constructed into the seawall were sluices to allow for water exchange and sluice grates (*mākāhā*) which allowed young fry to enter the pond for stocking and kept larger predators out. Milkfish or *awa* (*Chanos chanos*, Figure 2) and striped mullet or *'ama'ama* (*Mugil cephalus*, Figure 3), which are tolerant of fresh, brackish, and salt water, were the primary fish grown in these ponds. Other species undoubtedly were present but these two species appear to have been the primary ones under cultivation.

The cultivation of fish in fishponds by the ancient Hawaiians was never intensive and yields were apparently less than 800 kg/hectare per year. This compares to more than 8,000 kg/hectare per year for some modern aquacultural production

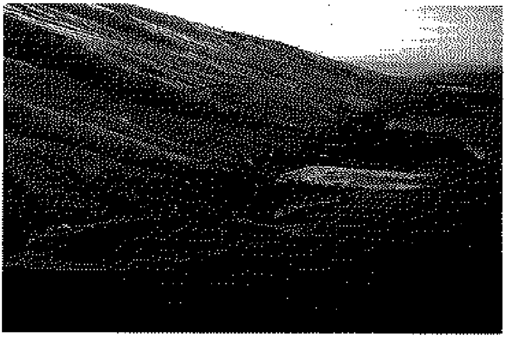


Figure 1. Photograph of a Hawaiian fishpond, loko kuapā *style.*

sites (e.g., intensive milkfish culture in Taiwan as summarized in Tamaru et al., 1995). On a per capita basis, the yield was also low and estimated to be about 3.5 kg per person. Pond production, however, was never intended as a food source for the general population but served instead as a readily available source of food in the same manner as certain agricultural plots (*kō'ele*) which were cultivated exclusively to feed the Hawaiian nobility (Kikuchi, 1976). Fishponds were thus exempt from the seasonal restrictions (*kapu*) placed on coastal fishing during fish spawning seasons.

The practice of *kapu* exists still with regard to at least one fish species prevalent in Hawaiian fishing lore, the striped mullet or *'ama'ama* (Hawaii Fishing Regulations, 1993). When the Kingdom of Hawai'i became a Territory of the United

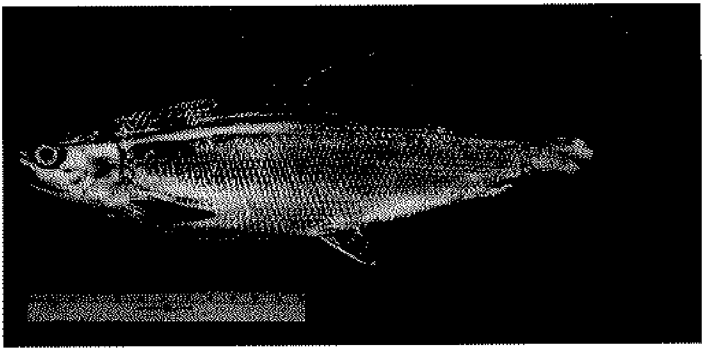


Figure 2. Photograph of the milkfish, Chanos chanos.

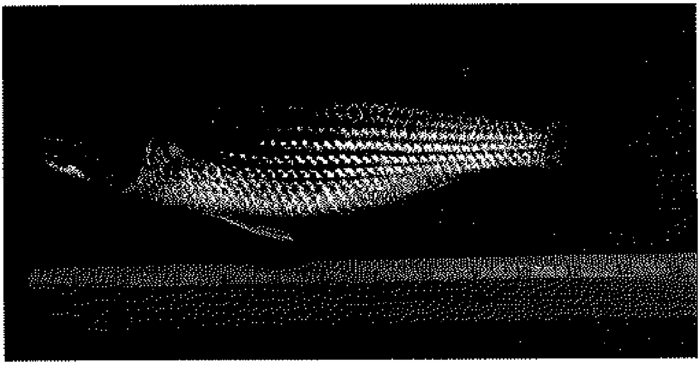


Figure 3. Photograph of the striped mullet, Mugil cephalus.

States at the beginning of this century, approximately 100 of the original 360 fishponds were still in operation (Cobb, 1903). The surface area of these ponds was described as half of that estimated a century earlier, but production was only about one-third of that estimated at the time of European contact with the islands. Seventy-five years later the 1975-1976 state records show less than 10,000 kg of total production from all fishponds or only 1% of pre-European contact production. The causes of this decline are many but key among them are changes in land tenure, loss of pond management practice due to the emphasis on sandalwood harvest, benign neglect, lack of repair of damaged pond wall and gate structures caused by natural events such as storms, tsunamis and lava flows, and finally, urban development.

It is unlikely that substantial recovery of fishpond production will take place in the future, for the economic climate in Hawai'i has changed drastically in recent years. Hawaiian pond culture systems were developed in a subsistence economy where labor had no cost and where the primary function was the storage of fish for the benefit of a few. In a market economy, the Hawai'i fishpond efficiency is too low to justify the cost. Nevertheless, efforts are being made to restore and place in service several of these ancient structures as sustainable development demonstrations for education purposes, and as an opportunity to maintain ties to an element of cultural heritage that is on the verge of being lost forever (Native American Fishpond Revitalization, Act 16, United States Congress 2801; Governor's Moloka'i Fishpond Restoration Workshop, 1991; Kāne'ohe Bay Master Plan Task Force, 1992).

The Recent Past

Despite the virtual demise of the ancient Hawaiian fishpond system, the promise of aquaculture for Hawai'i has long been recognized. For the ancient Hawaiians, control over water use and aquaculture represented power and provided a stable food supply for the ruling class. For present political leaders aquaculture represents an opportunity for economic expansion and diversification. Yet in spite of the past history of success and current encouragement, aquaculture has not achieved the level of success that was envisaged. It is therefore of interest to ask why this industry is not currently more prominent in Hawai'i as seen elsewhere.

One of the primary obstacles to aquaculture in 1980 was the availability of an adequate supply of post-larval stock, be it juveniles of prawn or finfish. However, great advances have been made in the development of hatchery operations. Most notable was the development of seed production techniques for the freshwater prawn *Macrobrachium rosenbergii* pioneered in Hawai'i. Likewise, research efforts during this time period led to the development of hatchery technologies for two fish species (milkfish and striped mullet) both important in Hawaiian fish culture but also among the most important species targeted for culture throughout the world (Tamaru et al., 1995). Research and development activities in Hawai'i have resulted in technologies for the artificial propagation of additional fish species such as mahimahi (*Coryphaena hippurus*), Pacific threadfin (*Polydactylus sexfilis*), big eye scad (*Selar crumenopthalmus*), and Chinese catfish (*Clarias fuscus*). More recently, Hawai'i has become recognized as a world leader in the culture technologies for the marine shrimp *Penaeus vanamei*. There is no paucity of expertise in Hawai'i in the area of research and development of culture technologies, however, even now there is not always an adequate or reliable supply of some juveniles for commercial culture of the species which have been investigated. It is clear that the conversion from research and development to commercialization has not taken place as one would logically assume.

A series of articles originally published by the *Pacific Business News* in January 1980 are very interesting and almost as relevant now as they were more than 16 years ago (Pulham, 1980). In the first of these articles John Corbin (then and currently the manager of the Hawai'i Aquaculture Development Program) points out an increasing demand for aquaculture products on a worldwide basis and that aquaculture could become a major industry in Hawai'i. Foreseen markets varied from fresh seafood products, such as oysters, prawns, and various fish, to the cultivation of bait fish for the tuna industry, and ornamental fish for the aquarium trade. All of these markets existed then and continue to exist today. Unfortunately, the growth of all of these fledgling industries has been less than expected.

In a companion article William Brewer facetiously suggested that the only possibility for a successful aquaculture enterprise was an infinitely strong membrane filled with water and suspended from a balloon in the sky. Why such an absurd concept? Because it was the only one that the regulations at that time might conceivably permit. Brewer felt then, and many others still believe today, that the unbelievably complex and vast web of government and permit requirements in Hawai'i provide an insurmountable obstacle to aquaculture development on a large scale. Locally, at least 16 overlapping and even redundant permits are required and each must be acquired separately and in sequence, not in parallel. Permit requirements may take many years to fulfill and may cost tens of thousands of dollars, all before aquaculture operations can commence. Horror stories involving the aquaculture permit process are common in Hawai'i but in other states they have been even greater. At one time, California law appears to have required 45 permits and a special act of the legislature. If any other aspect of farming were so severely over-regulated the world would not have a population problem for starvation would have been rampant long ago!

An illustration is the extensive effort in the research and development of hatchery technologies in Hawai'i focused on the striped mullet. Although the technologies were successfully developed, it was quickly found that the Hawaiian strain of striped mullet grew very slowly, taking three years to attain one pound. Investigations to improve the rate of growth were completed and a faster growing strain (Taiwan) of striped mullet was found (Figure 4). It is clear that the Taiwan strain would satisfy the concerns of the farmers who would like to culture a species that would reach one pound in weight within one year.

Because this species, *Mugil cephalus*, is not on the approved species importation list it is not allowed to be imported live into Hawai'i.

The process for approval of a species for importation into Hawai'i begins with a request to the Hawai'i Department of Agriculture Plant and Animal Quarantine Division. Selected individuals throughout the academic and public communities perform a technical review and recommend approval or disapproval. At monthly intervals, another technical review committee appointed by the Department of Agriculture, made up of individuals from various public (e.g., University of Hawai'i, Department of Land and Natural Resources, Office of Environmental Quality Control, Honolulu Zoo) and private agencies, meet to review the various requests and the commentaries. This committee meeting is posted and open to the general public at which time individuals may provide written and oral testimony in favor or against the request for importation. The committee provides a recommendation as to whether a species is suitable for importation without restrictions or whether it can be imported with certain conditions (e.g., not to be sold live, holding facilities must meet certain criteria, used for research purposes only), or whether the

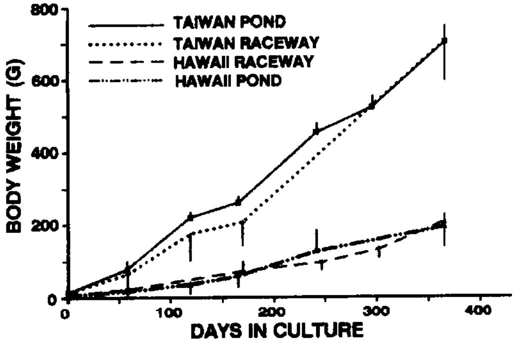


Figure 4. Comparison of growth between Taiwan and Hawai'i strains of striped mullet.

request should be denied. At this level, one of the primary concerns is potential impacts with the environment if the species to be imported somehow escapes into the wild, which is assumed as a worst case scenario. Environmental impacts also include possible effects on interbreeding of the introduction with native stocks. It is at this point that the classic "battle lines" are formed with environmentalist on one side proclaiming how fragile Hawai'i's ecosystem is and "farmers" on the other asserting the need for economic development.

The recommendations are then summarized by staff of Plant and Animal Quarantine and held until a sizable number has been accumulated and these are then forwarded to the Board of Directors, Department of Agriculture, who meet sporadically. The Board of Directors is made up mainly of department heads or representatives from various branches of state government who then approve, disapprove, or return the request to the technical committee for reconsideration with certain restrictions. Approved requests are then sent to the office of the State Attorney General for a legal review which may take more than one year. Public hearings of the requests are then scheduled in each county as the need arises. A summary by the Plant and Animal Quarantine office with inclusions from the public hearings is again submitted to the Board of Directors of the Department of Agriculture for final approval or disapproval. If approved, the submission will then go to the governor for signature. If signed the submission can finally be placed on the importation species listing with the requirements for its importation. At this point an importation permit is obtained from the Department of Agriculture and the species can be imported. The process for placement of a species on the approved importation list takes approximately two years not withstanding objections or delays. The striped mullet case illustrates a technology developed in Hawai'i over two decades with millions of dollars invested. Still the aquafarmers in Hawai'i are not able to profit from the research activities as regulations prevent full exploitation of the results. Other permit processes required for aquaculture in Hawai'i (e.g., water use, soil and water conservation, grading and grubbing, effluent discharge, historic preservation) are equally as time consuming and frustrating to obtain.

In addition to the tedious permitting process, another factor that has limited growth of the aquaculture industry in Hawai‘i is the simple fact that it is difficult to conduct business in Hawai‘i. The taxing and regulatory mandates placed on local businesses have been characterized as, “job killers,” as the consequences of an excessive government bureaucracy are higher production costs (Lubove, 1997). Hawai‘i’s labor, energy, water, land, taxes and insurance costs are among the highest in the nation as is government spending (Hawai‘i: $5,270/resident versus California: $2,980/resident). On top of that, being an island state means that products needed to conduct culture activities must be transported to Hawai‘i, thus adding to the overall production costs. While Hawai‘i does offer advantages such as mild climate and ocean location, there are also clear disadvantages to any agribusiness in Hawai‘i (Teichman, 1994). To compound the difficulties encountered by the private sector is that research and development activities are often conducted under “ideal” or laboratory conditions that do not mimic real-life circumstances faced by the private sector. The fallacy of concluding that technologies developed in the laboratory can be extrapolated to commercial scale has been proven many times over. Yet laboratory results are often used to project commercial production as they are often the only data available. Needless to say, this has often led to overly optimistic projections and it is not surprising then to hear of the many failures that have resulted when commercialization of a developed but not demonstrated technology is attempted. Validation of results at pilot-scale or at farm-site is necessary to determine whether the developed technology can overcome the constraints that face the private sector. Moreover, a change of attitude toward applied and/or demonstration research is needed along with a willingness to incorporate “real world” situations into research objectives.

A case in point was a project focused on developing a feed for tilapia that was supported for several years by the state and the Sea Grant College Program. The project took a more academic approach by investigating the physiological changes that accompany acclimation to various salinities as the tilapia are euryhaline and exhibit differences in their rate of growth in response to the salinity of the water in which they are raised. It was rationalized that by understanding these changes one could better understand the environmental affects on growth and exploit these inherent changes by using a feed that contained less protein, or in practical terms, a less expensive feed.

Experimental diets manufactured in the laboratory were defined and tested and a number of technical manuscripts were published in peer-reviewed journals. The logic of the approach seemed to be validated. In preparation for field testing a commercial feed manufacturer had to be employed as the amount of experimental feed to be produced exceeded the laboratory's processing capabilities. The recipes for two experimental diets were provided to the feed manufacturer and two experimental feeds were produced for testing. Farm sites were identified and the experiment was initiated with each farmer using his own commercially available feed as a control. It was soon found that the experimental feeds were not palatable to the fish being investigated. Upon close examination of the feed it was revealed that the commercial feed manufacturer had changed the formulation of the feed for economic considerations. In theory the experiment was accepted as valid. In practical terms, the experiment failed to achieve its main objective.

Hawai'i researchers recognized in 1980 that extensive efforts were needed to develop the various aquaculture technologies to an economically viable level. Moreover, it had to be a longterm sustained effort. At that time Hawai'i was at the forefront in both the planning and the funding needed for this effort. But in the ensuing years the level of commitment waned and the rate of progress in aquaculture development was considerably slowed for lack of adequate investment in research as well as infrastructure.

The Present

Agriculture in the state of Hawai'i is undergoing massive transformations due to closures of extensive sugarcane and pineapple plantations. The unemployment, social costs, and loss of tax revenues are adversely affecting the state economy. The need to diversify agriculture has never been greater and aquaculture has demonstrated potential for significant expansion. However, most of those involved in aquaculture in Hawai'i have continued with cautious optimism. For the past 10 years this optimism has been misplaced, since after 1990 the industry only grew to about 5% of the projections made in 1980. In large part, the modest increase was the result of development of a single aquaculture product, the microalgae spirulina produced by Cyanotech Corporation in Kona, Hawai'i. Approximately 50% of the value of Hawai'i's aquaculture industry in 1994 was the result of this one species filling a specific niche market (Corbin, 1996). According to the latest industry surveys, niche marketing applies to all other major aquaculture products currently produced in Hawai'i (*Tilapia*, Chinese catfish, *Gracilaria*, *Macrobrachium*, and marine shrimp). In contrast to the case with spirulina, however, the markets are restricted to local consumption, targeted to specific ethnic groups, and most profitable only in the short-term for local farmers who are capable of quickly adapting their operations to market demand and fluctuations. An example of the changes in one well-established niche market in Hawai'i is the Chinese catfish, *Clarias fuscus* (Figure 5). From the data presented it is easily seen that the growth of such a niche market is characteristically rapid, attaining a plateau in approximately six years. However, as more farms jump on the bandwagon, the local niche market is quickly saturated. This presents problems when established farmers and newly established farmers compete for the same market. The same scenario is being seen with the production of edible seaweed, *Gracilaria* sp. and *Tilapia*, both of which command the highest profit margins when sold as a fresh and/or live product. All the aforementioned cultured products are currently facing a limited

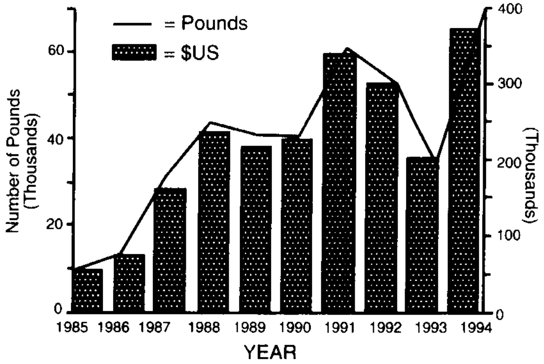


Figure 5. Temporal changes in Chinese catfish, Clarias fuscus, *production in Hawai'i.*

market with increased productivity. While the constraints are easily identifiable, efforts to alleviate impending problems (e.g., development of value added products, extended shelf life, marketing, etc.) often take place when the problem is already impacting the producer. We must learn to anticipate these needs while sufficient response time is still available.

Some of Hawai'i's advantages such as tropical climate and Pacific-rim location are currently capitalized on by a few aquaculture ventures that can be characterized as mass culture technology of early life stages of a cultured product to fill a niche market. Black Pearls, Inc., located in Kona, Hawai'i produces spat for growout. Their target species, the black-lip pearl oyster, *Pinctada margaritifera*, is native to Hawai'i (Walther, 1997) and thus one might expect the culture of it to rapidly become a major activity in the state. Unfortunately, the permit process discourages large-scale culture activities in Hawai'i. Instead, the company exports its spat for growout to Micronesia. Taylor United, a company based in Washington State, operates a hatchery in Hawai'i for year-round production of clam and oyster spat for shipment back to Washington. Since viral diseases have plagued the culture of marine shrimp throughout the world, a well-defined niche market also developed in Hawai'i is the production of specific pathogen free (SPF) broodstock or post-larvae, servicing the U.S.

mainland and abroad. This activity takes advantage of the geographic isolation of the Hawaiian Islands and all the other culture activities mentioned benefit from an established distribution network. But the growout of the shrimp to market size is rather limited, again apparently due to elevated production costs, permitting obstacles, and more recently, disease.

One unanticipated offshoot of the assembling of the expertise needed to develop culture technologies necessary for the growth of the aquaculture industry in Hawai'i is the creation of an aquaculture consulting industry within the state. This industry generally considered part of the service sector "research and technology transfer" is now quite substantial. This particular sector of the industry has steadily increased through a combination of public and private sector development and at present generates more revenue than the production sector (Aquaculture Development Program, 1993). Public institutions (e.g., Anuenue Fisheries Research Station, Hawai'i Institute of Marine Biology, Sea Grant College Program, Sea Grant Extension Service, Department of Environmental Biochemistry), as well as private non-profit groups (e.g., The Oceanic Institute, Oceanit Laboratories) and the private sector, have been relatively successful in obtaining funding from a variety of federal, state and private sources. Interestingly, a significant portion of the demand for these services (consulting, training) comes from out of state and in large part from lesser developed countries such as South America, Southeast Asia, and Micronesia.

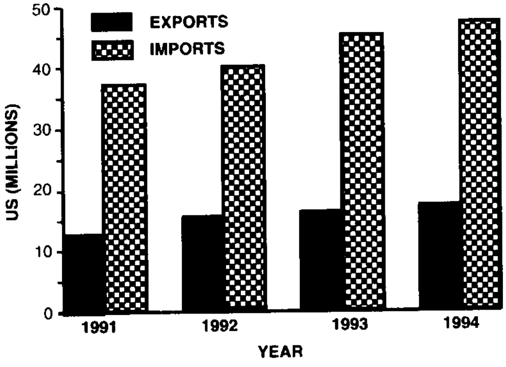
Supporting the expansion and diversification of tropical fish culture in Hawai'i is consistent with Hawai'i's longterm strategy for economic diversification through fostering the development of aquafarms which can produce commercial quantities of various freshwater ornamental fish species. There are specific reasons for the concerted efforts to develop the freshwater ornamental industry in Hawai'i. First is the large market that currently exists on the United States mainland. In 1992, 1,539 fish species imported into the United States were declared as ornamental fishes (Chapman et al., 1997). The volume of fish imported was reported to reach 201 x 10^6 individuals with an estimated value of $US 44.7 x 10^6. Although the total number of imported ornamental fish species is high, only 32 species dominate the numbers imported and a list summarizing the top 20 species is presented. The percentage of the total number of ornamental fish imported into the United States in 1992 is presented in Table 1.

Table 1. Summary of top 20 freshwater ornamental fishes imported into the U.S. in 1992 (data summarized from Chapman et al., 1994).

Common Name	Scientific Name	Percentage of Total Fish Imported (1992)	Number of Individuals Imported (1992) (x 10^6)
Guppy	*Poecilia reticulata*	25.8	51.9
Neon Tetra	*Paracheirodon innesi*	11.3	22.7
Platy	*Xiphophorus maculatus*	5.4	10.9
Siamese fighting fish	*Betta splendens*	2.7	5.4
Goldfish	*Carrasius auratus*	2.4	4.8
Chinese algae-eater	*Gyrinocheilus aymonieri*	2.4	4.8
Shortfinned Molly	*Poecilia sphenops*	2.0	4.0
Cardinal Tetra	*Paracheirodon axelrodi*	1.5	3.0
Glassfish	*Chanda lala*	1.5	3.0
Tiger Barb	*Barbus terazona*	1.3	2.6
Red Oscar	*Astronutus ocellatus*	1.2	2.4
Yucatan Molly	*Poecilia velifera*	1.1	2.2
Redtail Black Shark	*Labeo biocolor*	1.0	2.0
Coolie Loach	*Acanthopthalmus kuhlii*	1.0	2.0
Sucker Catfish	*Hypostomus plecostomus*	0.9	1.8
Harlequin Rasbora	*Rasbora heteromorpha*	0.9	1.8
Angelfish	*Pterophyllum scalare*	0.8	1.6
White-Cloud	*Tanichthys albonubes*	0.5	1.0
Green Corydoras	*Corydoras aeneus*	0.2	0.4
Leopard Corydoras	*Corydoras julii*	0.1	0.2
Total	**20**	**64.0**	**128.6**

All of these are characterized as freshwater species and form the nucleus of the aquarium industry in the United States. In contrast, although the total number of exports of ornamental freshwater fishes from the United States (mainly from Florida) has steadily increased from 1991 to 1994, a trade deficit of approximately $US 30 x 10^6 still remains (U.S. Department of Commerce, 1995). A summary of the changes in exports and imports of ornamental fishes from 1991 to 1994 is summarized in Figure 6. Second, the culture of ornamental fishes appeals to a much broader audience as opposed to the culture of food fish because of the relatively smaller spatial requirements of ornamental fish species. Hawai'i is home to the oldest ornamental fish club in the world whose membership include small-scale commercial breeders with considerable expertise. The outlook, however, must be tempered once again with the realization of the limitations that exist with any agribusiness in Hawai'i (Teichman, 1994).

These constraints clearly dictate that the culture systems for ornamental fishes in Hawai'i will be intensive systems and that growers must employ the latest technologies and keep up with demands for species diversification if they are to be successful. Yet research and development opportunities still abound with the freshwater ornamental fish industry.



Source: Dept. of Commerce

Figure 6. Summary of changes in imports and exports of ornamental fishes in the United States from 1991 through 1994.

A popular view amongst local government officials is that aquaculture should be focused only on stock enhancement purposes. Hawai'i, as with many other regions throughout the world are experiencing diminishing commercial catch of native stocks. The reasons, however, for the decline in fish to catch (overfishing, destruction of nursery habitat, lack of enforcement of established fisheries rules) are often overlooked in the process. While unintentional, this stock enhancement concept divides fishery and aquaculture scientists when in fact they should be working together. Many of the research objectives for development of hatchery technologies of a target species overlap with those of fishery scientists that use the same information to develop management scenarios. Most people lose sight of the fact that money fuels both the fishing and aquaculture industries and these activities are not mutually exclusive.

A case in point is the Pacific threadfin, *Polydactylus sexfilis*, commonly known in Hawai'i as the *moi*. Funding has been acquired through state and federal agencies to develop technologies for the artificial propagation of this species with a moderate degree of success. Currently, production throughout the state is approximately 100,000 lbs./year of cultured *moi* but farmers remain dependent on hatchery-produced seed by government funded institutions. The same institutions that developed the hatchery technologies are also engaged in developing stock enhancement protocols as the *moi* is a highly prized game fish in Hawai'i. Here is where time and energy must be invested in thinking this activity through. Although stock enhancement activities are initiated with good intentions, if conducted improperly they can have negative environmental impacts. Questions that should be asked are: How large is the current fishery? Is it threatened? Why is it threatened? Does stock enhancement of *moi* represent the most cost-effective means of managing the fishery? The first issue regarding the size of the *moi* fishery in Hawai'i can be accomplished by examining the commercial catch records of *moi* throughout the years (Figure 7). From the data presented it can clearly be seen

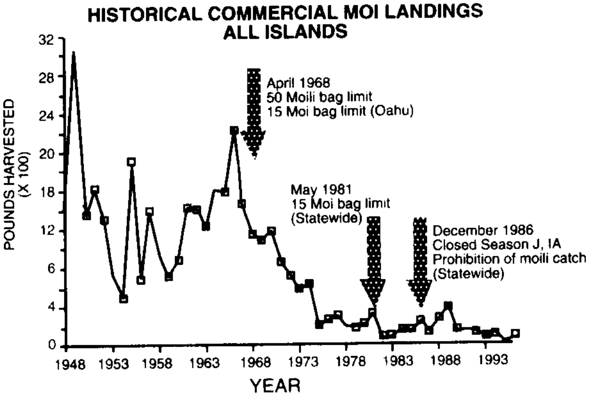


Figure 7. Commercial landings of the Pacific threadfin in Hawai'i between 1948 and 1996. Arrows indicate implementation of fishing restrictions. Source: Division of Aquatic Resources, State of Hawai'i.

that the *moi* fishery in Hawai'i was never a large or even moderate-size fishery, averaging 14,000 lbs./year. It was ranked 30th with the other species caught prior to implementation of restrictions in 1968 to manage the fishery. This was done to address the yearly decline in the presence of juvenile *moi* (*moi li'i*). As this species has always been considered a highly valued food fish, the restrictions on the commercial fishery increased the farmgate price of *moi* to over $5.00/lb. (Figure 8). It is logical to pursue the development and promotion of

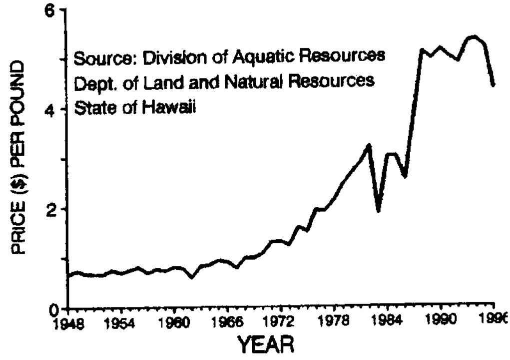


Figure 8. Temporal change in value of commercial landings of the Pacific threadfin in Hawai'i between 1948 and 1996. Source: Division of Aquatic Resources, State of Hawai'i.

aquaculture technologies for the culture of this species as the economics justify the development costs. As with most aquaculture activities, when technical constraints are resolved, culture capabilities attain levels that far exceed natural production in the wild. *Moi* are being cultured in numbers 10 times what was caught commercially back in the "good old days" (prior to 1968). Funding for stock enhancement of this species has been approved on the premise that there are not enough fish to be caught in the wild. There is obviously a contradiction. As pointed out previously, the *moi* fishery was never a very large fishery and there are fishing restrictions in place that limit the capture fishery. The implications based on the commercial landings are that the habitat of the *moi* in Hawaiian waters may be the limiting factor, for the size of the natural stocks were apparently never that large in the first place. Equally as disturbing is that there are no plans even to address investigation of this issue. However, successful lobbying of decision makers has resulted in a considerable amount of funding to be allocated for stock enhancement of *moi* and additional funding for stock enhancement of alternate species has been allocated. With fixed and even diminishing research dollars it is no wonder that fishery scientists and aquaculture scientists often view one another as competitors rather than colleagues.

The Future

While the physical restoration and revitalization of Hawaiian fishponds has begun, an obvious pitfall to the completion of these efforts is the absence of experienced Hawaiian fishpond operators (Henry, 1993) and, in particular, those of the *loko kuapā* style. Along with the demise of the fishpond in Hawai'i, so went the knowledge of maintenance and operation. As with most of Hawaiian history, the knowledge of fishpond operation was passed on from family member to family member or to a chosen few by word of mouth and example. Of the few fishpond operators still living, none have written down their legacy. Efforts to document this knowledge by those outside the family have been a low priority to state government and Hawaiian groups. Some argue that 20th century technology can easily and quickly reclaim this knowledge, but "few people would claim to know as much about how to catch fish as a good full-time fisherman" (Johannes, 1981) and the same can be said for one who grows fish for a livelihood. *Moli'i* Fishpond, a 124.5 acre *loko kuapā* on the windward coast of O'ahu, holds the distinction of being the only continuously commercially operated fishpond in the State of Hawai'i (Pfeiffer et al., 1993). The fishpond has been operated by the Uyemura family for nearly a century. George Uyemura, now age 78, is considered by many to be one of Hawai'i's living treasures. His wealth of knowledge and experience in the maintenance and operation of a *loko kuapā* "in the real old style" is in jeopardy of being lost forever. Efforts still continue to document his knowledge in order to preserve a tradition uniquely Hawaiian and to integrate that knowledge with the ongoing activities to restore and operate Hawaiian fishponds, particularly on the islands of Moloka'i and Maui.

One of the obstacles to revitalizing Hawaiian fishponds is the acquisition of permits. It may be necessary to obtain up to 17 permits (federal, state, and county) prior to reconstruction and repair of a fishpond or even prior to the operation of a pond where the outer wall is still intact. The permit process may take up to three years and cost over $100,000 to complete. One permit, in particular, that has hampered progress during the revitalization efforts requires the characterization of water quality effluent discharge from any type of facility, including aquaculture operations, that releases flow into coastal waters. Federal and state regulatory agencies require documentation of these parameters. The current standards that must be met were established by the federally mandated Clean Water Act of 1977 and fall under the jurisdiction of the State of Hawai'i Department of Health. Traditional Hawaiian fishponds that line the coast of Moloka'i and other islands of Hawai'i are subject to the same stringent regulations. For virtually all potential fishpond operators and pond owners, the process of establishing water quality parameters is both too time consuming and exorbitantly expensive.

Efforts are planned to assess and characterize the variables of water quality, within a pond and discharge effluent in the surrounding waters, of two Hawaiian fishponds currently in use and two ponds that are intact but not in production. In addition, water quality variables will be monitored during the restoration process on two demonstration fishponds that are designated by state government for repair and reconstruction. The data obtained will be used to establish baseline water quality parameters of fishponds. Along with the documentation of the working of a Hawaiian fishpond, this data will be used to develop a best management practice (BMP) plan for the use of traditional Hawaiian fishponds managed in an extensive (traditional) manner and used to preserve a historic aquaculture practice.

While culture technologies for freshwater ornamental fishes are well established in many parts of the world, the marine ornamental fish trade is almost solely dependent on collection of adults and juveniles from the wild. Hawai'i has been a major supplier of marine tropicals in the past. However, impending state legislation proposes to regulate/restrict the industry's main supply (wild stocks) and culturing of marine tropicals is now being considered as a viable alternative. Research and development in this arena can be considered relatively undeveloped in comparison to foodfish species. However, as mentioned previously, a considerable amount of expertise already exists within the state and the service sector is poised to exploit this change in regulatory status of this industry. It should be mentioned that the development of marine ornamental culture practices is not restricted to teleosts but spans several phyla (e.g., giant clams, hard and soft corals, aquatic plants), providing a multitude of research and commercial opportunities.

Continued development of aquaculture products that fill niche markets will remain as a focal point in future aquaculture development in Hawai'i. All of the new initiatives will be making best use of Hawai'i's advantages, such as strategic geographic location, mild climate, established distribution network, and strong core of competent researchers and extension personnel. Future targeted species include the deep water snappers, the freshwater catfish (*Pangasius sutchi*), and carangids that fill the local niche markets but also have potential growth in other areas besides food (ornamental fish trade). Another area that is receiving attention is the possibility of ocean ranching on structures to be located offshore, out of view from the shore or in sections of reef flat partitioned for culture activities. Hawai'i, as an island state, must investigate the aquaculture potential of perhaps its greatest resource, the surrounding sea.

Hawai'i's circumstances, such as limited fresh water, limited resources, increasing population, stagnant economy, strict land use regulations, and the sovereignty movement, might be considered similar to those existing on a global scale. The ruling class of ancient Hawaiians exercised their control in the development of an agricultural complex that stretched from the mountains to the sea (*ahupua'a*) and enforced cultural practices that insured a sufficient amount of resources for their people. The burden of controlling Hawai'i's natural resources is now shouldered by state political leaders, academicians, researchers and the private sector who face a multitude of social and economic issues. How we address these issues during the development of aquaculture in Hawai'i into the 21st century may have greater significance than any of us might predict.

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Concepts for Open Ocean Ranching

Artificial Up-Welling and Creation of Algae Community for Open Ocean Aquaculture

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Japan

For not only coastal aquaculture but also open ocean aquaculture, an urgent task today is to improve habitable environments and to develop related technologies that pay due consideration to the ecological systems of marine organisms.

Especially, creation of artificial seaweed communities is considered very important, as is the forestation of mountains, in that the formation of seaweed communities provides new habitable environments for marine organisms.

This paper describes a technology for artificially cultivating seaweed which was tested in Japan, and the effect that this technology had on the improvement of habitable environment and, at the same time, a concept that was combined with the above algae cultivating technology and artificial upwelling structure will be discussed for open ocean aquaculture of the next generation.

Technology for Creating Seaweed Communities Using Ferrous Sulfate

In coastal areas, concrete is used as a structural material in the construction of ports and harbors, breakwaters, revetments and many other marine structures. Once concrete structures are submerged in seawater, calcium hydroxide ($Ca(OH)_2$) liquates out from the concrete and reacts with the carbon dioxide in seawater to produce calcium carbonate. Because calcium carbonate is strongly alkaline, it converts the surrounding water area into a strongly alkaline region with pH of 10-11 for seawater and 13 for fresh water. In order for aquatic creatures and vegetation to survive, a natural environment suitable for each organism is required. To provide such suitable environments, the "Standard for Fisheries' Water" is stipulated in Japan as the standard for the habitable environment of aquatic life, according to which the standard pH value should be 7.8~8.4 for sea areas and 6.7~7.5 for rivers, lakes and marshes. When the calcium hydroxide liquated out from concrete converts the standard pH of these water areas to strongly alkaline values, not only are certain impediments placed on the growth of the benthoses that live their larval and fry stages in the sea areas. The ecological system of the aquatic animals and plants that have their habitats in such areas is also greatly affected.

To solve these problems, a technology has been developed (Tetsuo Suzuki in 1986), which prevents the liquating-out of calcium hydroxide from concrete structures and at the same time forms a coating of iron compounds, especially ferrous sulfate, on the surfaces of the concrete. This is important because iron is an essential element for the biological oxygen reduction of all organisms.

There are two methods to form this coating: 1) the formation of an osmosis coating through hydration reaction between ferrous sulfate and concrete, and 2) the application of ferrous sulfate as a coating material. Photo 1 shows the process by which a ferrous sulfate coat is formed on a concrete surface. In this process, strips of water-soluble plastic film (PVA film) affixed with ferrous sulfate crystals are lined inside the forms used to make concrete wave-dispersion blocks. Concrete is then poured into the form which is removed after the concrete is cured, thus forming the coating on the blocks.

The major characteristic of concrete blocks coated with

Photo 1. Concrete block transformed with ferrous sulfate.

ferrous sulfate may be cited as follows:

1) It is possible to prevent the inherently strong alkaline composition of concrete to liquate out.
2) Iron, as a trace-quantity nutrient necessary for organisms, is supplied.
3) Since the ferrous sulfate coating on the concrete surface, which is formed through a transformation of the concrete surface property itself, is semi-permanent, no particular maintenance work is required.
4) The concrete structure thus manufactured can promote adhesion for seaweed by providing raggedness with its surface.
5) The process for forming the ferrous sulfate coat can easily be applied to large structures regardless of configuration.

Experiments were made at the practical sea field concerning what changes are observed in the adherence of seaweed, employing two kinds of concrete blocks — one having a ferrous sulfate coating and the other manufactured without the use of ferrous sulfate, and the effects of ferrous sulfate on the seaweed adherence were discussed.

Method of Experiment and Results

Since 1981, many experiments have been conducted in different places in Japan and good results were observed in most cases. In this paper, typical examples and their results, as well as application to lobster reefs, will be described.

Experiment at the Kochi Prefecture

Experiments were carried out at Yasucho Tei, Kamigun, Kochi Prefecture, in January 1984, in which 10-ton trapezoidal concrete blocks – some coated with ferrous sulfate and others uncoated – were submerged in water 8 m deep. Survey on marine organisms were conducted by Prof. M. Ohno of the Kochi University (1992 Ohno).

It was found that diatoms began to adhere to the blocks coated with ferrous sulfate (Fe block) one month after submersion. The diatoms then turned to brown, and two months later filamentous entromorpha had grown to 1-2 cm high. On the other hand, it was found that diatoms began to adhere to the uncoated blocks (not coated with ferrous sulfate) two months after their adherence to the Fe blocks.

The transition in seaweed adhesion to the Fe blocks showed a seasonal shift in the formation of the plant community from calpomenia sinuasa of brown algae to zonaria diestingiana, as seen in Table 1. The kinds of seaweed that adhered to the uncoated blocks was similar to those on the Fe blocks, but their growth tended to be delayed and the extent of their growth was less.

Entering autumn, there were certain changes in the kinds of seaweed that adhered: seedings of padia arborescens of brown algae and sp. siiliquastrum of sargassum were confirmed on both types of blocks. Seedings of ecklonia cava on the Fe blocks were further confirmed. In autumn, brown algae grew remarkably, and at the same time the amount of growth increased. The amount adhering to the Fe block was larger, but the kinds of seaweed that adhered showed the same patterns for both kinds of blocks. Two years and four months later (June 13, 1986), large-size brown algae of the perennial type, such as sargassum, had adhered to both the Fe and uncoated blocks. Table 2 shows a comparison in marine plant growth between these two block specimens. The dominant species adhering to the Fe blocks included ecklonia cava, surgassum tortile, padia arborescens and agar-agar. On the uncoated blocks, similar plants adhered, but the amount was larger for Fe blocks than the uncoated blocks.

Table 1. Early period changes in the growth of algae on the Tei test block.

	Fe Coated Block											Concrete Block										
	4	5	6	7	9	10	11	12	1	2	3	4	5	6	7	9	10	11	12	1	2	3
Enteromorpha intestinalis	·	·							·													
Baronia							·															
Cladophora sp.			·	•	·	·	·	·	·		·			·	·	·	·	·	·	·		•
Bryopsis plumosa						·																
Monostroma nitidumw																				·		
Ulva Japonica													·					·				
Ectocarpus siliculosus		·											·	·								
Shpacclaria sp.			•	·	·	•			·					•	·	·	·	•	•	•	•	•
Dictyota dichotoma						•	·										·			·		
Dictyopteris plifera		·		·					·											·	·	
Zonaria diestingiana		·	•	•	•	•	•		·					·					·	·	·	·
Padia arborescens						·	•	●	⬤	⬤	⬤						·	•	•	•	●	⬤
Calpomenia sinuasa	●	•	•									•	•									
Sargassum tortile					•	·	•	•	•	•	•					·	•	•	•	•	•	•
Ecklonia cava				·					·	·	·											
Pachydictyon coriaccum																					•	
Sargassum okamurae																					·	
Gelidium pusillum				•	·																	
Gelidium amansii											•										·	
Pterocladia capilacea							·	·			•									·		
Peyssonclia caulifera						·																
Lithothamnium cystocarpideum				·																		
Amphiroa dilatata				·		·	·	·	·	·	·				·		·	·	·	·	·	·
Corallium pilulifera							·										·	·	·	·	·	·
Jania sp.				•	·	•	·	●	●	●	•				·		·	•	•	•	•	·
Plocamium telfaria							·															
Hypnia chariodes				·	·	·	·								·	·	·					
Tylotus lichenoides						·																
Champia parvula				·			·	·	·	·	·				·				·	·		
Wrangelia japonica			·	·		·	·										·					
Spyridia filamentosa				·											·							
Ceramium sp.			·	·	·	·				·					·	·	·					
Congregatocarpus pacificus						·		·	·								·					
Heterosiphonia sp.				·																		
Polysiphonia sp.				·	·	·	·		·	·					·	·	·	·	·			
Laurensia sp.				·	·	·	·		·	·	·						·	·	·			
Symphyocladia marchantioides						·	·		·								·					
Herposiphonia tenella		·	·	·	·	·	·		·							·	·	·	·			
Ulvaia obscura						·												·				
Lomentaria catenata																						·

·	•	●	⬤	⬤
10 g/m^2	10-50 g/m^2	50-100 g/m^2	101-500 g/m^2	50- g/m^2

Table 2. The algae growth two years and four months after being submerged.

Location	Fe Coated Concrete Block				Concrete Block				
	Upper		Side		Upper		Side		
Name	1	2	Upper Surface	Below Surface	1	2	Upper Surface	Below Surface	
Ulva perutusa			0.9				0.5		+
Enteromorpha intestinalis									
Cladophora ohkuboana			+		0.1				+
Cladophora sp.						+			
Cheatomorpha sp.						0.3			+
Codium adhaerens									+
									+
Sphaecclaria sp.	+						+		+
Dictyota dichotoma									+
Dictyopteris prolifera	5.6		1.2	0.4			16.3	4.8	+
Zonaria diestingiana			3.4	2.2			2.3		+
Pockockillavariegata									+
Padia arborescens	1,040.8	485.6	1,340.0	445.2	615.0	1,398.4	1,865.6	770.0	+
Ecklonia cava	1,382.8	864.4		212.0	246.4		183.6	31.2	+
S. patens							73.2		+
Sargassum tortile	52.0		1,751.6	1,355.2		46.8	790.5	342.8	+
Sargassum okamurae			9.4	0.8	2.6	102.8		6.4	+
S. tortile		3.2			297.6	38.0	141.2		
									+
Actinotirchia fragila				0.1					+
Galaxaura fastigiata			11.1						+
G. falcata									+
Gelidium amansii	25.6		15.1	52.0	10.8	0.7	5.0	11.3	+
G. pacificum	25.6	37.2		15.8		2.6			+
Beckerella subcoasttata									+
Pterocladia capilacca	28.0	23.2	7.9	9.8	11.8	6.7	8.2	16.1	+
Chondrococcus japonica									+
Peyssonclia caulifera									+
Peyssonellia									+
Posliella sp.	+	+	+	+	+	+	+	+	+
Amphiroa zonata	3.6	2.8	14.0	12.3	5.6	6.5	3.6	0.9	+
A. dilatata						1.1		0.3	+
Marginisporum aberrans			5.0	16.0	4.6		3.0	5.8	+
M. crassisimum									+
A. dilatata sp.	1.2	1.6		1.3	12.8	4.4	1.2		+
corallium pilulifera		6.0	4.4	0.02		9.1	5.8	2.9	+
Jania decussato-dichotoma			0.5		0.4	2.2			+
Carpopeltis angusta									+
Carpopeltis angusta sp.	2.0								+
Plocamium telfaria		0.1			0.4	1.9	3.6		+
Hypnia chariodes					66.7				+
Hypnia chariodes sp.		0.2							+
Gymnogongus flahelliformis						2.4			+
Gogartina intermedia						11.0			+
Chondrus occellatus				0.6	5.8				+
Champia parvula			6.6	0.1		0.3			+
Centroceros elavulatum						+			+
Microcladia elegans	+								+
Ceramium sp.		–		+	+	+		+	+
Nitophyllum sp.	+				+				+
Martensisia denticulata									+
Laurensia sp.		21.2	0.1	0.7		1.2	8.8		+
Total	2,567.2	1,445.5	3,171.2	2,124.7	1,220.6	1,636.4	3,112.4	1,182.5	

Experiments at the Kanagawa Prefecture

(1) Concrete block installation site and method:

A total of 14 X-shaped concrete blocks, weighing 40 tons each, were submerged in water 6-7 m deep off Enoura and Miyukigahama in Nebugawa, Odawara City, Kanagawa Prefecture in November 1993 (Fisheries Research Institute of Kanagawa Pref. 1995). As shown in Table 3, the surface of each block was processed in one of following ways: 1) lattice shaped, 2) lateral-strip shaped, 3) broken-stone embedded, 4) not processed and 5) ferrous sulfate coated. Both ferrous sulfate coated and uncoated blocks were prepared. These experimental blocks were first submerged in November 1993 in the sea area where seaweed grows in order for seaweed to adhere and grow on the concrete blocks. Then, in December 1994, these blocks were transferred to an underwater experimental site at Miyukigahama, and discussions were made on seaweed growth conditions and the effects on the gathering of aquatic creatures after the transfer.

Blocks were submerged in fiscal 1994		
Block No.	Surface processing	Ferrous-sulfate coating (O)
1	Lattice shaped	O
2	Lattice shaped	—
3	Lateral-strip shaped	O
4	Lateral-strip shaped	—
5	Broken-stone embedded	O
6	Broken-stone embedded	—
7	Not processed	O
8	Not processed	O
9	Not processed	—
10	Not processed	—
11	Not processed	—
12	Ferrous-sulfate coated	—
13	Ferrous-sulfate coated	—
14	Ferrous-sulfate coated	—

Table 3. Surface Processing of the Concrete Box.

(2) Seaweed adherence conditions by visual observation:

Table 4 shows the monthly adherence area (%) for the seaweed and the number of kinds that adhered on the surface of each block, and Figure 1 shows the seasonal changes in the quantity that adhered and tangle length of ecklonia cava grown on the blocks.

The number of kinds of seaweed that adhered was small — one or two — in December 1993 after two months of submersion, but it increased from January 1994 to record 11 at maximum (average for 14 blocks) by April. When observing the effect of surface processing and ferrous sulfate on the seaweed adherence, there was a difference in the number of kinds for each block by around May to June, and after June the trend was that the number of kinds was small for the ferrous-sulfate coated block and for the lattice shaped and lateral-strip shaped blocks coated with ferrous sulfate. The cause for such seaweed adherence conditions is considered to be attributable to the fact that the ratio of coverage of the block surface with ecklonia cava was extremely high during summer and thus sunlight was cut off by the ecklonia cava to arrest the growth of the weeds below the ecklonia cava.

After transferring the blocks to Miyukigahama, follow-up surveys were made on four of the 14 blocks. Compared to the adherence level before transfer, the number of kinds that adhered was small — two — for the ferrous-sulfate coated block and no difference in the number of kinds was observed for other blocks between 1993 and 1994. The adherence ratio stood at less than 5% to 15% by January 1994 but increased from February to show more than 80% for almost all blocks in April to September. When examining the emergence conditions of common seaweed, the adherence ratio of ecklonia cava was high on the ferrous-sulfate coated block and then on the lateral-strip and broken-stone embedded blocks on which ferrous sulfate was coated. On the ferrous-sulfate uncoated and not processed blocks, the adherence ratio of ulva pertuna was high while that of ecklonia cava tended to show a lower level.

Table 4. Conditions of emerging algae

(Blocks were submerged in October 1993.) Number of kinds that adhered (adherence area in %)

Block No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Surface processing	Lattice shaped	Lattice shaped	Lateral-strip shaped	Lateral-strip shaped	Broken-stone em-bedded	Broken-stone em-bedded	Not process-ed	Not process-ed	Not process-ed	Not process-ed	Not process-ed	Ferrous-sulfate coated	Ferrous-sulfate coated	Ferrous-sulfate coated	Average
$FeSO_4 \cdot 7H_2O$	m	—	m	—	m	—	m	m	—	—	—				
Dec. 1993		1 (0)									2 (0)		1 (0)	2 (0)	0.4 (0)
Jan. 1994	7 (0)	7 (0)	8 (0)	5 (0)	5 (5)	9 (10)	7 (0)	6 (0)	6 (0)	7 (0)	7 (5)	6 (0)	8 (15)	7 (5)	6.8 (3)
Feb. 1994	10 (60)	11 (30)	10 (50)	10 (20)	10 (35)	10 (20)	10 (25)	10 (20)	9 (0)	9 (10)	9 (10)	9 (50)	9 (45)	10 (60)	9.7(31)
Mar. 1994	8 (70)	8 (60)	8 (90)	8 (40)	7 (70)	8 (60)	7 (60).	7 (50)	7 (30)	6 (40)	6 (50)	7 (90)	7 (80)	7 (100)	7.2 (64)
Apr. 1994	11 (80)	13 (70)	12 (90)	12 (70)	12 (90)	12 (80)	10 (80)	10 (80)	9 (50)	11 (60)	9 (70)	12 (105)	10 (90)	11 (95)	11.0 (79)
May 1994	9 (80)	9 (70)	9 (80)	5 (90)	8 (80)	10 (90)	9 (70)	10 (70)	10 (90)	9 (70)	7 (90)	7 (90)	7 (90)	9 (90)	8.4 (82)
June 1994	6 (90)	9 (80)	4 (100)	6 (75)	9 (80)	9 (80)	9 (80)	7 (100)	10 (80)	8 (50)	7 (70)	3 (90)	3 (90)	3 (90)	6.6 (83)
July 1994	3 (80)	4 (60)	3 (90)	8 (80)	5 (100)	6 (70)	5 (90)	6 (90)	6 (80)	5 (60)	6 (70)	3 (100)	3 (90)	3 (100)	4.7 (84)
Aug. 1994	3 (80)	5 (70)	3 (90)	8 (80)	5 (90)	6 (70)	5 (70)	6 (100)	6 (80)	5 (70)	6 (80)	3 (100)	4 (80)	3 (100)	4.9 (83)
Sept. 1994	* (80)	* (80)	* (80)	* (60)	* (70)	* (70)	* (60)	* (70)	* (40)	* (50)	* (30)	* (90)	* (90)	* (90)	* (69)
Oct. 1994	6 (80)	7 (70)	7 (70)	7 (90)	5 (90)	4 (70)	5 (60)	6 (80)	7 (50)	6 (60)	8 (50)	4 (80)	1 (80)	3 (80)	5.4 (72)
Nov. 1994	2 (60)	5 (50)	7 (80)	6 (70)	5 (80)	8 (30)	5 (20)	5 (50)	6 (30)	7 (50)	8 (80)	3 (60)	3 (50)	3 (20)	5.2 (52)
Dec. 1994	Blocks were transferred to an underwater experimental site at Miyukigahama.														
Jan. 1995		6 (60)	7 (50)									8 (80)	7 (30)		7.5 (55)
Feb. 1995		10 (100)	10 (100)									9 (110)	11 (100)		10.0 (108)
Mar. 1995		7 (100)	7 (80)									2 (100)	10 (120)		6.5 (100)

Notes:

1) Because of bad seawater transparency, observation of only ecklonia cava was conducted in September 1994.

2) The kinds and adherence areas of theca-state seaweed (posliella sp. and peyssonelia) and micro-seaweed (sphacelaria sp.) are excluded from the table.

3) An adherence area of 0% indicates a value less than 5%.

When observing changes in the quantity of seaweed, the quantity that adhered was large for the ferrous-sulfate coated and processed blocks and the ferrous-sulfate coated blocks in the period from February to April. Accordingly, it is considered that these facts show the effectiveness of ferrous sulfate in the adherence of ecklonia cava. However, the density of seaweed brought about by their steady growth since August had become uniform and the difference in the amount that adhered by block had thus become small. The maximum length of tangles reached 70 cm in August to September, and the growth of tangles by block showed the tendency toward longer tangles in the broken-stone embedded blocks on which ferrous-sulfate was coated and ferrous-sulfate coated blocks.

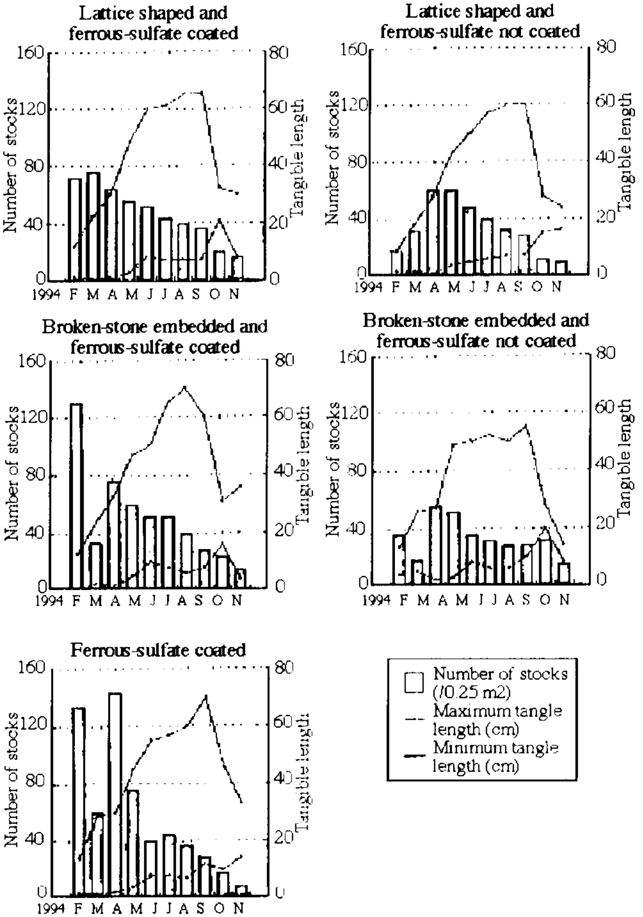

Figure 1. Seasonal changes in the quantity (number of stocks) and tangel length of ecklonia cava.

As stated above, it was confirmed that the concrete blocks whose surface properties were transformed by the use of ferrous sulfate were more effective in causing the adherence and breeding of seaweed.

Application in lobster reefs:

Next, examples of experiments conducted on blocks coated with ferrous sulfate for use in breeding lobsters is introduced below.

Generally, lobsters grow by consuming fishery products and fishery products grow by consuming seaweed (lobsters are eaten by octopuses) — thereby establishing a food chain.

The blocks for use in these experiments were submerged in water 12.5 m deep, 2,300 m off Kogachi, Agocho, Shimagun, Mie Prefecture on November 12, 1983 (Tetsuo Suzuki, 1993). Figure 2 shows the configuration of the submerged blocks. The seabed around the blocks was covered with sand, debris and boulders, where only siiliquastrum, ecklonia cava, gelidium amansii and other seaweed grew naturally.

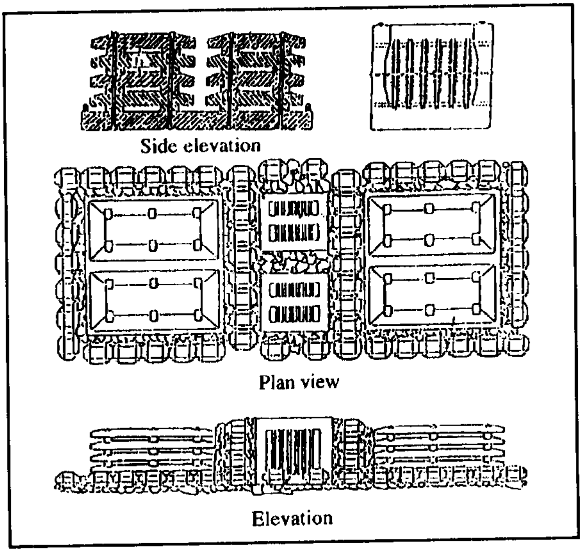

Figure 2. Block arrangement for lobster habitats.

In the surveys made the day after submersion of the blocks, 70 fish comprising six varieties were observed around the blocks. Every year since then, follow-up surveys have been conducted, with the first one showing that ecklonia cava communities had formed on the blocks one year after submersion. Along with this, lobster fry were stocked among the blocks, and surveys were made on the growth conditions by implementing trace stocking as the fry grew. After the lapse of about three years, a new ecological system of seaweed — fish and fishery products — lobsters had formed in the area centering on the submerged blocks. In the surveys conducted in September 1993, the growth of innumerable fishery products and lobsters was confirmed, fully proving the effectiveness of Fe blocks in the breeding of seaweed as well as lobsters.

Technology for Artificial Upwelling in Japan

It is known that nearly 100 times more fish can be produced in an upwelling area (Ryther 1969). In Japan, since 1986, research on artificial upwelling has been carried out and actual size of experiment was conducted at Toyama Bay through 1989 to 1990.

As can be seen in Figure 3, recent research using six sets of cement concrete wall stands with 10 m in height and 20 m in width on a shallow ocean floor with a depth of ca 30 m was conducted by the Marino Forum 21 and Ehime Prefecture and its upwelling effects of surface water was evaluated. Those six wall stands were set on a line within 190 m in perpendicular to 29.4 degree east from north, and there were six small wall stands of 10 m high and 10 m wide in both sides of the wall line about 35 m away from the main wall. After setting the wall stands, tidal current speed was increased about 20% in the area, vertical mixing velocity increased about 60.5, nutrient concentrations in the euphotic zone increased 2-4 times compared with background condition without the wall stands, chlorophyll concentrations increased 2-3 times as well as significant increases of zooplankton biomass and settling materials to the bottom (Yanagi and Nakajima, 1991: Imamura and Suzuki, 1993). Test catch of fishes was at least 142 Kg

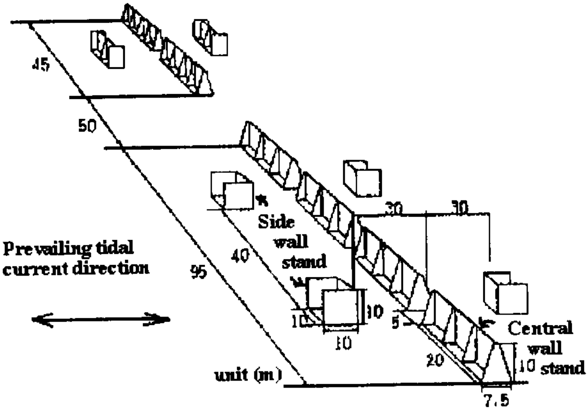

Figure 3. Size and structure of wall stands for upwelling.

(fresh weight)/Km^2/year in the area of 24 Km^2 within a few years after the wall stands were set (Nakamura, 1993). The success of this experiment encourages the idea of upwelling by constructing man-made structure at the sea bottom.

Nutrient rich water is also good for growth of algae. So, when we think about next generation type of open ocean aquaculture, in combination with artificial upwelling and algae cultivating technology which was mentioned in this paper, there might be a great opportunity to newly create a habitable environment for fish and marine organisms.

Conclusion

The creation of artificial seaweed communities is deemed very important, as is the afforestation of mountains, in that the formation of seaweed communities provides new habitable environments for marine organisms. Presently, the areas where green, brown and red algae, called seaweed, can grow are said to account for 3% of the world's total sea area, and it is estimated that in only 0.3% of this 3% can vegetation be observed.

On the other hand, there is a large stock of nutrients in suitable proportion for plant use in the subsurface water below ca 100 m in the world ocean, surface water of the ocean can then be fertilized if the subsurface water is lifted up to the euphotic zone.

In this paper, experimental results, both artificial cultivation of algae and upwelling structure, were introduced.

The author strongly believes that combination system of these technologies gives us new ideas and possibilities for developing the next generation type of open ocean aquaculture.

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Open Ocean Mariculture with Nutrient-Rich Deep Ocean Water

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Abstract

Researchers at the University of Hawaii at Manoa have been engaged in the study of artificial upwelling and mixing (AUMIX), a new technology essential for the realization of the idea of open ocean mariculture using nutrient-rich deep ocean water (DOW). A complete realization of an open ocean aquaculture with deep ocean water requires technological advances in physical oceanography, ocean engineering, and marine biology. A wave-driven artificial upwelling device has been developed on the basis of mathematical modeling and a series of hydraulic laboratory experiments. Performance of this device was tested by a field experiment conducted in ocean waters off the southern coast of Oahu, Hawaii. Further research and development in the area of DOW plume mixing in the ambient ocean and the DOW-enhanced marine productivity are anticipated.

Introduction

Many of the world's fishery resources are presently over exploited and in a state of decline. This is happening in a period when the world population continues to increase. Increase in fishery yields will require better management at both national and international levels. Also necessary will be the development of new technologies such as stock enhancement to restore many of these resources. A technology that could enhance fishery resources is the application of deep ocean water (DOW) to the surface through artificial upwelling to enhance food webs. With the exposure of these relatively high nutrient waters in sufficient volumes to sunlight and surface residing communities, local increase in production may be possible.

Land-based aquaculture using deep ocean water pumped from the ocean depths into man-made ponds and enclosures has been in existence for more than a decade. It has been conducted on an experimental basis in the U.S. Virgin Islands, and on a commercial basis at the Natural Energy Laboratory of Hawaii (Daniel, 1984) and at Kochi Artificial Upwelling Laboratory in Japan (Nakashima et al., 1989). These land-based aquaculture enterprises have used DOW for growing algae at the base of the food web (kelp, *Gracilaria* and *Spirulina*) as well as in the aquaculture of primary herbivores (e.g., abalone) for commercially successful ventures in Hawaii.

However, land-based aquaculture is small in scale: providing adequate food supply for the world's increasing population requires a large-scale development of open ocean mariculture. Increasing fish production in the ocean enriched by DOW can occur through either increased primary productivity or a shortening of the food chain. A very important aspect to this enhancement is undertaking the effort at a sufficiently large scale to allow meaningful surface enhancement to occur. Theoretically, the larger the scale of enhancement, the longer and more complex the enhanced food web will become. Preliminary experiments in Japan have demonstrated the viability of combining artificial reef and fish aggregation devices with deflectors that alter current flow and cause upwelling which attracts fishes as well as enhances local productivity in shallow waters (Grove et al., 1989).

One of the major deterrents to a large-scale development of open ocean mariculture has been the energy costs associated with artificial upwelling. The objective of the first phase research is to develop a wave pump which brings DOW cost-effectively to the surface.

Development of a Wave-driven Artificial Upwelling Device

Wave-driven artificial upwelling, which converts the wave power to the kinetic energy of upwelled DOW, can be achieved by a device shown in Figure 1. As the wave crest approaches, the flow-controlling valve of the device is closed and the water column inside the device rises together with the device. As the wave descends, however, the valve is open and the water column inside the device continues its upward movement due to inertia. Therefore, when a device moves up and down in the ambient waves, the water column inside the device keeps moving upward thus bringing the DOW to the surface.

The performance of the device can be evaluated by a set of mathematical equations which describe the simultaneous movement of the water column inside the device and the device itself.

When the valve is closed, the velocity of the water column relative to the device is zero or,

$$U = 0 \tag{1}$$

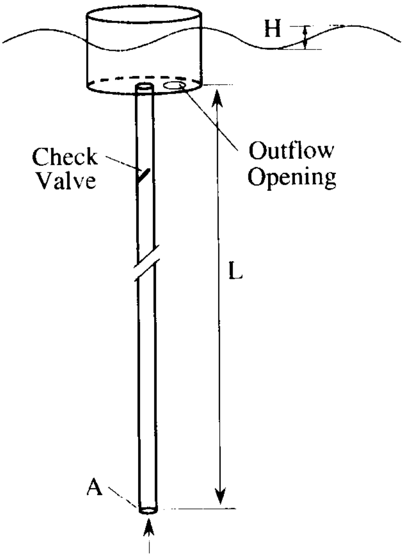

Figure 1. Wave-driven artificial upwelling.

Under this condition, the equation of motion of the device takes the following form:

$$(m+m_w)\ddot{z} = -m_a\ddot{z} - b\dot{z} - \beta|\dot{z}|\dot{z} - \rho g S_w z + F_e \qquad (2)$$

where $\mathbf{m_w}$ is the mass of the water in the pipe; **z** is the displacement of the heave of the buoy above still water line; **m** is the mass of the floating system; $\mathbf{F_e}$ is the wave exciting force in the vertical direction.

When the valve is open, the relative acceleration of the water column to the device can be determined by:

$$\dot{U}+\ddot{z}+\frac{z+h}{L+h}g = 0 \qquad (3)$$

In deriving Eq (3) the dynamic pressure produced by surface waves is ignored.

The equation of motion of the device when the valve is open takes the form of:

$$m\ddot{z} = -m_a\ddot{z} - b\dot{z} - \beta|\dot{z}|\dot{z} - \beta' U^2 - \rho g S_w z + F_e \qquad (4)$$

Eq (2) and Eq (4) are similar except that in Eq (4) only the mass of the floating system is considered, and in Eq (4) the viscous effect due to relative movement of the water inside the pipe is included.

The added mass $\mathbf{m_a}$, damping coefficient **b**, and exciting force $\mathbf{F_e}$ are important parameters describing the wave and device interaction. The exciting force indicates the magnitude of external force acting on the device and is a function of incident waves. The added mass and damping coefficient indicate the extent of resistance and are functions of device design, i.e., the dimensions of the device, tail pipe length, etc.

According to the three-dimensional linear wave theory, values of added mass, damping coefficient and exciting force can be determined by integration of velocity potentials over wetted surfaces (Faltinsen and Michelsen, 1974).

The modeling equations, along with known added mass, damping coefficient, and exciting force constitute a general mathematical model of wave-driven artificial upwelling. A computer program was prepared to solve the modeling equations numerically by a Runge-Kutta method (Liu and Jin, 1995).

Various device designs were considered and evaluated by mathematical modeling and by a series of hydraulic experiments which were conducted in a wave basin at the Oceanographic Engineering Laboratory of the University of Hawaii testing (Chen, Liu and Guo, 1995). The final design of the device selected consists of two principle parts; (1) a buoy with a water tank of 4.0 m in diameter and (2) a long tail pipe with flow controlling valves 300 m long and 1.2 m in diameter. This device can produce an upwelling flow of 0.95 m^3/sec in random Hawaiian waves (Liu and Jin, 1995).

A simple predictive equation for a quick estimation of the rate of upwelling flow was formulated based on the dynamic consideration of the movement of the water column relative to the movement of the device. This simple equation takes the following form:

$$Q = \frac{\alpha A H}{T} (1 + \beta) \tag{5}$$

Where Q is the rate of upwelling flow; A is the cross section area of the tail pipe; H and T are the wave height and period; α and β are empirical constants.

The empirical constants α and β can be determined using hydraulic experiments and mathematical modeling. The coefficient a represents the ratio of the oscillation displacement of the device to the wave amplitude. It approaches 1 when the wave period is large and the device nearly follows the wave motion. However, for ordinary wave periods of 8 to 12 seconds, mathematical modeling suggests that α is about 1.5. Wave period and the length of the tail pipe determine the values of β, or β = *f* (T, L). When the wave period ranges from 8 to 12 seconds and the tail pipe length ranges from 150 m to 350 m, the coefficient β can be determined by:

$$\beta = \frac{17}{T} \left[1 - \exp\left(-\frac{100}{L}\right)\right] \tag{6}$$

Field Testing

A wave-driven artificial upwelling device was designed and constructed in the Hydraulic Modeling Laboratory of the Department of Civil Engineering, University of Hawaii at Manoa (Figure 1). It is a 1/10 model of the full size device. The buoy, made of a syntactic foam, is a 40-inch diameter vertical cylinder with a height of 20 inches. The center of the buoy is hollow with a 20-inch diameter cylindrical water chamber. The top and bottom of the buoy are reinforced with sheets of 0.75-inch thick marine plywood. The cylindrical water chamber extends from the lower plywood sheet to the upper plywood sheet. The center of the upper sheet has a 16-inch diameter hole for ventilation. A 2-inch outflow pipe, made of plastic, is 10 inches above the lower sheet. The entire buoy is held together with eight 5/16 inch threaded rods which extend from the bottom sheet to above the top sheet. The entire buoy, excluding the tail pipe, weights about 90 pounds when wet.

A 4-inch diameter PVC tail pipe protrudes from the bottom of the buoy. The pipe is connected to the lower plywood sheet by a bolted flange. The flow-controlling valve is a rising stem type and is constructed of light-weight materials to allow the valve to open and shut with minimum of force. The end of the stem is threaded to allow weight to be easily added or subtracted from the valve stem so that the performance of the valve can be adjusted during field operation. The tail pipe is made of five 20-foot sections, which are connected together by threaded couples. Each pipe section weights about 90 pounds. The bottom three feet of the last tail pipe section is made of steel to provide a stabilizing weight.

The field experiment was conducted on July 20, 1996. The buoy and tail pipe sections were transported from the Holmes Hall of the University of Hawai'i to the Ala Wai Boat Harbor by a cargo van, and then manually loaded on a 43-foot vessel *Una Mara*. The vessel has a flush deck with no cabin which is ideal for this experiment. The first two tail pipe sections were connected to the buoy before leaving the dock.

The vessel was then sailed to the test site located approximately one mile off the south coast of Oahu.

The buoy with initial 40-foot tail pipe was placed in the water first, while the end of this pipe was kept in the boat. The remaining three 20-foot pipe sections were then screwed on and were fed out until only the end section was on the boat. The last steel section of the pipe was then screwed on. At this time a retrieval rope was attached and the end section was placed in the water and allowed to sink.

During the experiment, ocean waves were three feet high and choppy. The smallest weight available was first attached to the flow-controlling valve. As soon as the buoy was deployed, it started to pump water. Therefore, the weight on the stem of the valve was not modified again. A fluorescent dye was released to measure the rate of upwelling flow produced by this device. This was accomplished by a scuba diver who descended to the lower end of the tail pipe and released a dye packet. The rate of upwelling flow can be estimated in terms of the time required for the dye to travel through the entire length of the tail pipe. The experimental data showed that the dye traveled through a 80-foot section of the tail pipe in 50 seconds, or an average upward flow velocity of 1.6 feet per second. This corresponds to an upwelling flow of about 0.14 cubic feet per second (cfs), which is very close to the value of 0.11 cfs as calculated by Eq (5).

Conclusion

Mathematical and hydraulic modeling experiments indicate that a wave-driven artificial upwelling device consisting of a buoy with a water chamber of 4.0 m in diameter and a tail pipe with flow controlling valves of 300 m long and 1.2 m in diameter can produce an upwelling flow of 0.95 m^3/sec in typical ocean waves off the Hawaiian Islands.

A predictive equation was derived based on mathematical and hydraulic modeling analysis. It calculates the rates of flow rate produced by the wave-driven artificial upwelling device with different dimensions and under different ambient wave conditions. A preliminary field testing has shown the viability of this predictive equation as an engineering design tool.

Further research efforts will be made in the following areas: (1) the design of DOW effluent diffusers based on a better understanding of the transport and mixing characteristics of DOW plume in the open ocean, (2) experimental and field investigations to determine both pelagic and shallow benthic community responses to the addition of DOW, (3) the development of an ocean ecosystems model of upwelling mariculture, and (4) field implementation of the deep ocean water (DOW)-enhanced open ocean mariculture.

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Farming the Ocean

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"It is clear that the return to the world from the success of this endeavor leading to the farming of selected portions of the almost three-quarters of the earth covered by the oceans, will be great indeed."

Executive Summary

Ocean Farming is the modification of the ocean surface by the addition of nutrients to greatly enhance the productivity of the resource. When applied to large areas of the barren tropical seas, ocean farming can increase the phytoplankton, the base of the food chain, bringing the productivity up to the level that occurs naturally off of the coast of Peru. This can result in an increase in fish catch by a factor of 400 or more. A 53,000 square mile ocean area might see the fish catch go to 50 million tons per year. The carbon dioxide absorbed initially could exceed the production by the United States from the burning of fossil fuels. While the concept of farming is well accepted on land the extension to the ocean is new. It requires the investment in the resource to increase productivity so the "commons" approach which has been the tradition in the ocean fisheries does not suffice. A measure of private property rights are needed, at least within the national exclusive economic zone (EEZ) of the host states.

U.S. Governmental interest so far has been minimal. Other governments have found it difficult to step up and say "yes" to these activities in their jurisdiction. Environmental regulators consider adding anything to the ocean "dumping," in which case overriding advantage must be available to move forward. Small tropical Pacific island nations with large EEZ areas have been the most welcoming of all possible host states. Therefore, we intend to concentrate initial commercialization efforts in those areas.

The response of much of the oceanographic community has been negative, but after careful study some key oceanographers have endorsed the validity of the project. Some are on our Advisory Board or have consulting contracts with us. At this point, initial seed capital has been raised, a fertilizer system developed and laboratory testing is underway. Open ocean tests in the Gulf of Mexico are planned for late spring.

Success of the commercialization of ocean farming will increase the fish production and biodiversity of the barren tropical ocean, sequester $C0_2$, and feed our increasing world population with high quality protein from a completely renewable resource.

Background

The earliest history of the human race shows us as hunter-gatherers taking what the land produced but being a part of the natural scene, rather than changing it to our purposes. Some ten thousand years ago in the Middle East, this changed with the domestication of wild animals, i.e. the cow, pig, goat, sheep, and dog. Now our ancestors became herdsmen, moving their domesticated animals to the best pastures with the changing seasons. They continued to hunt and gather but found herding more productive.

Then, about 5,500 years ago, a new invention swept the then-civilized world, the moldboard plough. This increased the productivity of the farmer by a factor of seven. It also changed the way we looked at the land, from passive acceptance to active intervention. This resulted in planting of favored crops, rather than accepting what had always grown there, and making additions to the soil of water and nutrients to further increase productivity.

The transition of people from hunter-gathers to using present farming methods has greatly increased the food output of the world. Half of the increase can be measured by the population increase from about six million to six billion people and the other half by our higher protein diet from feeding grains and leafy materials to animals to produce milk, eggs, meat and aquaculture fish.

These transitions were not always smooth or without controversy. The USA had free range in the western states for many years. For some, there was an almost religious quality to it, and they argued strongly against fences, roads, houses, farms, and railroads. Let these things happen and cities will follow they argued, and they were right.

While these transitions are largely complete on land, they have hardly begun on the three quarters of the earth's surface covered by oceans. We can start a similar change there with a similar return for our efforts.

The fishermen of the world have known for many years that there is great variation in the productivity of the different areas of the oceans. Within the last 10 years, the extent of this variation has been measured and the reason for it determined. The necessary nutrients to support a phytoplankton bloom only occur in a very small fraction of the ocean surface. This gives us a picture of the ocean as a vast desert with only a few verdant zones where life abounds. It is easy to spot the difference. For most of the ocean, you can see 150 feet through the water as you can in the Gulf Stream. In the productive zones, you can see only a few feet, the living matter is so dense. This is the case in the upwellings off the coast of Peru.

These zones have been sampled and the difference is now obvious. The productive zones are rich in iron, phosphorous, trace metals, silica, and nitrate. Each ocean zone must be sampled and the nutrient requirement ascertained to bring it to the level of the Peruvian upwelling. In the barren tropical oceans we expect the main fertilizer to be iron with some phosphate.

It is estimated and now well accepted, that 60% of all the life in the ocean arises from 2% of the ocean surface. Therefore, if all the ocean was like the 2% verdant zone we would have 0.6/.02 or 30 times the present ocean life. If all the ocean was like the 98% nutrient poor zone we would have .4/.98 or .41 times the present ocean life. The ratio of the verdant to nutrient poor is therefore 30/.41 or 73.5 times. That is, if we fertilize a nutrient-poor region of the tropical ocean to conditions such as exist off of Peru, we should get an increase in phytoplankton production of 73.5 times.

A recent paper (*Nature*, March '95) by Pauly & Christensen gives a measure of the "primary production ratio" including catches and discards. This is the pounds of fish caught per pound of phytoplankton produced. The open ocean value is 1.8%, but the tropical upwellings value is 25.1%. For ocean farming we would use the 25% value. This gives us a picture of transfer of biological material between trophic levels that is much more efficient than previously thought. Fish farming gives values of pounds of fish produced per pound of feed of 50% to 90%. The key is to be sure that the fish expend minimal energy to obtain their next meal. In order to achieve the 25% value the efficiency of transfer between trophic levels must be between 50% and 70%. This is only possible in a very dense ecosystem where the energy loss for capture is small as occurs in fish farming. The highest value from the Pauly paper is for non-tropical shelves at 35.3%.

The increase in fish catch per 100 pounds of phytoplankton from the Pauly paper is from 1.8 for the open barren ocean to 25.1 for the tropical upwellings, a multiple of 14 from extra nutrients. Multiplying this increase times the increase in phytoplankton gives 14 X 73.5 or 1025.

Some confirmation of these trends can be obtained from data on the effects of the El Nino event of 1982-3. The anchovetta catch was reduced to 1/600th of its normal value. Since the fishing effort per ton of catch went up during the event we expect that the fish stock went down by a factor of about one thousand. This gives a reasonable check with the factor of one thousand to one estimated above. It is interesting to note that these large changes in productivity at all levels of the food chain took place in a time scale of a year or two indicating the likelihood of a similarly rapid response to ocean farming in the tropical ocean. There is also a rough check with the 2,000 times increase in food production from farming on land.

Farming the Ocean

The ocean differs from the land in several regards: (1) there is never a drought, (2) it moves, and (3) it mixes both vertically and horizontally. The first difference means that we only have to add minor constituents. The second difference means that where we add nutrients and where we harvest are likely to be many miles apart depending on the current. The third difference means that we must do our farming in the open ocean on a large scale or we will never be able to find the results. Finally, we must do our fertilization in deep water so that the deep ocean currents can process the rain of organic materials produced without becoming anoxic, leading to conditions that will kill the very fish we wish to produce.

What are the parameters of ocean farming? First and foremost it must be done on a large scale relative to farming the land because of the movement and mixing of the ocean surface. There is a size where the edge-to-area ratio becomes so small that the fish are essentially trapped within it. All except migratory fish tend to remain in the verdant waters. Secondly, it differs from aquaculture in that it is based on the enhanced production of plant life in the ocean waters. The Redfield ratios describe the response of the ocean plant life to critical nutrients. One pound of available iron can lead to the production of 100,000 pounds of biomass. To the iron we must add some phosphate, a float material to keep the fertilizer in the photic zone and, perhaps, a seed material of phytoplankton to fix the nitrogen required. By the time we have done all this, one pound of fertilizer produces about 10,000 pounds of biomass. The ocean is not a controlled, uniform resource. Therefore, we estimate, conservatively, that one pound of fertilizer will produce 4,000 pounds of biomass in barren tropical waters.

The productivity per acre should be higher in a nutrient-rich ocean than on land. However, we use 40 tons per acre per year, which is the same as for sugar cane cultivation. That calculates out to be 25,600 tons per square mile per year.

We are familiar with planting and fertilizing in the spring and harvesting in the fall where we deal with land farming. In the ocean, under ideal conditions the phytoplankton double every day or two producing a bloom of 20 to 30 times in about five days, seven hundred to one thousand times in 10 days. Then the zooplankton graze on the phytoplankton, the bait fish eat the zooplankton, and on up the food chain to the large mammals and apex predator fish whose life cycles approach decades. We plan to fertilize in areas of the open ocean where the currents maintain the fertilized water within our control for at least twenty days, consistent with the life cycle of the upwelling-fed blooms off of Peru. Longer available time for the blooms will reduce the seeding requirements for both plants and fish, and therefore increase productivity of the resource.

The credibility of these predictions has been greatly enhanced by the publication of the results of the IronEx II experiments in *Nature* of October 10, 1996. In this experiment ferrous sulfate was added to the waters of the tropical Pacific ocean in an area of high nitrate, low chlorophyll, HNLC, water. Page 497 of *Nature*, reproduced here as Figure 1, shows the variation in chlorophyll, nitrate, $C0_2$ and iron over 17 days from the first iron addition (day 1), second iron addition (day 3) and third iron addition (day 7). The chlorophyll bloomed on days 5, 6 and 9, as shown in green. Nitrate was used up as shown in pink where darker is lower nitrate concentration. Carbon dioxide was also used up as shown in blue, where darker is lower concentration of $C0_2$. The chlorophyll concentration increased by a factor of twenty-seven times by day 9 in spite of a loss of about 95% of the iron to precipitation. We expect to achieve essentially 100% utilization of the iron by phytoplankton growth in our fertilizer system. These results are the first that show that iron is the controlling nutrient in these high nitrate low chlorophyll open ocean waters.

While not its primary purpose, ocean farming may affect how we think about the atmosphere $C0_2$ balance. The U.S. produces about 1,340 million tons of $C0_2$ per year from burning of fossil fuels (gas, coal, and oil). One ton of fertilizer produces 4,000 tons of biomass and removes (initially) 5,500 tons of $C0_2$ from the ocean. Therefore, to equal the U.S. fossil

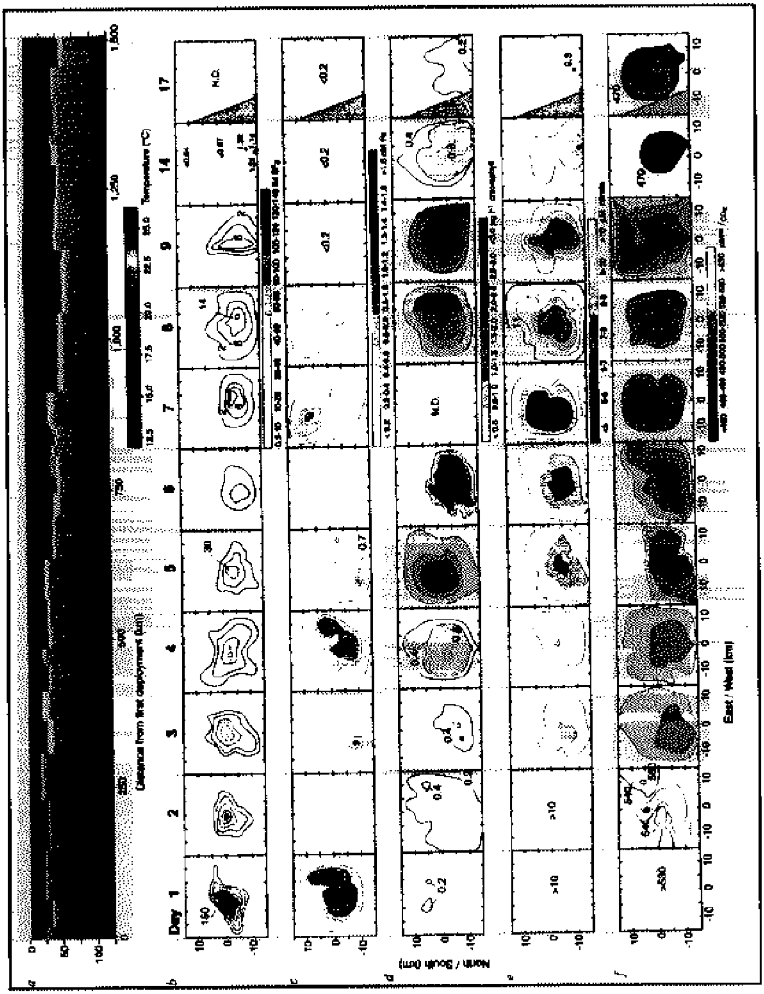

Figure 1.

fuel CO_2 production we need to spread about 250,000 tons of fertilizer. This amount of CO_2 can be taken out of the ocean initially by fertilizing an area about 100 miles wide and 530 miles long, about the same area as the Chesapeake Bay. The algae produced by fertilization will remove CO_2 from the water and indirectly from the air. Thus the food chain organisms will "lock up" CO_2 at all trophic levels up to and including the large, apex predator fish, and whales. The animal life will oxidize the biomass and return some $C0_2$ to the ocean as well as some to the atmosphere. Some of the biological material will descend to the ocean bottom in the form of droppings and shell carbonates, where it will ultimately be picked up by the bottom currents and eventually recycled into upwelled water on a geological time scale. The total carbon that becomes part of this cycle is thus removed from the ocean waters and the atmosphere for substantial periods of time, giving us an avenue of positive action to ameliorate our concern with regard to the effects of burning fossil fuels.

While we do not now know all of the environmental impacts of converting areas of the ocean from barren deserts to verdant blooms we can outline some of the expected effects. Since the plant life will be dense, fish will expend less energy to get to their next meal and the ratio of pounds of fish per pound of phytoplankton will increase greatly. The whales and porpoises will increase in the fertilized area gaining weight rapidly during the time they spend there. These are migratory species and we expect them to congregate where the food supply is plentiful. Over a long period of time the total world count of porpoises and whales will increase, but slowly due to the long doubling time for these species. This positive trend due to ocean fertilization could, of course, be reversed by adverse actions in other parts of their habitat. The effect on large pelagic and migratory fish will be similar. Tuna, for example, increase rapidly in mass during the time they are in verdant waters. They then move to breeding grounds where they spawn. The increased food availability will increase the numbers of tuna, bill fish and dolphin in the fertilized area as they seek new food sources. They will be very happy fish.

There are other ecosystems in the fertilized area that may not be as happy. Coral reefs have evolved to be able to grow in low nutrient ocean waters. When the nutrient levels are increased they grow faster until a level is reached where the nutrients produce so much algae that it shades the coral and kills it. We do not know where our nutrient level will fall, but it may happen that some coral must be shaded in order to achieve the increased productivity that we seek. In the commercialization of ocean farming, large areas of the tropical ocean will be involved. Therefore, some adverse effects on local corals could occur. We will endeavor to minimize any such adverse effects.

The great environmental plus for ocean farming is that, unlike erosion on land, none of the changes are permanent. We only have to stop fertilizing and all traces of the nutrients are gone in a short time.

The overall effect of ocean farming will be to greatly increase the amount and diversity of the marine ecosystem in the fertilized zone. This is a positive answer to the worldwide problem of over fishing, since we will always create more fish than we harvest. This will be done in the context of private property rights so that conservation and the creation of value will be a part of everything that is done.

Technology Development

The proposed fertilizer materials will have special features such as: particle size, dissolution rate, density, and ratios of critical nutrient constituents. Since sea life appears ultimately able to process nutrient materials regardless of chemical makeup or form as long as it remains in the photic zone, we believe that the least expensive, most readily assimilable forms of raw materials having the appropriate chemical compositions should suffice. The fertilizer must not contain traces of toxic chemicals, especially those known to bioaccumulate in marine organisms, as they move up the food chain, and they must also be free of pathogens that could be passed up and ingested by fish destined for human consumption. It appears that many present-day waste streams offer possibilities to produce nutrient constituents at low cost, with concurrent benefits to both public and industrial community recycling programs.

The fertilizer design concept is to obtain a rapid phytoplankton bloom that fixes nitrogen and further promotes accelerated growth of oceanic biomass at successively higher trophic levels. To do this, the buoyant fertilizer system should contain the limiting nutrients such as iron, phosphate and other trace nutrients. A strain of phytoplankton specifically selected to initiate the process may also be seeded in the broadcast stream. There are difficult technical problems associated with the design of the fertilizer. The added nutrients must be in a form that permits them to remain in the ocean surface water for an extended period and not sink to the bottom as a precipitate. The optimum ratio of phosphate to iron and any other missing nutrient must be determined in order to design the fertilizer system for the ocean area selected.

Experimental Program

A three phase technology demonstration program has been designed and is presently underway.

Phase I. Fertilizer Development

This phase is to design the ocean fertilizer materials and to assure that they meet the requirements of density, solution rates and performance. The ability of the fertilizers to support a phytoplankton bloom under laboratory conditions is tested. This phase is now nearing completion.

Phase II. Fertilizer Evaluation and Refinement

This phase will test the phytoplankton response to fertilizers developed in Phase I in open barren tropical ocean. The plan is to use nine square mile test areas in placid waters away from coral reefs. The results will be used to perfect the distribution and seeding protocols. We expect to begin testing this spring in the Gulf of Mexico.

Phase III. Full-Scale Fertilized Ocean Testing

This phase is to demonstrate the production of fish from fertilization of barren tropical ocean. This will require the fertilization of a larger area than Phase II and for a longer time. The fertilized area will be seeded with filter-feeder fish that live on the phytoplankton produced and their growth rate determined. The fertilized area will be about 500 square miles, depending on the currents and mixing of the ocean surface and will be away from coral reefs. The test will last about six months.

Suitable ocean areas have been selected for Phases II & III in the Gulf of Mexico. Experienced organizations are under contract to carry out the three phase program. With the successful completion of these experiments the fertilization of the ocean will be demonstrated and the resulting increase in fish production documented. The commercialization of Ocean Farming can then begin.

Commercialization

The ocean is an economic "commons." That is, if there is one fish left, it is to my advantage that I catch it and not you, and there is no advantage to me to invest in enhancing ocean productivity for you to catch the extra fish. Both aspects of the "commons" problem must be solved in order to enhance the ocean resource.

We have arrived at a situation in the ocean where we have the technological and economic capacity to decimate any fishery within a year or two given the necessary effort, dedication and perseverance. Once this has happened the open "commons" approach to exploiting the resource can no longer be sustained. The fishery will always be over fished and the stock reduced to an uneconomic level. This has already happened in the Georges Bank of the U.S. and to other fisheries around the world.

One method of dealing with this problem for countries with a history of commercial fishing is to use government regulation. This has been tried in New England and many other fisheries with uniformly poor results. It is always to the fisherman's advantage to ignore or circumvent the regulations since he gets no return for fish left in the sea. Also, government regulators respond to political pressures and have no stake in maximizing the output of a resource.

The answer that has worked wonders on land is the introduction of private property. For the oceans this has taken the form of longterm individual transferable quotes or ITQ's.

These give the owner the right to a percentage of the allowable catch for that fishery and hence a financial stake in its health and productivity. The only other way for investment to occur is for the current owner, the government, to sell or lease the rights to the resource to a private entity. The lease would have to be longterm and would have to be for a large area of ocean, possibly in the range of 200,000 square miles. This is a real possibility for island nations, many of which already lease fishing rights within their EEZ.

Among these nations that do not have a "Commons Problem" a search can be made for tropical ocean areas within their Exclusive Economic Zone (EEZ) that have suitable properties to be an area for Ocean Farming. These properties include a large contiguous area, preferably over 500,000 square miles of barren tropical ocean; ocean depth of at least 1,000 feet but preferably greater; benign currents that allow the fertilized ocean water to stay in the host country EEZ for at least 20 days and preferably 60 days in spite of storms; and an indigenous artisanal, but not commercial, fishing tradition. The creation of private property rights in the EEZ will require licensing, purchase or leasing of a large area of ocean of up to 200,000 square miles. It will also be important that the host nation be willing to use its sovereignty to control poaching.

There are several island nations in the tropical Pacific that meet these criteria. These nations are characterized by large barren ocean areas, small land areas, small populations and low national income. Therefore, there is a real incentive for their government to say "yes" to new initiatives. Where the incentive is missing a "no" or "not now" is always the easy answer.

The host nation can look forward to a steep increase in available jobs for its nationals as companies locate there to service the new industry. It should be possible to start commercial ocean farming by using foreign vessels to spread the fertilizers, foreign commercial fishing boats to catch the fish produced and foreign factory ships to process the catch.

On the technical side, we expect that there will be a long period of learning associated with the commercialization of

Ocean Farming. We will be optimizing the selection of the areas for fertilization as a function of weather, time of year, etc. and the selection of the optimum fertilizer composition and amount. We will also be optimizing the amounts and varieties of plants and fish to seed the fertilized areas to obtain the maximum return from our investment.

Like any farmer, we will be faced with conservation decisions. How much of the resource is available for today's catch and how much should be left for tomorrow? The answer to these questions will demand a much more detailed understanding of the conditions of the fishery than is customarily available so that the management of the fishery can lead to optimization of the financial returns from the resource. This is a dynamic system and steady state results may not be approached for some years.

Expected Results

The fertilization of 100,000 square miles of barren tropical ocean is estimated to produce 2,000 million tons of phytoplankton per year and require about 500,000 tons of fertilizer per year. The ratios from the Pauly paper would predict a catch, including discards of 500 million tons of fish. Since this has never been done before and we have only marginal control of the ocean we predict a catch of 100 million tons. This is a very large number, essentially equal to the current world catch. Even if the fertilizer costs $1,000 per ton delivered, the cost of fertilizing is $500 million per year. The value of the U.S. fish catch is now about $0.37/lb at the dock. If we use a value of the expanded catch of $.30/lb the catch for 100,000 square miles is $60 billion per year. We get about $120 worth of fish per dollar of fertilization cost. The cost of fishing and processing should be much lower than for barren open ocean fishing due to the higher concentration and greater predictability of the fish stocks, perhaps $0.05 to $0.10 per pound. We would probably not reach these large numbers for some years as we gradually expand our fishery and the migratory fish became accustomed to the new conditions.

These are very big numbers indeed. The current world fish catch is approximately 100 million tons, so we would be doubling the current world catch in a few years. We would try to reach this level by slow increments. However, commercialization cannot be accomplished on small patches. The normal storms and turbulence of the oceans would destroy our small farm and we would not be able to find the results of our efforts.

Many environmentalists will contend that anything that mankind puts in the ocean is dumping and they are against dumping. Fortunately, some realize that ocean farming will create new verdant habitats for their favorite species.

Many oceanographers have a hard time with the Ocean Farming concept. One view is that the ocean is so complex that you cannot tell what will happen when you change one part (like fertilizing). A second more profound viewpoint comes from the fact that oceanography is an observational rather than an experimental science. That is, the natural ocean is there only to be studied and understood. Any change is to be resisted. In this view man can only do bad things to the ocean. None of his actions can result in longterm good, like more and happier fish, whales, dolphins and turtles.

Upon long reflection, some senior oceanographers have agreed to advise the project because they really can't find anything wrong with the scientific logic and all the latest findings support the general thesis. They are excited by the impact that ocean farming may have on the science of oceanography and the positive effect on food supply.

Financing

Whenever a really new enterprise is launched there is always the difficulty of raising the necessary capital to fund the technological development and launch the commercialization. This is often a daunting task, filled with hard lessons learned.

After working on the concept for about a year, I interested some friends in backing the launching of a new company, Ocean Farming, Inc. (OFI) to license the patents that were about to issue and get the technology development and demonstration phases underway. One of my previous patents had lead some of these same people to found a company for its exploitation which is now quite successful, making a profit of several million dollars per year. I had also founded an environmental company, grew it to about 800 employees and taken it public. Some of my associates in this venture are the providers of the seed money for OFI.

The first approach was to look for U.S. Government funding for the development. After all, projections showed that fertilizing the Gulf Stream off the Atlantic coast could create a new industry with over half a million new jobs along with all the other advantages mentioned. The key agency is NOAA and we had an all day symposium including the key NOAA, Navy and National Science Foundation personnel. No support was forthcoming and no more effort was wasted in seeking support from the U.S. Government.

The second attempt to obtain backing was from the U.S. fishing industry and the U.S. Congress. The Congress was needed to address the common problems. The fishermen could then, through the regional fishery management councils, be the focal point to attract funding for the project. This seemed like a good approach given the state of the New England fisheries. An article was published in the Commercial Fisheries News and the executive directors of the Atlantic Coast councils were contacted. No interest was expressed by anyone at any time. Evidently, small scale day-to-day problems were so overwhelming that no time or energy remained to address a possible solution to the larger problem. Without a solution to the common problems or some sort of help from the government or the fishing industry, the U.S. EEZ was deemed unattractive and effort was directed elsewhere.

With the issuance of the first two patents which teach increasing the productivity of the open ocean by the addition of missing nutrients, a creditable management and a compelling story, initial capital was raised and the enterprise got underway.

The ocean are planned for the Gulf of Mexico outside of the EEZ of any country so that no one had to say "yes." It is planned to commit three to five million dollars to the Technology Development and Demonstration Program. The key contractors are International Fertilizer Development Center in Muscle Shoals, Alabama, for fertilizer development and pilot production and the University of South Florida for oceanographic support. When significant results are available we look forward to a public offering of about $100 million. This will carry OFI until revenues commence with successful commercialization. The OFI corporate structure is planned for a small technical and management team that then contracts with the various entities that make commercialization possible. We envision a long term lease of all or part of the EEZ of one or more tropical island nations. We plan to contract the manufacture of the fertilizer materials to our specifications, the seeding of the area with phytoplankton and fish, the catching of the fish to OFI's resource management plan, the processing of the catch, and finally transportation and sale to wholesale markets.

The current average value of fish at the dock, worldwide, is about $0.37/lb. We expect this to fall to $0.30/lb for the increased catch. Since we will have a managed resource concentrated in a predictable area we expect significant economics of scale that will more than outweigh the cost of fertilizing and host country licensing. We will also be able to design our processing to utilize every part of every fish caught. Non-edible materials will be processed into fish meal, fish oils, and fertilizers. There should be no by-catch and no waste. We expect the cost of the fish at the dock to be between $0.10/lb and $0.15/lb, including license fees and host state charges, providing a favorable profit margin.

This is a new concept, based on new technology. There is much to be learned as we apply it to the ever changing ocean. It is clear that the return to mankind from the success of this endeavor leading to the farming of selected portions of the almost three-quarters of the earth covered by the oceans, will be great indeed.

Ocean Microcosm: Elements of an Ecological and Freshwater Buoy Design

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Abstract

The ocean microcosm is a modification of a basic buoy directed toward mitigating some of the deleterious effects of invasive ocean development. It specifically employs creature friendly materials of glass and concrete, it utilizes passive energy of the sun and wind, and promotes marine colonization. This design expands the range of the structure beyond its singular human service of floatation or aggregation site to one capable of cultivating and sustaining a resident ocean population. Given the reality of offshore development, the need to conserve the common heritage of the oceans, and the involvement of the international community in legislating ocean degradation, the microcosm is designed to increase integration and stewardship, and comply with the most stringent environmental regulations.

> "... People have lived naturally since time began ... the sooner they do it again, the less dependent they will be on imported oil and nuclear energy ..."
>
> *The New Wind Power* by Jon Naar.[1]

Concept

Enough ocean structures require floatation to make the study of modified buoy design worthy of consideration. All offshore structures need to minimize their disruptive impact on the ocean envrionment.

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[1] Naar, Jon. *The New Wind Power.* 1982 Penguin Books.

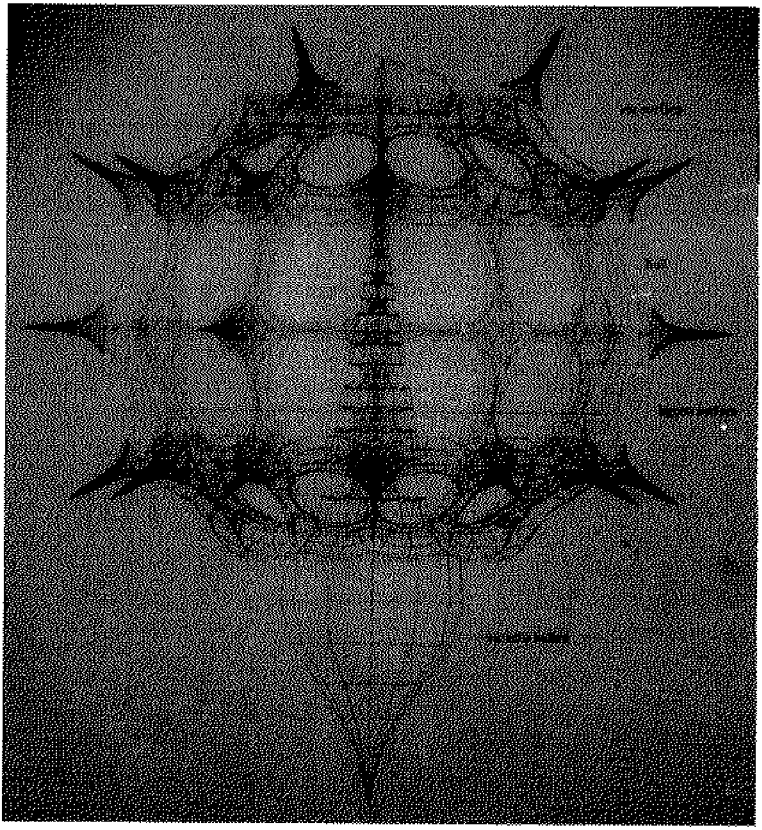

Figure 1. Ocean Microcosm. Solid modelling modifications of spherical buoy. Concrete hull with glass portholes, variable ballast, internal planter, and protective projections. Sphere diameter: 120 ft. Internal lagoon surface: 66 ft. depth.

Because the ocean is a common heritage resource, there is the obligation to insure all structures placed there respect the interests of local populations when being exploited by nonlocals, and preserve the oceans' resources for populations distant in time and space.

The ocean microcosm is a merging of ecology and engineering in order to transform a buoy or caisson used in service for floating human enterprises offshore, into a similar structure that is illuminated inside and that can now cultivate a food web; a transformation that is relatively low-tech. The choice of concrete and glass materials for the hull imparts to the buoy cavity the capacity to increase phytoplankton production and to generate freshwater through solar desalination, while wind pumps can aereate and circulate deep ocean water for condensate production. Furthermore, the actual form of the hull can be modified to collect and contain rain. Thus by providing sunlight and establishing a freshwater source, new niche space is conveyed to the ordinary buoy that converts it into a multifunctional subsurface greenhouse that can reside in the open ocean in compliance with environmental and international standards.

Size and Logistics

Ideally no man-made objects have permission to be stationed or disposed in a region held in common with others such as the ocean frontier, without universal consent. Although it is an international crime for an entity to degrade foreign property as well as that which is held in common[2], this crime is being perpetrated in modern times by entities whose capital and technology are in greater abundance than vision, integrity and dicipline. Already, large scale coastal and offshore developments are underway in a style that is in disregard of other contemporary nations and future generations. Some mega-enterprises are not in the best interests of a planet whose

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[2] *Basic Documents in International Law 4th edition*. edited by Ian Brownlie. 1995 Claredon Press, Oxford. (Law of the Sea chapter)

evolution is dependent on adaptability, which is dependent on diversity... the diversity of human and creature populations, and the natural environment. Mega, in the form of nuclear waste, in the form of offshore urban-sprall landfills, in overfishing and deforestation, in overproduction and, in general, in the over-consumption of world resources by developed countries, is a largess that cannot be humanely sustained nor ethically promoted. Well educated citizens are equipped to pursue saner options. According to Tawney, the most obvious facts are the most easily forgotten. Both the existing economic order and too many of the projects advanced for reconstructing it break down through their neglect of the truism that since even quite common men have souls, no increase in material wealth will compensate them for arrangements which insult their self respect and impair their freedom. A reasonable estimate of economic organization must allow for the fact that unless industry is to be paralyzed by recurrent revolts on the part of outraged human nature, it must satisfy criteria which are not purely economic.[3] For the ocean frontier, those criteria involve cultural and environmental integrity. The international community is pressed to devise a means to both advance modern human enterprise on the ocean front and to simultaneously safeguard resources essential to the support of all present and future life on the planet. There is an urgency to provide alternative designs for prospective development and management that reflect a more universal environmental application.

Some decision makers, with the power of capitol and public influence, but lacking the understanding of environmental consequence, have been making choices designed to sustain existing abuses of petroleum and nuclear energy in disregard of appropriate reductions and alternatives. Without intervention of the international community and global perspective, they deliberately continue to effectively diminish the collective resources of mankind, to defy and to undermine

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[3] Naar, Jon. *The New Wind Power.* 1982 Penguin Books.

saner and more humane management. As Naar puts it, "If the mainstream of wind power research and development since the 1970s has been dominated by the high technology world of aerospace and the Dept. of Energy, a minor but important tributary is the diffuse movement known variously as alternative, appropriate, intermediate, or soft technology with its antecedents in Schumacher's *Small is Beautiful*, and the teachings of Buckminster Fuller, and Amory Lovins. For this movement, which is particularly strong in the universities in the Pacific NW and in New England, solar wind, and other forms of renewable energy are seen not merely in terms of bottom line accounting but truly alternative forms of energy that are valid because they are in harmony with the environment."[4] The value in designing for a scale that is humane and sustainable has economic viability.

The microcosm is an ocean structure design that invites more harmony with the natural environment, that complements the flow of nature rather than attempting to resist it or control it. Unlike the conventional expenditure of energy combating inexorable natural processes like fouling and condensation on a surface, the microcosm incorporates them into its design. Encrusting will strengthen the concrete while enriching the habitat, and the freshwater will broaden the range of aquatic life cycles. In the same vein, the wind and ocean currents that impinge on offshore structures can be turned into a source of circulation energy.

The ocean microcosm is intended to support a climax marine community on passive energy and expand human space with its buoyancy. It's designed to evolve relatively naturally to a size and level of productivity well below that of mega operations yet above the norm. A fish aggregation site that can be cultivated is one way of moving agriculture offshore on a small scale, that is as natural and benign as a family farm. When the international Law of the Sea evolves to reflect

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[4] Schumacher, E.F. *Small is Beautiful.* 1973 Harpers and Row.

genuinely effective environmental standards and global stewardship of the high seas, the ocean microcosm style buoy will already be in compliance.

Passive Energy Systems

Solar radiation entering the cavity of the microcosm buoy is the source of energy that powers the process of desalination through evaporation and condensation. It is the force stimulating photosynthesis and increasing primary production of algae in the area; productivity that can be enhanced by introducing deep, nutrient rich water to photic zone layers, along with limiting agents like iron. After increasing the primary productivity of the buoy field, secondary consumers and members of the food chain can colonize the area. Designing the habitat to favor plant life is also a means to oxygenate the internal air cavity.

The **thermal** properties of the structure, atmosphere and ocean affect the dynamics and production of the freshwater system. The difference in temperature of the surface and deep water can be a source of energy for desalination, pumping, and OTEC.[5] **Wind and wave** energy can also serve to pump and circulate air and water. Various propellers and pistons for both mediums have been developed that have improved output.

The interplay of light, temperature, winds, creatures, stable materials, and environmental purpose are what distinguish the microcosm from conventional buoy structures and recommend it to offshore development.

Freshwater Sources

Solar Desalination

Like a simple solar still, the microcosm buoy traps solar energy and converts it into latent heat of vaporization within the air cavity. Water inside the buoy is warmed, the cavity air

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[5] *Ocean Thermal Energy Conversion: A Source Guide.* 1991 Gordon Press.

becomes saturated, and the vapor condenses on the inside surface of the hull and flows downward toward the internal sea surface.[6] Being less dense, it will eventually form a lens of freshwater over the ocean water. Some major factors influencing the amount of condensation within the buoy are: insolation intensity, ambient temperature, brine depth, slope of glass, vapor tightness of the cavity, and heat losses through the elements.[7] The atmospheric pressure of the air cavity is reflected in the depth of the internal sea surface. This elevated pressure on the surface of the lagoon influences evaporation because of the resistance thus offered to the escape of the vapor.[8] The ocean microcosm is affected by the ocean regime, being 9/10ths submerged in the ocean temperature that varies little around 68° F in the tropics. On the other hand, a much larger change in apparent extraterrestrial radiation is caused by the seasonally changing path of the sun through the sky.[9] Other heat loss, some trivial, depends on wind velocity, or rather, ocean current velocity, air, sky, ocean temperatures, angle of incidence, size of aperture, density of glass, heat capacity of the various materials and water... Actual measurements and predictions about performance are difficult for collectors in which the geometry is not simple enough to permit a closed form solution of convective heat losses. The sun is intermittent, and designs can be modified to reduce heat losses, increase condensation surface area, etc. Suffice to say, the variables affecting performance are numerous.

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[6] Porteous, Andrew. *Desalination Technology*. 1983 Applied Sciences Publishers.

[7] Ibid.

[8] Rogers, William. *Pumps and Hydraulics* vol. 2. 1905 Theo. Audel & Company.

[9] Lunde, Peter J. *Solar Thermal Engineering*. 1980 John Wiley and Sons.

Condensation Enhanced by Deep Ocean Water

Rough estimates indicate that two liters of freshwater per day are sufficient for human subsistence, and that the conventional stills produce from 1-3 liters/m^2 on the average.[10] Given the tempering effect of the ocean immersion and near steady 68° F surrounding waters, the microcosm is expected to produce only a small fraction of what its terrestrial counterparts are capable. A more continuous source of freshwater can be obtained by pumping cold subthermocline water to the surface and through materials in the saturated air upon which condensation can take place[11] and drain into an area where it can form a lens above the denser salty layer. Cultivation of terrestrial plants by the condensation from DOW pipes has been successful and yielded surprising results at Hawaii's Natural Energy Lab at Keahole Point.[12] The ocean microcosm is designed to drain into an area for the cultivation of terrestrial species (see "planter" in illustration) in the central region of the buoy cavity. This is to be further terraced to the water level in a series of ponds of increasing salinity.

Rain Catchment

A remaining source of freshwater is the collection and containment of rain. Although it is possible to design basins to save the rainwater, it remains to make them secure from inundation by storm waves. Recuperation from what is unavoidable is also a design strategy, such as having deep, open-ended catchment holds with vertical depth that would retard dilution and enable denser water to settle out. There are many modifications that can be attached to, or made in the hull of, the microcosm to receive and channel rainwater, such as spiraling, and grooving of the collection surface, while

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[10] Yates, Woto, and Tlhage. *Solar-Powered Desalination.* 1990 International Development Research Center.

[11] Ibid.

[12] Craven, Presentation at Ocean Cities '95 Symposium, Monaco.

conforming the shape to a torus provides an open ocean lagoon separated horizontally from the ocean waters.

By the methods of solar desalination, DOW condensation, and rain catchment, the ocean microcosm can establish its own independent freshwater source. As mentioned in size and logistics, the maximum production is on a small sustainable scale. This is not an obstacle for the ecosystem evolution being cultivated for the microcosm habitat. Although slow, it eventually can provide a gradation of fresh, brackish to saline waters, so that the buoy acquires the capacity to serve as a hatchery site for those marine species whose larvae spend time in estuarine waters.

Circulation System

Wind Pumps

Circulation of the water and air will affect the climate of the microcosm habitat. While still waters promote vertical stratification, they also promote the blooms of nuisance algae. Nutrients are available in deeper waters that are depleted at the surface. Old fashioned wind powered piston pumps can lift water from a hundred meter depth.[13] Other passive pumping can be generated by wave motion. The low output of this sort of alternative energy is less an obstacle for the microcosm than it is for mega operations. What more than compensates is that it is free, virtually inexhaustible, and clean. In the long run, this dependence on nature's bounty, and not human capital, better serves a structure that's designed to endure centuries.

A different version of the pumps compresses air and can be employed to adjust buoyancy and to circulate air in the cavity. In fact, mechanical motion derived from wind power can be used to drive heat pumps or to produce heat from the friction of solid materials or by the churning of water ... then be

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[13] Rastogi, Miss T. *Windpump Handbook.* 1982 Tata Energy Research Institute.

stored in materials having high heat capacity, such as water, stones, eutectic salts so the heat can be used directly[14]... Ideally, the microcosm can be designed to be self evolving and self sustaining with the minimum of post-inception management. Mechanical devices like pumps and compressors have a shorter lifetime than the microcosm and will involve human maintenance. One desirable feature of the microcosm buoy is its absence of artificial noise. The pumps are an exception to this plan and as with most equipment, should be dispensed with where possible and minimized where not. In fact, the microcosm should be serviced by sailing vessels rather than motorized ones.

Conclusion

The ocean microcosm demonstrates some of the advantages of designing structures with ecology in mind. A basic common object like the buoy, with a few simple modifications in materials and form, can be transformed from a relatively inert object to one that is virtually organic. By scale and by resource impact, such modified structures recommend themselves to offshore placement because they possess features that render them relatively non-invasive in the human or environmental realm. The merit in this type of design lies in the savings made preserving what is irreplaceable and doomed to perish if disregarded ... the vitality of the world's oceans.

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Open Ocean Aquaculture '97
Program

SECOND INTERNATIONAL CONFERENCE ON OPEN OCEAN AQUACULTURE

APRIL 23-25, 1997
MAUI, HAWAII

WEDNESDAY, APRIL 23

7:30 - 8:30 a.m.	Continental Breakfast and Registration (*Plumeria Room*)
8:30 - 9:00 a.m.	OPENING SESSION (*Maile Room*)
	Charles E. Helsley: Overview & Introduction
	Senator Daniel Akaka: Welcoming address
9:00 - 9:30 a.m.	**Governor Benjamin Cayetano**: Proclamation of Open Ocean Aquaculture Day
	Mayor Linda Lingle, Maui County: Welcome
	Remarks by Sponsors
9:30 - 10:00 a.m.	**James McVey**: Overview and Future Directions for the National Sea Grant Aquaculture Program
10:00 - 10:15 a.m.	Morning Break
10:15 a.m. - 12:15 p.m.	SESSION 1 (Moderator - **James Sullivan**)
	Michael Champ: Global Review of Ocean Technologies for Open Ocean Aquaculture
	Michael Markels, Jr.: Farming the Ocean

10:15 a.m. - 12:15 p.m	**Clyde Tamaru** and **C. Carlstrom-Trick**: Aquaculture in Hawaii - Lessons from the Past
	Paul Jokiel, **D. Sarver**, and **N. Sims**: Open Ocean Culture of Hawaiian Black Lip Pearl Oyster (*Pinctada margaritifera*)
12:15 - 1:30 p.m.	Luncheon Speaker - **John Craven**: The Open Ocean Aquaculture of Humans as Marine Mammals
1:30 - 3:00 p.m.	SESSION 2 (Moderator - **James McVey**)
	Michael De Alessi: Marine Tenure
	Peter Petrusevics and **S. Clarke**: Optimization of Southern Bluefin Tuna Resource in Semi-Open Ocean Farming, Boston Bay, S. Australia, Using Numerical Simulation
	Gary Loverich, **N. Best**, **C. Goudey**, and **N. Hahn**: Discussions of the Predicted Performance of the Ocean Spar Sea Station Based Upon Large Model Tests in a Sea Keeping Basin
3:00 - 3:30 p.m.	Afternoon Break
3:30 - 6:00 p.m.	SESSION 3 (Moderator - **William Rickards**)
	Mark Drawbridge: The White Seabass (*Atractoscion nobilis*) as a Candidate Species for Open Ocean Culture: a Review Based on Four Years of Culture in Nearshore Cages
	Daniel Margulies, **V. Scholey**, **A. Nakazawa**, **R. Olson**, **J. Wexler**, and **J. Suter**: Development of a Spawning Population of Yellowfin Tuna (*Thunnus albacares*) in Landbased Tanks in Panama

3:30 - 6:00 p.m.	**David Condron** and **E. Powell**: A Deep-Water Mooring Concept for Open-Ocean Aquaculture
	Godfrey Savage, **J. Howell**, **B. Celikkol**, and **R. Barnaby**: Results of 18 Month Open Ocean Codfish Aquaculture Demonstration Project
6:00 - 8:00 p.m.	POSTER SESSION AND BEER & PUPUS (that's Hawaiian for appetizers) (*Jade* and *Plumeria Rooms*)
	German Merino: Considerations for Culture Design Systems for Scallop Production
	Peter Petrusevics: Ocean Cage Tuna Farming in Spencer Gulf, South Australia
	Daniel Margulies: Video of Spawning Population of Yellowfin Tuna (*Thunnus albacares*) in Land Based Tanks in Panama

THURSDAY, APRIL 24

7:30 - 8:00 a.m.	Continental Breakfast (*Plumeria Room*)
8:00 - 10:00 a.m.	SESSION 4 (Moderator - **Michael Hightower**) (*Maile Room*)
	John Corbin and **L. Young**: Ocean Leasing in Hawaii: Origins, Status and Future Prospects
	John Bonardelli and **M. Levesque**: Economics of Longline Technology in Offshore and Drift-Ice Environments: How to Make or Lose Money
	Henri Gignoux, **L.D. Thompson**, and **R.H. Messier**: Computational Model of Aquaculture Finfish Net-Pens

8:00 - 10:00 a.m.	**Tohru Morikawa**: Current Development of Open Ocean Aquaculture in Japan
10:00 - 10:30 a.m.	Morning Break
10:30 a.m. - 12:30 p.m.	SESSION 5 (Moderator - **John Corbin**)
	Leonid Bugrov: Biological and Engineering Aspects of Underwater Fish Farming Technology in Open Sea Areas
	Michael Gosz, **K. Kestler**, **R. Swift**, and **B. Celikkol**: Finite Element Modeling of Aquaculture Net-Pen Systems
	Anne Hayden: Aquaculture on the High Seas: Who Will Be Watching?
	Neville Thomson: The Australasian Offshore Shellfish Longline Experience
12:30 - 1:30 p.m.	Luncheon (no luncheon speaker)
1:30 - 3:00 p.m.	SESSION 6 (Moderator - **Neville Thomson**)
	Ljudmila Bougrova, **S. Matveev**, and **L. Bugrov**: Pelagic and Bottom Versions of SADCO Underwater Cages - Experiences and Latest Developments
	Michael Chambers: Potential Offshore Cage Culture Utilizing Oil and Gas Platforms in the Gulf of Mexico
	Takashi Kano, **K. Torii**, and **H. Kawamoto**: A Design of Flexible Submerging Artificial Fishing Reef
3:00 - 3:30 p.m.	Afternoon Break
3:30 - 5:00 p.m.	SESSION 7 (Moderator - **Anthony Ostrowski**)
	John Ericsson: Permitting Difficulties and Procedures for Establishing Open Water Mariculture in U.S. Federal Waters

3:30 - 5:00 p.m.	**Leonard Young** and **J. Corbin**: Selecting Nearshore and Open Ocean Mariculture Technologies for the Hawaii Environment
	Richard Taylor: Early Sea Scallop Growout Studies in the Gulf of Maine
	John Ericsson: Sea Star Oyster Relay Systems: a Solution for Pollution of Oysters
5:00 - 8:00 p.m.	Hawaiian Style Luau and Polynesian Entertainment

FRIDAY, APRIL 25

7:30 - 8:00 a.m.	Continental Breakfast (*Plumeria Room*)
8:00 - 10:00 a.m.	SESSION 8 (Moderator - **Rollie Barnaby**) (*Maile Room*)
	Gary Loverich and **L.R. Gace**: The Effect of Currents and Waves on Several Design Classes of Offshore Sea Farming Cage
	Takashi Kano, **H. Yamakawa**, **K. Torii**, and **T. Abe**: A Field Study on Artificial Reef for Exploitation of Algae Plantation
	Joseph McElwee: Practical Experiences in Rearing Fish in Offshore Cages in Ireland, The Good, The Bad and the Ugly!
	Clark Liu: Open Ocean Aquaculture with Nutrient-Rich Deep Ocean Water
10:00 - 10:30 a.m.	Morning Break

10:30 a.m. - 12:30 p.m.	SESSION 9 (Moderator - **Anne Hayden**)
	Apostolos Mihelakakis and **A.S. Tzoumas**: Integrated Fish Farm in Mediterranean: Case Study of NIREUS, Chios Aquaculture S.A. in Greece
	Anthony Ostrowski: Candidate Species of the Pacific: the Hawaiian Fisheries Development Project
	I Chiu Liao, **Ya-Ke Hsu**, and **W. Lee**: Marine Aquaculture in Taiwan
	Daniel Curran, **P. Hoagland**, and **D. Jin**: An Access System for Ocean Mariculture: Influences of Current United States and International Law
12:30 - 1:30 p.m	Luncheon (no luncheon speaker)
1:30 - 3:30 p.m.	SESSION 10 (Moderator - **Joseph McElwee**)
	Sergey Matveev and **L. Bugrov**: Automation of Fish Farming Processes for Offshore Cages
	Patrick Takahashi: The Ultimate Ocean Ranch
	Kenji Hotta: Artificial Upwelling and Algae Structure for Open Ocean Aquaculture
	Syd Kraul: Mahimahi Aquaculture – Pros and Cons of Cage Trials to Date
3:30 - 4:00 p.m.	Afternoon Break
4:00 - 5:30 p.m.	CLOSING SESSION (Moderator - **Charles Helsley**)
	Round Table Discussion: Where To From Here? (Panel - **Neville Thompson, James McVey, Gary Loverich, Michael De Alessi, Joseph McElwee**)

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