

**PRELIMINARY DESIGN OF A RECIRCULATING AQUACULTURE SYSTEM
IN BOSTON HARBOR**

by

Neil A. Best

B.S. Ocean Engineering
Massachusetts Institute of Technology, 1995

SUBMITTED TO THE DEPARTMENT OF OCEAN ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF


MASTER OF ENGINEERING IN OCEAN ENGINEERING
PROGRAM IN MARINE ENVIRONMENTAL SYSTEMS

AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

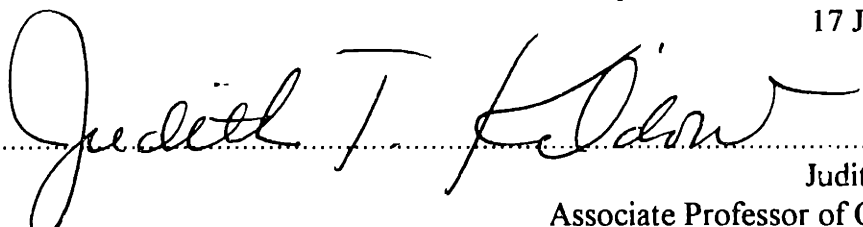
FEBRUARY 1997

© 1997 Massachusetts Institute of Technology. All rights reserved.

Signature of Author:


Department of Ocean Engineering
17 January 1996

Certified by:


Judith T. Kildow
Associate Professor of Ocean Policy
Thesis Supervisor

Accepted by:


J. K. Vandiver
Chairman, Department Committee on Graduate Students

APR 29 1997

LIBRARIES

ARCHIVES

PRELIMINARY DESIGN OF A RECIRCULATING AQUACULTURE SYSTEM IN BOSTON HARBOR

by

Neil A. Best

Submitted to the Department of Ocean Engineering on 17 January 1997
in partial fulfillment of the requirements for the degree of
Master of Engineering in Ocean Engineering, Program in Marine Environmental Systems

ABSTRACT

Aquaculture has been developing as an industry in the United States for over twenty years mainly in rural areas or on sparsely populated coasts where land and water resources are relatively cheap. Today, however, there is a real opportunity for an aquaculture industry to establish itself in the metropolitan Boston area. Despite Boston Harbor's myriad uses as a commercial crossroads and recreational haven, under-utilized parcels such as the abandoned reservoirs on Moon Island present opportunities for aquaculture development. Improved water treatment methods capable of reducing operational costs are available. Large-scale systems incorporating these ideas have the potential of increasing profitability and reducing the risk of crop loss. The regional seafood tradition presents opportunities for marketing of numerous species including shellfish, crustaceans, and finfish. Aquaculture in Boston Harbor would benefit from the proximity of processing facilities, local markets, and fast air freight to the global market.

The Moon Island reservoirs feature fifty million gallons of confined capacity with direct access to harbor waters. This thesis presents ideas for equipping and operating a marine aquaculture production facility on this site that will produce seafood without negatively impacting local water quality. Methods of water treatment and filtration throughout the process are described including air lift pumping, foam fractionation, and floating-bead biological filters. A production example featuring Atlantic cod (*Gadus morhua*) describes a spreadsheet-based model for determining the production capability of the facility based on a temperature-sensitive growth model and seasonal water temperature fluctuations characteristic of Boston Harbor.

Technical Advisor: Clifford A. Goudey
Research Engineer
Center for Fisheries Engineering Research
MIT Sea Grant College Program

Thesis Supervisor: Judith T. Kildow
Associate Professor of Ocean Policy

TABLE OF CONTENTS

1. INTRODUCTION	8
1.1 GLOBAL CONTEXT	8
1.2 BRINGING AQUACULTURE TO BOSTON HARBOR	10
2. DESCRIPTION OF MOON ISLAND AND THE RESERVOIRS.....	15
2.1 LANDSCAPE, SURROUNDINGS AND HISTORY	17
2.2 CURRENT CONDITION OF THE FACILITY	21
2.3 RENOVATION OF THE FACILITY	22
2.4 WATER QUALITY CONTINGENCIES	24
3. ENGINEERING OF RECIRCULATING AQUACULTURE SYSTEMS	27
3.1 ECOLOGICAL PRINCIPLES	28
3.2 APPLICABILITY OF RECIRCULATION.....	33
3.3 SUGGESTED SYSTEM COMPONENTS.....	37
3.3.1 CONTAINMENT.....	37
3.3.2 PUMPING AND AERATION	39
3.3.3 SOLIDS REMOVAL AND BIOLOGICAL FILTRATION.....	41
3.3.4 FOAM FRACTIONATION	48
3.4 COMPONENT COMPATIBILITY	53
4. A PRODUCTION EXAMPLE: ATLANTIC COD.....	55
4.1 BACKGROUND	55
4.2 GROWTH MODEL	58
4.3 BOSTON HARBOR TEMPERATURE MODEL.....	61
4.4 RESULTS.....	67
5. CONCLUSION.....	87
6. REFERENCES	89
7. APPENDIX: MWRA WATER QUALITY DATA	93

LIST OF FIGURES AND TABLES

Figure 1. Boston Harbor. Adapted from NOAA chart, 1994.....	15
Figure 2. Features of Moon Island and local bathymetry. Adapted from NOAA chart, 1995.....	19
Figure 3. The nitrogen cycle in aquatic systems. Adapted from Spotte, 1979.	31
Figure 4. Diagram of a floating-bead up-flow biofilter.....	43
Figure 5. Four operational modes of the floating-bead biofilter. Adapted from Malone and Coffin, 1991.	45
Figure 6. Representation of DOC molecules adhering around an air bubble during foam fractionation. Adapted from Ng & Mueller, 1975.....	51
Figure 7. Diagram of a foam fractionation column.	51
Figure 8. Atlantic cod (<i>Gadus morhua</i>) (Kales, 1976).....	55
Figure 9. Growth rate model for Atlantic cod.	59
Figure 10. Growth rates for cod of three weights.....	60
Figure 11. Boston Harbor water temperature history (MWRA, 1996). Station 48 is Moon Island; Station 139 is Hangman's Island	63
Figure 12. Temperature model using three quadratic curve fits.	65
Table 1. Sensitivity of final weight to starting date, length of grow-out period, and temperature control (weight in grams).....	69
Figure 13. Growth history of 20g cod started on 1 August, no temperature constraint.	71
Figure 14. Growth history of 20g cod started on 1 April, no temperature constraint.....	73
Figure 15. Growth history of 20g cod started on 1 August, 8.5°C minimum temperature.	75
Figure 16. Growth history of 20g cod started on 1 April, 8.5°C minimum temperature.	77
Table 2. Six growth stages at two-month intervals, target final weight of 1500g.	82
Table 3. Choice of tank sizes based on stocking density of 70 kg m ⁻³ (0.58 lbs gal ⁻¹).	84
Table 4. Floor space required for one six-stage production unit	85
Table 5. Available floor space at Moon Island, number of six-stage grow-out units, and total production.	85

1. INTRODUCTION

This thesis is intended to convey the general issues surrounding the design and establishment of a commercial-scale recirculating aquaculture facility in Boston Harbor. General discussions of the status of aquaculture in the world and the renaissance of Boston Harbor are included to provide scope and context. The nature and necessity of recirculating aquaculture systems in this case is addressed in general terms before subsequent sections commence with discussions of technical details.

1.1 GLOBAL CONTEXT

Aquaculture is the deliberate rearing, cultivation, and harvesting of any aquatic species for human consumption. Subsistence farming has been supplemented by aquaculture from ancient times to present day in various regions of the world. Farmers working inland, for example, have learned to incorporate the production of freshwater animal species in ponds into their overall production scheme by providing agricultural products or by-products as feed and utilizing the feces-laden effluent as fertilizer for nearby irrigated crops. This and other forms of low-technology, labor intensive aquaculture are still prevalent in many developing nations around the world.

It is at first astonishing to realize that the technological advances of the twentieth century have not been applied to aquaculture as they have to agriculture. This has been explained through three general observations. The wealthy nations of the industrialized world have been blessed with abundant fisheries and have traditionally relied on gathering from the sea to meet seafood demand. No wild-harvest alternative to terrestrial agriculture exists and

modernized nations have met growing food demands by scientifically increasing crop yields. Finally, a fundamental lack of biological knowledge has been a barrier to entry into aquaculture production for many species (Iversen, 1968).

Today these assumptions deserve re-evaluation in light of exploding populations, depletion of wild fisheries, and the biotechnology revolution. Nations are realizing that the bounty of the sea is limited and that wild catches need careful management to preserve natural populations for the future. Demand for protein will continue to grow and aquaculture is already meeting the challenge, accounting for 19 percent of total edible fish production in the world in 1988 (NRC, 1992; FAO 1990). The world's rate of wild catch has reached an apparent maximum with most fisheries experiencing drastic population collapses while aquaculture production continues to grow by 7 percent per year. The resulting margin between supply and increasing demand in the seafood market has encouraged aquaculture's technological and commercial development over the past twenty years. Research efforts in marine biology are identifying the developmental patterns of candidate culture species for incorporation into hatchery and production systems management.

Aquaculture in America has shown profitability in both freshwater and marine domains for crustacean, molluscan, and piscine species alike. Recent decades have seen the success of low-technology, inexpensive approaches to the maintenance of water quality. Pond culture of catfish in the south, raceway arrays for trout in the north, and floating net pens for salmon in coastal regions of Maine and the Pacific northwest are the United States' best examples of successful approaches in the finfish sector of aquaculture. These systems rely on the availability of cheap, clean water from nature. The constant interaction of these operations with natural waters has led to their designation as "open" systems since water flows through

once and the local environment is forced to absorb artificially intense concentrations of nutrients.

These methods are not applicable to the urban setting of Boston Harbor because of their environmental impacts and exclusive use of large areas of land or coastal waters. The alternative is the implementation of a “closed” system which draws water from a natural body in smaller amounts and recycles it within a set of culture tanks while removing waste products before returning effluents to the environment. These “recirculating” systems require more investment in equipment such as filters and pumps and energy to move water than the passive open systems. For many years, closed system designs have been applied in research settings and hatchery operations where profit was not the motivation and environmental interaction was minimal. Only in recent years have recirculating systems shown promise of profitability as aquaculture grow-out facilities that can produce large quantities of quality seafood with less water consumed per weight of product, less living space per fish, and more efficient separation of waste products. This technological trend combined with the dynamics of seafood supply and demand makes recirculating aquaculture technology a natural choice for Boston Harbor.

1.2 BRINGING AQUACULTURE TO BOSTON HARBOR

Boston Harbor has played a major role in the New England tradition of seafood harvest. Fishermen have plied Massachusetts’ coastal waters for centuries and returned to the wealthy urban market to get top dollar for their catch. The northwestern Atlantic is known historically for its bounty of cod and other popular species but over-fishing due to ineffective management has decimated many populations of native fish. Recently large areas of this

highly productive area have been closed to all fishing in hopes that the stocks could recruit their numbers and lasting damage could be prevented.

This crisis is a classic example of the "tragedy of the commons" (Hardin, 1968) described by economists in reference to public property. The ocean's status as a common resource has discouraged restraint of fishing activities since what one law-abiding or conscientious fisherman does not take will be gathered gladly by another. This issue has received considerable publicity and the ensuing discourse among policy makers and scientists has established an advocacy for the preservation of wild stocks. The time is ripe for aquaculture to appeal to consumers who wish to improve their diets without compromising the availability of seafood to future generations.

The City of Boston has recognized aquaculture as a potential growth sector for its marine economy. In May 1996 the office of Mayor Thomas Menino announced a request for proposals concerning the development of a production facility at Moon Island. Moon Island features an abandoned sewage storage facility with fifty million gallons of capacity and convenient access to harbor waters. As is, the facility extracts an opportunity cost from the city due to the under-utilization of property and presents the risk of significant liability in the event of personal injury on the premises. Eliminating the physical hazard and generating economic output and tax revenue will justify the city's effort toward fostering enterprise in aquaculture. The attractiveness of the project to the entrepreneur lies in the city's offer for exclusive use and development of waterfront property at very attractive lease rates. The presence of established research, engineering, processing, and marketing organizations related to ocean science, biotechnology, and seafood is expected to support the growth of

aquaculture in metropolitan Boston and presents realistic prospects of financial and intellectual return for those involved.

The development of Moon Island will rely on the demonstration of economic viability and net benefit to all parties affected. This not only includes the academic and commercial entities with explicit involvement, but also the local populace because of the facility's use of city property and a common resource of the commonwealth, the waters of Boston Harbor. The rate payers of the metropolitan Boston region have approved a multi-billion dollar improvement to the sewer system in hopes of repairing three centuries of wanton pollution. Since the activation of upgraded treatment facilities on Deer Island, natural flushing has improved the general water quality conditions of the harbor as shown by the return of marine mammals and sea birds that have not frequented the harbor for generations. Only recently has Boston Harbor again become an enjoyable place for boating and swimming and any negation of this progress is intolerable.

This thesis presents a conceptual framework for the conversion and operation of the Moon Island reservoirs as a recirculating aquaculture system capable of producing seafood without compromising the public's investment toward improving the aesthetic and ecological condition of Boston Harbor. Engineering a system of this scale capable of quickly growing fish and reliably treating their metabolic byproducts will be a demanding, complex problem. It will require identifying and properly implementing hardware that will prevent excessive amounts of suspended fecal solids and dissolved nitrogenous waste products from reaching the harbor as mandated by public policy. These regulatory pollution limits are based on knowledge of local ecology and rational predictions of its response to the spectrum of pollution associated with aquaculture. The engineering challenge is satisfying these statutes at

a cost that meets the financial limitations set by the value of the product and the expectations of investors. It is beyond the scope of this paper to address the financial details of interest to a potential investor, so economic issues are mentioned for completeness of a technical discussion rather than validation of a business plan. The goal here is to capture innovative ideas concerning component selection and system integration for the benefit of those who will have a chance to prove and implement them in the future.

The body of this thesis is comprised of three distinct sections. The description of Moon Island points out the attributes of the site that make it attractive as a site for aquaculture production. The engineering section of this thesis identifies specific components that show great potential in reducing capital, operational, and maintenance costs through simplicity and efficiency. The production example presented in the fourth section is based on a temperature-sensitive growth model for Atlantic cod (*Gadus morhua*) that estimates the production potential of the facility assuming total dedication to a single species.

2. DESCRIPTION OF MOON ISLAND AND THE RESERVOIRS

The granite-lined reservoirs on Moon Island have played an important role in local history that is not obvious from their current condition. This section provides some historical background and a physical description of the island. The former function of the reservoirs as sewage capacitors is explained.

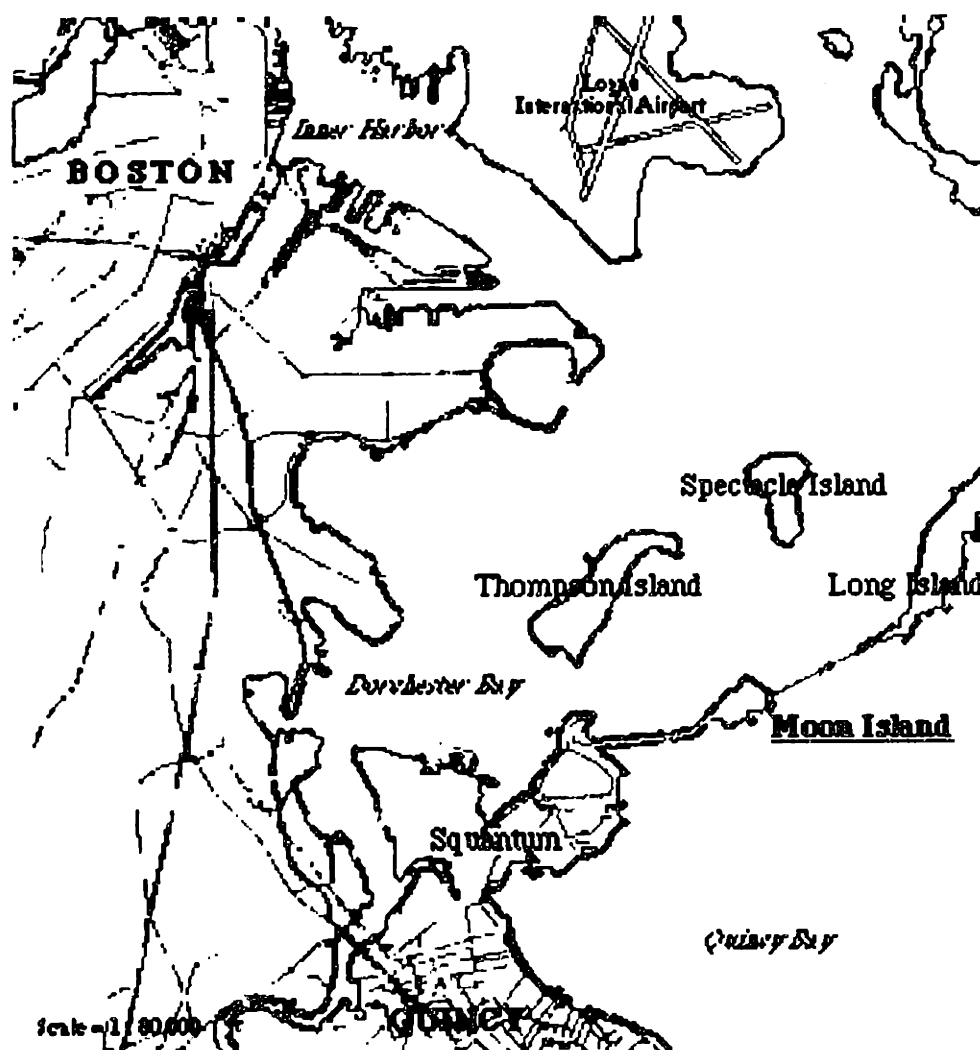


Figure 1. Boston Harbor. Adapted from NOAA chart, 1994.

2.1 LANDSCAPE, SURROUNDINGS AND HISTORY

Moon Island is found south of Boston's Inner Harbor near the town of Quincy as shown in Figure 1. It is connected to the Sqauntum peninsula by an earthen causeway on the western side and by a bridge to Long Island at its eastern end. To the north lies Spectacle Island where dredged material from various municipal projects such as the Central Artery expansion and the third harbor tunnel have been deposited. The waters of Quincy Bay lie to the south.

Moon Island is a 44.6 acre drumlin that was used in colonial times for grazing and farming. The peak of the island known as Moon Head is found at the eastern end. This hill top is partially wooded today and affords an excellent view of the nearby harbor islands and the Boston skyline. The southern side of the island features a gently sloping rocky beach and extensive tidal flats with abundant clam beds. The northeastern shore of the island that overlooks the straits between Moon and Long Islands is reinforced with a granite sea wall. The northwestern shore is similarly protected from erosion by rip-rap that has been installed along its length.

Training facilities for the Boston police and fire departments take up approximately one third of the island. The police have a shooting range at the southeast corner and the fire fighters have permanent offices and practice structures along the eastern shore. The relatively intact structures of the abandoned sewage storage facility occupy the central portion of the island. These properties are indicated in Figure 2.

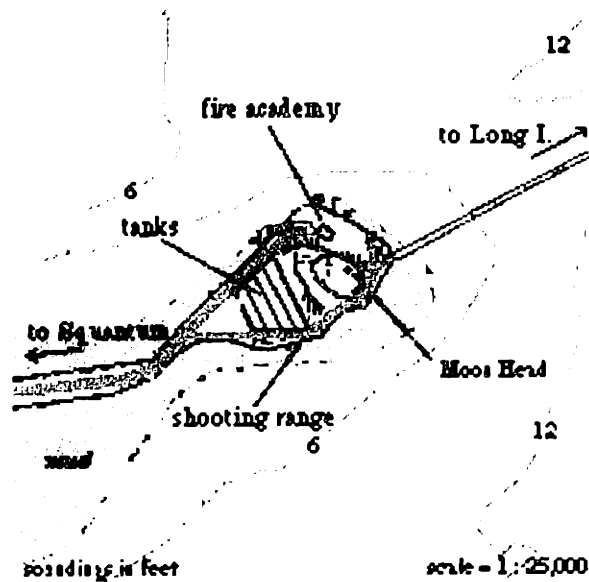


Figure 2. Features of Moon Island and local bathymetry. Adapted from NOAA chart, 1995.

In 1878 the City of Boston began construction of a brick sewer that brought sewage under Dorchester Bay to Squantum and then to Moon Island (MAPC, 1972). This outfall ended at an elaborate facility which embodied a revolution in urban sewage disposal in those days. Four granite-lined reservoirs covering approximately ten acres were constructed to hold fifty million gallons of raw sewage during the incoming tide and then release it along with the steady inflow into the harbor on the ebbing tide. Boilers and steam pistons were used to actuate the floodgates that separated the reservoirs from the dual 12-foot-diameter outfalls. In the flow-through mode the sewage stream coming from the city was partially diverted to the far end of the tanks through a flushing sewer to prevent accumulation of debris on the tank floor. This system carried the city's liquid wastes and rain water further out to sea and was seen as an improvement over the older practice of continually sending sewage directly into the Inner Harbor (Clarke, 1888).

The facility was relied upon for this function until 1968 when the treatment facility on Deer Island was activated in an effort to abate the pollution of Boston Harbor (Dolin, 1990). The reservoirs continued to handle sewage from Squantum and part of Dorchester through 1972 at rates on the order of one million gallons per day (MAPC, 1972). Until 1990 the sewer to Moon Island continued to function as a combined sewer overflow (CSO) during periods of heavy rainfall (MWRA, 1991). The Moon Island outfall was one of many relief valves for the undersized treatment system that directed untreated, albeit diluted, sewage into the local watershed. The eventual elimination of the CSO's from the system will further enhance the natural processes that are already making Boston Harbor more enjoyable and healthy than anyone alive can remember.

2.2 CURRENT CONDITION OF THE FACILITY

The first impression of the reservoir complex based on a cursory scan of the existing structures is one of decay and neglect. A quarter-century of disuse has allowed the deterioration of the wooden structures and the transformation of the tank bottoms into a littered salt marsh. A lack of railings or barriers leaves an open approach to the edge of the reservoir overlooking a seventeen-foot drop into a marshy mire strewn with litter. The tank ducts have been left open since the closing of the facility allowing a constant cyclic exchange of tidal waters between the harbor and the reservoirs through the outfall tunnels. Over time, sediments have accumulated around the high spots on the tank bottoms while channels mark the path of water that rushes out with the tide's ebb.

Although the main drainage facility has not been maintained since its decommission, the structural integrity of the reservoirs and outfall tunnels has not visibly declined. This is not

surprising considering the materials and clever design that went into its construction. The walls that enclose the basin and separate the individual reservoirs are composed of large granite blocks. These blocks were fitted and laid in mortar to seventeen feet in height with a thickness that varies from 6' 10" to 7' 10" top to bottom (Clarke, 1888). These walls are structurally intact along all four tank perimeters. The floors of the basins were lined with concrete to form alternating ridges and gutters that directed the flow during the drainage mode. The plans for the facility indicate that these floors are protected from seepage accumulation by a set of drains under the floors. Where visible under the accumulation of sediment, these floors and brick-lined gutters also seem to be in good condition.

Inspection of the discharge sewer leading from the reservoirs to the harbor water reveals little damage other than a collapsed section at the outfall's termination. The tunnels appear to be in superb condition all the way back to the reservoir gallery. The remnants of chimney-like structures that once served as gas vents can be distinguished among the rubble. An arched granite structure that was once fitted with a set of control locks remains at the northern corner of the island at the termination of the original outfall.

2.3 RENOVATION OF THE FACILITY

The Moon Island site will require extensive clean-up and refurbishment in order to provide the dependable infrastructure that an aquaculture production plant will require. One of the early steps in this process will be characterizing the sediments in the reservoirs in order to remove them legally to an appropriate dump site. An engineering assessment of the structural integrity and possibilities for improvement of the existing buildings will be necessary. The buildings will be remodeled according to the expected needs of the business

for offices, laboratories, and other support environments. Basic infrastructural improvements such as upgrading the delivery of electricity to the island, reinforcing the access road for continuous truck traffic, and reconstructing the old pier for water access will have to be identified and completed.

Once the accumulated sediment and garbage has been safely disposed and the stone surfaces have been cleaned, the floor space of the production area will be prepared. The reservoir bottoms have a slope that kept fluid moving towards the outlets during the drainage phase of the sewage handling process. This slope will have to be leveled to provide a flat surface for the installation of the culture tanks. It is important to consider other functions of this floor in choosing its materials and construction. The floor must be able to withstand the weight of the tanks' contents without shifting over time. In case of an overflow or pipe failure, it would be preferable to allow for a drainage network under the floor. Installation of drainage ducts along the existing floor gutters under a layer of graded gravel is one conceivable solution. Analysis of the settling behavior of such a porous foundation will indicate the relative benefit of reducing construction costs at the outset versus risking extensive repairs later or using a sturdier, more expensive floor design. Perhaps it will prove more cost-effective to entirely replace the existing surface to provide a more reliable foundation.

The main production area within the existing reservoirs will require a roofed enclosure to isolate it from the environment. This will protect the fish from physiological stress associated with temperature variations. The plumbing and recirculation equipment will be protected from damage due to freezing. Creating a sealed volume around the production units will curtail water consumption by limiting evaporative losses to the atmosphere. Taking

in less water and allowing it to reside in the system longer will reduce pumping and heating costs. The benefits of this roof are essential to the efficacy of the system, especially if a species chosen for production requires elevated temperatures with small temperature fluctuations.

At this juncture the site will be ready for further construction and engineering improvements more specific to aquaculture, but not yet at the level of the individual production units. The need for a continuous supply of clean sea water to the production area will have to be addressed. Determining potential locations for water intake equipment will require a survey of chemical water quality indicators, local water circulation patterns, and bottom sediment composition. The seasonal and weather induced variations in water quality, currents, and the possibility of contamination through suspension of polluted sediments must be understood as thoroughly as possible before installing the pumps and pipelines that will bring new water to the system. This water will receive some amount of pre-treatment before its introduction into the production tanks, such as biological sanitization and removal of suspended particles and fine organic debris. Heat exchange between ambient-temperature inflow water and heated effluent will improve the facility's overall energy efficiency and reduce thermal pollution. The discharge points of sufficiently polished waste waters will have to be arranged in a manner that protects the supply of oxygenated water and prevents unsafe accumulation of dissolved nutrients in local waters.

2.4 WATER QUALITY CONTINGENCIES

The designers of the facility will have to consider the possibility of extended unavailability of clean water in the event of an oil spill or toxic algae bloom. The probability

of these events might not seem alarming but to ignore this danger is to put the entire living inventory at risk. Therefore the farm must be able to isolate itself completely from the external water source until the contamination has dissipated. Contingency planning for this kind of emergency will require comparison of multiple procedures in terms of various parameters such as cost and worst-case mortality rates, for instance. The specifics of these plans will be determined by managerial criteria and the biology of the fish, but a fundamental consequence of closing the system completely will be an increase in the residence time of system water for the duration of the crisis. This means that each parcel of water will have to be cleaned and reoxygenated more often than under typical operating conditions. Including a storage area for reserve water in the facility design would mitigate this effect and allow the continued introduction of new water to the system in case of a pollution event or other problems with the intake system. It is appropriate to identify the need of such a reservoir in the initial improvement phase of the site because it will be part of the plumbing layout that supports the production units that are chosen later. A possible location for this storage volume would be within the sewer tunnel that extends through the length of the causeway back to the Squantum peninsula. The construction of this containment will require an assessment of the structural condition, water-tightness, and residual contamination of the sewer tunnel. Perhaps the tunnel can be sufficiently reinforced and sealed so that the entire volume can be utilized for storage, otherwise installing a smaller container might be expected to be more effective.

These improvements will require a significant effort in planning, research, and construction that must be justified by expectations for economic benefit. Certain benefits can be rationally anticipated in terms of reducing the city's liability by eliminating the hazardous

conditions that exist today. The opportunity cost to the city incurred through under-utilization of urban waterfront property can be offset by effecting tangible economic outputs and revenue sources like food production and employment on the parcel. The success of such an enterprise would bolster the popularity of public efforts to improve the condition of Boston Harbor and enhance Boston's global reputation as a crossroads of seafood commerce. The remaining challenge is the design and installation of recirculating production units that are capable of reliable, affordable, and adaptable production of aquatic food species.

3. ENGINEERING OF RECIRCULATING AQUACULTURE SYSTEMS

Any form of aquaculture requires application of engineering methods in order to create the culture environment, to contain the animals while they grow, and harvest them efficiently. The engineering challenges presented by an aquaculture operation are determined by the culture techniques employed, the technological sophistication of the equipment, the stocking densities achieved, and the relative priority of protecting the environment (Huguenin & Colt, 1989). The choice of a suitable culture technique relies on biological understanding of the desired species and qualification of the environmental attributes of the production site. The combination of these factors leads to an indication of the equipment that will be necessary to support the culture process. For example, filter-feeding shellfish culture is successful when the animals are attached to a reliable, retrievable contraption that suspends them in a body of clean, comfortable water that is rich in plankton (Hardy, 1991). In that case, nature provides for the biological necessities of the animals and the equipment only needs to be designed for restraint and collection of the crop. However, as production intensity increases, the potential for disturbance of ambient conditions also arises. The resulting increase in waste production alters the chemical composition of the water and the bottom sediments, thereby threatening the favorable attributes that made the site attractive in the first place. This kind of environmental feedback has been observed in many coastal open-system aquaculture around the world (Pillay, 1992). Intensive production methods that have little or no regard for protecting the water resource on which they depend have proved unsustainable due the sacrifice of long-term environmental quality to achieve maximum yield (NRC, 1992)

The Moon Island operation will be confined to a small area of land and its intake and release of harbor water will be limited. The profitability of the Moon Island aquaculture operation will be maximized by utilizing the land and water made available to their fullest. The longevity and image of the fish farm will be served by protecting the state of nature in its surroundings by reclaiming pollutants before releasing its effluent. Recirculating aquaculture systems have these capabilities and the following section will describe their advantages over other styles of aquaculture and present the component types that will be incorporated.

3.1 ECOLOGICAL PRINCIPLES

Before beginning a technical discussion it is worthwhile to consider the underlying natural processes. Although aquaculture involves a great deal of engineering, it is governed by chemical and biological processes that have arisen in nature. The clever manipulation of these processes has brought human agriculture to its advanced state. The complex and foreign nature of aquatic biological systems has postponed mankind's graduation from hunter-gatherer to farmer in the realm of aquatic food. Modern circumstances and our ever-broadening understanding of aquatic ecology are presenting aquaculturists around the world with intriguing prospects for success.

An animal growing in a recirculating system does not enjoy the benefits of nature's expansive and intricate ecosystems to protect it from exposure to dangerous concentrations of poisonous waste products. Fish excrete feces and urea as byproducts of metabolism just like any other form of animal life. The consequence of maintaining elevated stocking densities in culture systems is the need for rapid removal of these toxic waste products. Techniques for removing toxic waste products from recirculated water incorporate

the same processes that occur in nature. Biological filters rely on bacteria to process toxic ammonia (NH_3) waste into nitrate (NO_3^-) that is relatively harmless to fish (Forteath, et al., 1993). These processes form the nitrogen cycle with different species of bacteria deriving energy for cell production from each reaction.

The nitrogen cycle, depicted graphically in Figure 3, is an ecological model that tracks nitrogen in organic and inorganic compounds through organisms and the environment (Odum, 1983). In aquacultural systems nitrogen enters the cycle through two paths, either direct decomposition of uneaten feed or excretion of waste products from growing fish. Two types of bacteria, *Nitrosomonas* and *Nitrobacter* (Wheaton, et al., 1994), utilize ammonia and nitrite respectively for energy to produce cell growth, fixing oxygen in the process. Other complex compounds decompose through oxidation which creates an additional removal of oxygen from the water. These processes decrease the efficiency of an aquacultural aeration system by reducing the amount of dissolved oxygen that the fish are able to use for respiration. This fact and the inherent toxicity of reduced nitrogen species are the driving factors in the need for rapid-removal filtration systems.

High concentrations of ammonia (NH_3) in the culture system indicate potentially dangerous levels of contamination. Ammonia is excreted directly into the system by the fish and also appears as other complex nitrogenous chemicals degrade. Therefore elevated concentrations of ammonia may also indicate the presence of other metabolic wastes. Whether the ammonia or the more complex compounds are more dangerous is unclear (Forteath, et al., 1993), but their presence often explains problems with fish stress and

mortality. These chemicals serve as sources of energy for many species of heterotrophic bacteria which can infect the animals and limit the supply of dissolved oxygen.

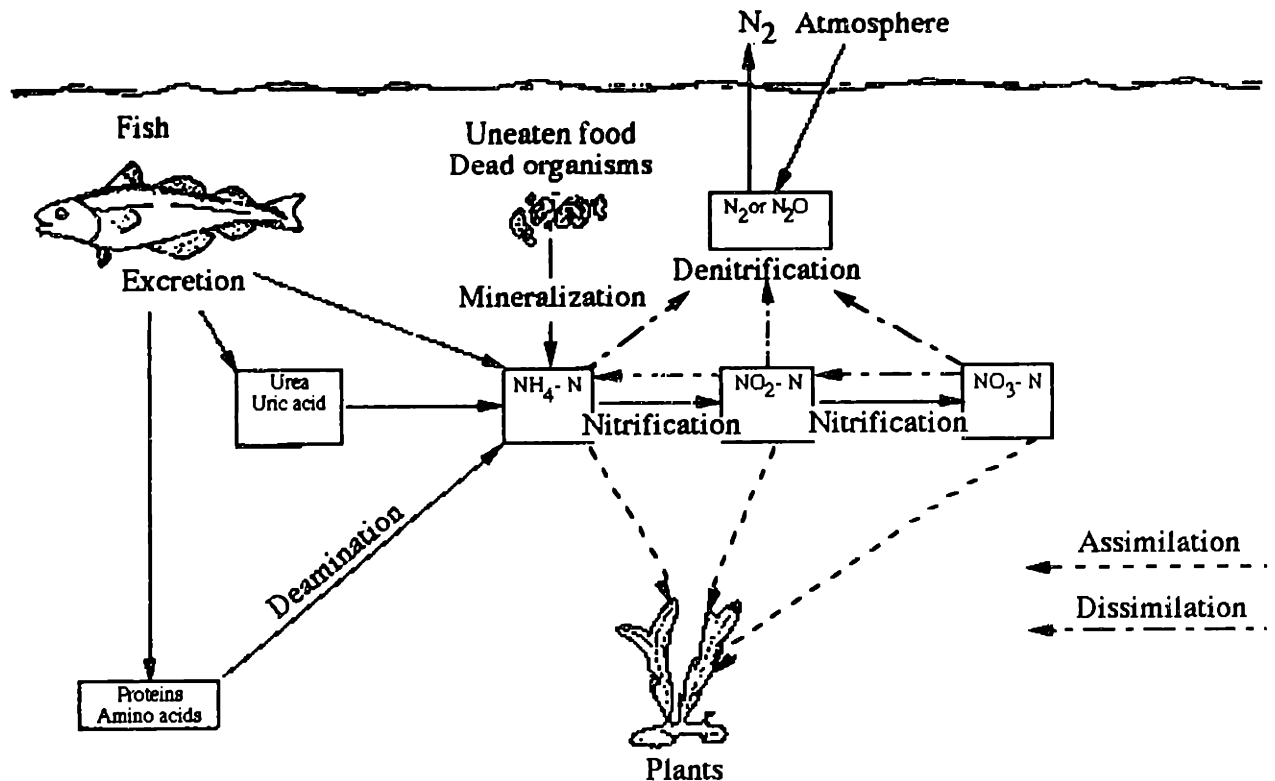


Figure 3. The nitrogen cycle in aquatic systems. Adapted from Spotte, 1979.

Nitrogen compounds are often major culprits in disturbances of marine ecosystems. As shown in Figure 3, aquatic plants use the nitrogen compounds as nutrients for growth. A shortage of nitrogen is sometimes the only limitation on plant growth until a pollution event inundates the water column with this fertilizer. A body of water can become choked with rampantly growing plants, and when these plants finally die the process of decomposition can completely deplete the dissolved oxygen present in the water column. Other organisms that

depend on this oxygen or are disturbed by the change of scenery will vacate the area in search of more pleasant surroundings if possible. The aftermath of this eutrophication process can be an unsightly, stinking, rotting mess. Since nitrates will be present in the effluent of the Moon Island recirculation systems, it will be important to understand the impact of nitrates into the harbor and model its transport and concentrations in local waters to identify the need for final effluent treatment from the system.

The complexity of these ecological systems is only hinted at here. The engineering of the Moon Island systems will not be successful or sustainable without detailed knowledge of local ecology and the chemical and physical processes of the harbor.

3.2 APPLICABILITY OF RECIRCULATION

In order to illustrate the applicability of recirculating aquaculture to the Moon Island scenario it is natural to describe other types of systems in terms of their advantages and drawbacks. In the context of finfish, other methods of aquaculture that are found in the United States include ponds, raceways, and net pens (NRC, 1992).

The first type, the pond system, is not difficult to imagine; a hole is dug, filled with water, and the animals to be raised are tossed in. This approach is not capital intensive or expensive to maintain, but requires large areas of land and significant amounts of water to compensate for evaporation. These outdoor systems are typically found at more southern latitudes where winter is not a factor and resources are cheaper, especially in Latin America and the Caribbean islands. However higher temperatures reduce the solubility of oxygen which demands heartier species. The animals that are raised must be tolerant of turbidity due to algae growth, sediment suspension, and dissolved feed. Species produced in these systems

include tilapia (an African river fish) and prawn (the freshwater equivalent of shrimp).

Environmental regulation tends to be less strict in these developing regions which gives aquaculturists considerable freedom in waste disposal. These aspects of successful pond aquaculture are not representative of any New England scenario.

Raceway systems are common in the United States and typically produce catfish (Parker & Nash, 1995) or trout (Novotny & Nash, 1995). These systems involve more advanced construction of concrete-lined channels but are similarly inexpensive to operate. Raceways mimic the conditions of a river or stream by flowing water through a graded course. In fact these systems often run parallel to natural flows, drawing water out and returning it downstream. The water is used only once and the river is relied upon to absorb the input of fecal matter and uneaten feed. These operations can have deleterious effects on downstream water quality through oxygen depletion and nutrient loading (Snow-Cotter, 1995). The pollution of a sensitive ecosystem or municipal water supply can damage the environment and threaten human health. This flow-through approach would not be acceptable in Boston Harbor due to its inability to protect the coastal environment from pollution.

The development of the floating net pen has fostered the success of salmonid aquaculture in America (Novotny & Nash, 1995). Fish are contained in rectangular or cylindrical volumes by panels of nets sewn together and weighted to retain their shape. The nets are attached to moored floating frames that provide structural strength. Extensive arrays of these pens are found all along the coast of “down-east” Maine and in Puget Sound where numerous deep inlets provide vigorous tidal currents and shelter from extreme weather. This industry has expanded to the point where few sites are available for new enterprises due to environmental restrictions (Novotny & Nash, 1995). The extensive use of Boston Harbor’s

surface for leisure and commercial activities precludes exclusive commitment to large anchored structures.

Poorly placed arrays of net pens can cause the local waters to suffer the effects of accumulation of feces and feed on the sea floor (NRC, 1992). These decomposing materials change the composition of sea floor sediments and deplete the oxygen available to benthic organisms. These anoxic sediments accumulate over time and can lead to asphyxiation of the caged fish if they become re-suspended in the water column, and threaten the health of the cultured animals. Although it is conceivable to fill the Moon Island reservoirs with water to contain similar floating structures, such a flow-through approach to life support negates the potential benefits of the reservoirs' complete isolation from surrounding waters and complicates the problem of waste removal.

The application of recirculating aquaculture technology can overcome the problems associated with these other forms when the system is properly integrated and operated. Determining the most efficient mode of operation for each component requires a systems approach analogous to the engineering of a chemical reactor. The state of the system is defined by many variables that may be affected by multiple components. As the term implies, recirculating systems are designed to reduce the amount of water necessary to raise each animal to market size by cleaning and reusing its water as often as possible. These closed systems offer a greater degree of isolation from the environment, thereby reducing stress on local ecosystems by reducing pollution and water diversion.

Although other forms of aquaculture are less capital intensive, modern recirculating systems can justify the costs with their potential of consistently increased production volume and superior quality. Unlike the natural environment, these highly-regulated systems

constantly supply clean, oxygenated water, allowing the stocking density can be increased beyond that which is possible in any other land-based setting. The reuse of culture water increases the practicality of heating water in order to maintain elevated metabolism and growth rates. The ability of a well-managed closed system to precisely monitor and adjust the conditions of the holding environment opens up the possibility of raising more sensitive and exotic species. Moon Island's proximity to a virtually bottomless market for seafood featuring many niches for specialty products will justify the costs of a technologically advanced system that can produce more fish with less water.

An entrepreneurial effort in aquaculture requires advance research and preparation in order to decide which species to produce. Each species that is chosen for culture will require individual study and understanding in order to anticipate the changing needs of the animal through its life cycle. Typically a variety of species will be examined until one or two candidates are identified for their exceptional potential for profitability. This potential has a number of influencing factors such as culture expertise, climate, engineering, and marketing possibilities. Climatic conditions and location will determine the nature of locally available water as characterized by temperature, salinity, dissolved oxygen concentration, and microbial populations. It is crucial for aquaculturists to know that their production and demand come together in a timely and cost-effective manner. Understanding the behavior and metabolism of the cultured organisms allows informed choice of components that will perform efficiently under anticipated conditions. The scale of production and the constraints on water quality determine the rates of component operation (i.e. pumps, heaters, aerators) and feeding that allow the fish to concentrate raw energy into valuable flesh.

3.3 SUGGESTED SYSTEM COMPONENTS

Any design for a containment system that recycles water may function as a life-support system for aquatic animals, but commercial aquaculture requires life enhancement. The animals must be housed in an environment that allows them to grow as quickly as their physiology and genetics can support. The goal of the design is to meet standards for water purity and composition that allow this rapid growth while keeping production costs sufficiently below the expected market price. The process of design and construction that culminates in an effective biological reactor in which fish thrive begins by selecting components of necessary function and capacity. The system components described below have been chosen for their mechanical simplicity and ease of maintenance. These characteristics will help to reduce the initial and operational costs of the facility without compromising the system's ability to maintain a near-perfect growing environment.

3.3.1 CONTAINMENT

The most basic and obvious physical element of the recirculating aquaculture system is the tank where production occurs. The phrase "fish tank" reminds one of home aquariums with bright tiny fish that are only meant to look pretty and provide a hobby. Ornamental fish enjoy spacious quarters in comparison to cultured animals and are not expected to compensate monetarily for the equipment, energy, and feed that sustain them. For an aquaculture operation to run like a business, it is necessary to derive the most benefit from the constructed tank volume by maximizing the stocking density. Each incremental increase in the amount of fish mass contained within a unit of tank volume increases the utilization of the capital invested in the tank and the equipment that supports it. This desire to hold more and more

fish in a given tank is moderated by behavioral aspects of the culture species. Overcrowding makes it difficult for individual fish to get the food they need without expending excessive energy to fight through a crowd. Fish that fall behind in food consumption will lag in growth and could become the object of harassment from bigger fish. The volume allotted to each individual fish must provide reliable access to the oxygen and nutrients needed to maintain a maximum growth rate.

A consequence of this premium on production volume is the need for uniformity in water quality throughout that volume. The water in the tank should be well mixed so that each parcel of water is guaranteed a minimum frequency of exposure to the treatment system. This way the fish are indifferent to their position in the tank and utilize its entire volume rather than avoiding areas where pollution has built up or oxygen is scarce. This will allow maximum stocking densities without risking unnecessary stress to the animals which local overcrowding in some portion of a tank could cause. Understanding the circulation patterns produced by the shape of the tank and the positions of intakes and outlets to and from the treatment hardware will shed light on the degree of mixture in the tank.

Typical designs in the industry today have a cylindrical shape which is readily available and easy to construct. These tanks feature one or more columns of injection nozzles installed on the circumference of the tanks. The nozzles are directed tangentially to the tank wall so that a circular flow is established within the tank. At the center of the tank is a drain that returns the water to the filtration system. This flow pattern insures that the water is turned over and cleaned at a dependable rate to insure water quality homogeneity and oxygen delivery. Even solid particles that are large enough to settle to the bottom before reaching the

center of the tank are pulled across the bottom by the shear flow to the center drain (Lindell, 1995).

The dimensions of the tank and the flow rates established by the pumps will determine the current speeds and the average residence time of a parcel of water within the tank. These parameters must be optimized for the oxygen uptake and waste excretion rates of the fish and the ability of the treatment system to maintain the desired levels of water quality. The assessment of these variables and the optimization is an exercise in experimentation and tuning to establish a cost-effective operating mode.

3.3.2 PUMPING AND AERATION

These functions have been combined under a single heading because of the capability of the component described in this section to perform both. This element is known as the air lift pump. Its functional multiplicity is achieved by using air to move water, which refreshes the supply of dissolved oxygen in the process. Air lift pumps exploit the physical properties of a two-phase mixture of air and water which creates an upward flow in a standpipe while contacting air and water for gas exchange. This flow is a result of the reduced density of the air/water mixture below the water line. The weight of the water outside the pipe forces the bubbly mixture to rise in the pipe allowing it to be diverted to the filtration system by the force of its own weight.

Air lift pumps are attractive for application in aquaculture by virtue of their mechanical simplicity and low cost (Van Gorder, 1991). The absence of moving parts makes them dependable and long-lasting. Their construction requires only a length of tube and a means of injecting air into the water. Air diffusers that create small bubbles are optimum because of the

increased area of the air/water interface. Air lift technology is especially attractive at a site like Moon Island to circulate salt water since using mechanical pumps for pumping sea water will corrode and increase operational costs, either by shortening the life of the pump or incorporating more expensive, corrosion-resistant materials.

The performance of the air lift pump has been studied for many years (Nicklin, 1963; Castro & Zielinski, 1980) to understand how changes in the tube diameter, the submergence ratio of the tube, and the air flow rate affect the pumping rates. There are simple equations available to estimate the flow rate for certain sizes of air lifts (Forteath, 1993). The test of an airlift pumping system will be its energy efficiency in moving water and maintaining dissolved oxygen concentrations in comparison to a mechanical pumping system with a separate aeration device. The literature available to the author did not address this facet of the problem. The energy expended by the air blowers is determined by the static head at the outlet and the frictional losses in the tubing and the air diffuser. The efficiency of the blower will be compromised by forcing it to overcome the weight of water above the diffuser, but the tradeoff is prolonged contact of air and water. Running multiple diffusers from one blower is an advantage that cannot be matched by mechanical pumping, but excessive lengths of tubing must be avoided to minimize energy loss to viscous friction. The final determination will be influenced by economic factors. Designers will have to compare the construction cost, energy consumption, operational efficiency, and failure scenarios for separated and combined arrangements of aeration and pumping.

3.3.3 SOLIDS REMOVAL AND BIOLOGICAL FILTRATION

As in the case of aeration and pumping, the goal of achieving multiple functions in the filtration of solid and dissolved contaminants is attainable. Various designs either perform mechanical straining of particulate matter or bacterial treatment of dissolved chemicals, and a subset of those achieve both to some degree. The floating bead up-flow arrangement described in this section meets both needs with minimal construction costs, energy consumption and maintenance.

Brief descriptions of other types of filters, including trickling filters, down-flow sand filters, and rotating drum filters follow for comparison before describing the floating bead filter in detail. In a trickling filter, a bed of gravel or beads provides a large surface area for bacterial attachment and exposure for the nitrification process. The simplicity of these static filters is attractive but over time the bed will clog with dead cells and trapped particles, requiring the entire volume of substrate to be manually washed. Other problems of evaporative cooling and loss of gravitational potential require additional energy for heating and pumping and make them unsuitable for large-scale application.

High-pressure down-flow sand filters perform mechanical filtration by trapping particles in the interstices of a bed of fine sand. A fresh bed of sand performs this function very well, but over time, as more particles are trapped, the resistance across the filter increases, requiring additional pumping energy. At this stage the filter becomes less efficient because the water creates paths of lesser resistance in the form of channels through the sand where water passes without treatment. Once the sand is saturated in this fashion it is necessary to replace it because of the difficulty in cleaning. This approach to mechanical

filtration is unacceptable for a large-scale system because of the labor to maintain the filters and the need for a landfill site for the contaminated sand.

Rotating drum filters pass culture water through fine screens mounted on circular drums with orifices measuring tens of microns across. The screen assembly is mounted on a rotating shaft and is suspended over a basin that collects the filtered water. Dirty water is introduced to the filter inside the drum and particles are trapped on the screen as it flows downward. The bottom portion of the screen becomes clogged and the level of water in the tank containing the drum rises. A float switch activates a motor that turns the drum to bring a clean section of screen to the bottom and a jet of water cleans the clogged portion of the screen. A trough opposite the jet catches the spray and the entrained solids. This backwash process concentrates the sludge and removes it efficiently, but there is no opportunity for bacteria to attach themselves, which makes these filters useless for nitrification. Mechanical complexity and high costs of these machines increases the attractiveness of installing fewer units of greater size. These units would be more useful for post-treatment of the farm's effluent before returning salt water to the harbor. Washing the screen with fresh water may be effective in diluting the salt content of the sludge so that settled, composted solids may have value as agricultural fertilizer.

The up-flow bead filter elegantly combines performance in solids capture and microbial treatment with the additional benefits of minimal costs of installation and maintenance and energy efficiency (Malone & Coffin, 1991). The mechanical design of the filter is surprisingly simple and relies primarily on gravity to move the water through. Figure 4 shows a diagram of such a filter and indicates its major components. An injection pipe connects to the culture system and opens into the bottom of the filter chamber. The filtration

media is composed of small buoyant beads that are readily available as cheap surplus from plastic manufacturers. These beads are restrained by a fine screen that allows treated water to exit at top through the return pipe. A motor driven propeller is situated within the filter bed for agitation of filter media. Simple plumbing arrangements allow the bypass and drainage of the filter chamber.

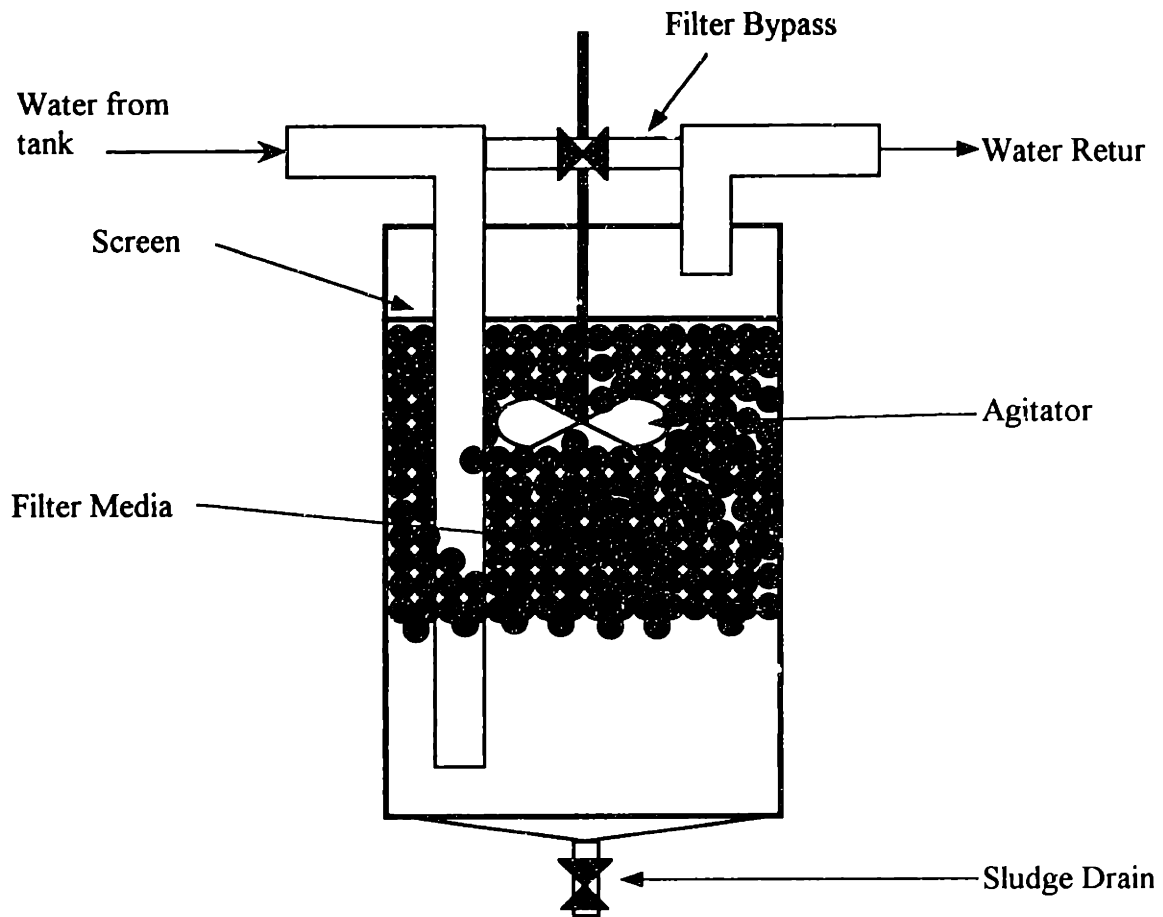


Figure 4. Diagram of a floating-bead up-flow biofilter.

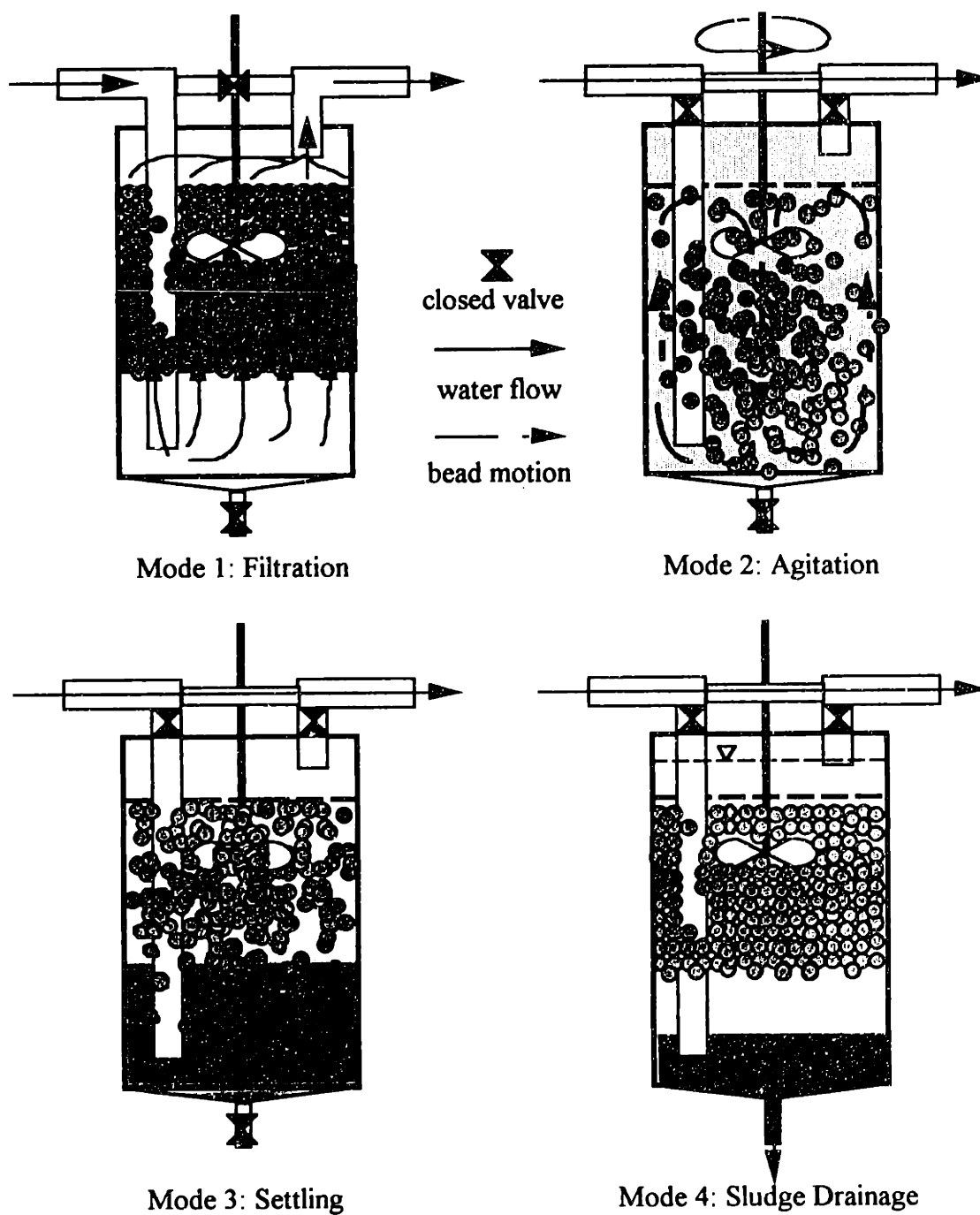


Figure 5. Four operational modes of the floating-bead biofilter.
Adapted from Malone and Coffin, 1991.

The filter's four basic operational modes are illustrated in Figure 5. During most of its duty cycle, the filter is cleaning the water that comes from the culture tank. The floating beads perform mechanical filtration by capturing suspended particles in the interstices between each other which causes a cake of feces and uneaten feed to form. As more solids enter the filter, this cake will grow and increase the pressure needed to keep water moving through. A conditioned filter that is running in a steady state will have a host of nitrifying bacteria attached to the bead surfaces. These bacteria perform the chemical filtration of the water by consuming ammonia and other dissolved compounds.

As the sludge cake grows, the flow through the filter will steadily slow and eventually it is necessary to extract the accumulated solids. This is not only important for maintaining the desired rate of water circulation, but also improves the aeration efficiency of the system by removing decomposing material that create an oxygen demand in addition to the animals' respiration. The filter is temporarily bypassed while the agitator is activated so that the water in the filter chamber is still but the remaining water in the tank continues to circulate and receive new oxygen. The agitator's stirring action re-suspends the particles that have been trapped between the beads and shears accumulated dead cell growth from the beads' surfaces. Selection of the propeller and determination of its rotation speed and duration deserve further study since excessively vigorous stirring will shear living bacteria from beads, thus depleting the microbial population of the filter (Malone & Coffin, 1991).

Once the bed has been expanded and sufficiently stirred, the agitator shuts off to allow the solids to settle. After settling the sludge drain is opened and the wastes are drained away for post-treatment. This process not only removes solid wastes, but helps to control the nitrate concentrations and salinity of the culture water by replacing the drained water with

new water from outside the system. The only other way that water leaves the system is by evaporation which leaves the nitrates and dissolved salts behind. Although nitrates are relatively harmless compared to ammonia and nitrites, there is a level (which varies from species to species) where the comfort of the animals is compromised (Forteath, et al., 1993). Marine animals can tolerate some variation in culture water salinity, but adjusting to changing osmotic pressure diverts energy away from growth, and drastic changes in salinity can be damaging.

The drainage from these filters will require treatment to meet the regulatory guidelines for the facilities effluent water quality. In an aquaculture facility of this proportion many individual culture systems, each with their own dedicated biofilter, could send sludge to a single post-treatment sub-system. This may incorporate the larger drum filters mentioned above and a hydroponic horticulture setup which employs plants to remove dissolved nitrates and other nutrients. This is not a new idea and many aquaculture operations create additional cash flow by raising a variety of herbs or vegetables (Rakocy, et al., 1992). The challenge for the designers of the Moon Island aquaculture center will be identifying a salt-tolerant species with sufficient market value to justify the effort needed to produce it.

3.3.4 FOAM FRACTIONATION

Once the floating bead filter has performed its function of removing ammonia and capturing suspended solids, its effluent may still require some “polishing” before returning to the main tank. This may be especially true following the backwash of the filter when the finest particles have not completely settled before drainage. Foam fractionation is useful in the

removal of dissolved organic carbon and suspended particulate matter of 30 μm diameter and smaller. (Chen, et al. 1994, from Chen, 1991)

Foam fractionators process system water by injecting small bubbles of air to concentrate and capture these carbonaceous substances in a foamy head that forms at the free surface. These long carbon-chain molecules have a polar charge which affects the way they interact with water. One end will tend to move away from the water once the molecule has become attached to a passing bubble, hence the descriptors hydrophilic and hydrophobic found in Figure 6. These surface-active molecules may also combine chemically with other non-surfactant substances (Rubin et al., 1963). This congregation of large molecules on the surface of a bubble increases its tensional strength thereby allowing it to resist gravity and maintain its structure. Over time many bubbles will pile up and perhaps collapse in an erratic fashion, but the undesirable matter will remain concentrated near the air-water interface until it can be removed.

Typically these devices involve a closed column with incoming water introduced at the top and treated water escaping at the bottom. An air stone or diffuser produces small bubbles at the bottom of the column that rise against the incoming flow. This counter-current configuration stimulates turbulent mixing of the column's contents ensuring thorough treatment. Figure 7 shows a conceptual diagram of a foam fractionator with a full head of foam spilling over into the collection tray.

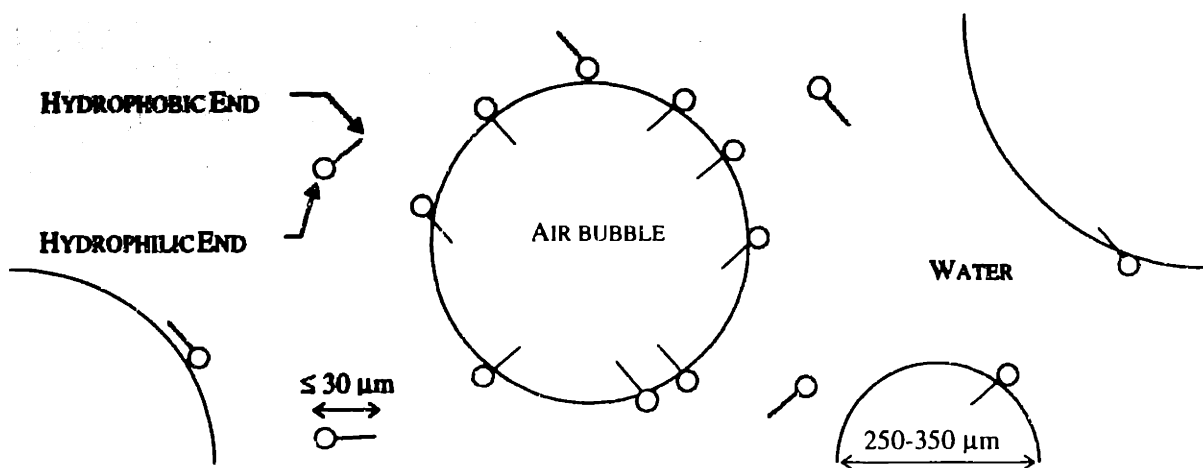


Figure 6. Representation of DOC molecules adhering around an air bubble during foam fractionation. Adapted from Ng & Mueller, 1975.

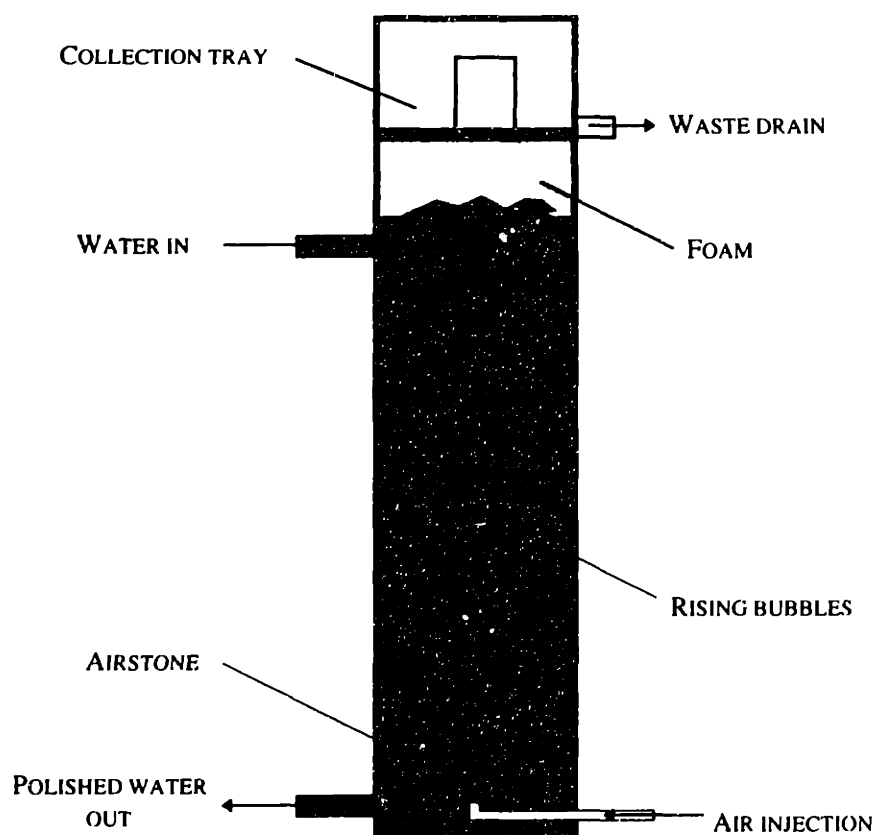


Figure 7. Diagram of a foam fractionation column.

Contact time and bubble size have been identified as the major factors determining the effectiveness of the foam fractionator. Contact time is prolonged by lengthening the foam chamber and decreasing the inflow rate. Bubble size results from the physical properties of the air diffuser producing the bubbles. Optimal ranges of these parameters will depend on the rates of particle adsorption to the bubble surface and the ratios of flow and volume of air and water. For instance one could imagine that excessive airflow would cause the small bubbles to merge into bigger bubbles and decrease the removal efficiency. The turbulent mixing action in the column minimizes the average rising velocity of a bubble and prolongs the contact of air and water. Bubbles of 250 to 350 μm have been shown to provide the most efficient ratio of contact surface area to the volume of the column (Wilis, 1993).

The attractiveness of these devices is their ability to remove fine particles and large molecules that are chemically active and will rob oxygen from the water if allowed to remain. Instead that oxygen can be saved for the respiration of the animals. Foam fractionators also clarify the water and can help avoid veterinary problems in gills and other tissues that can plague a sensitive species in overly turbid water.

3.4 COMPONENT COMPATIBILITY

This section has described a selection of components that perform a core set of necessary functions. This is not an exhaustive list of devices that are employed in modern systems, but the components here stand out in terms of their simplicity and ease of operation. The functions they perform, containment, circulation, aeration, mechanical filtration, and biological filtration are not strictly independent because of the chemical complexity of these processes, but the functions are sufficiently distinct to allow confidence that they will not

interfere with each other. The equipment described here goes one step further by incorporating functional multiplicity wherever possible. The air lift pumps aerate the water while circulating it between the tank and the filter system. The bead filters can be relied upon for mechanical and biological filtration. The foam fractionator removes the finest particles and large organic molecules while replenishing the concentration of dissolved oxygen. The final choice of the system configuration for installation at Moon Island will depend on the objectives of production and the anticipated cost and performance of commercially-available components. The sizing and arrangement of these components will require a level of detail that is not approached here, but the basic functions have been described as a foundation for further work.

4. A PRODUCTION EXAMPLE: ATLANTIC COD

One species that has been identified as a candidate for production at Moon Island is the Atlantic cod (*Gadus morhua*). The symbolic association of cod with the New England fishing industry makes it a popular product in markets and restaurants, appealing to tourists and residents alike with its unique flavor and texture. The decline of cod landings from the wild presents an opportunity for aquaculturists to profit by delivering this popular fish to a growing market. This section presents an approach to estimating the production capability of the Moon Island fish farm based on a temperature-dependent growth formula for cod and temperature data from Boston Harbor.

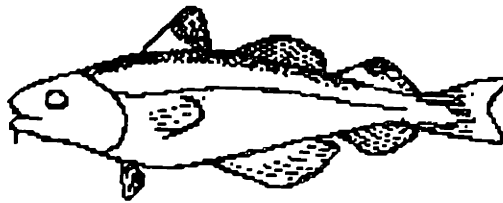


Figure 8. Atlantic cod (*Gadus morhua*) (Kaies, 1976).

4.1 BACKGROUND

The cod fishery of the northern Atlantic has a rich history reaching back to the fifteenth and sixteenth centuries when substantial catches were first recorded. The cod's importance as a commodity in the economy of Massachusetts has been recognized since colonial times when it was protected as early as 1639 by an early manifestation of conservation law. This law of the Massachusetts Bay Colony ordained that cod was to be excluded from use as an agricultural fertilizer. The "sacred cod" is a symbol of the

commonwealth and a golden likeness of a codfish hangs in the Massachusetts State House (Kales, 1976).

Unfortunately the cod's revered status has not protected it as a common resource. Groundfishing activity on George's Bank in the Gulf of Maine has traditionally focused on cod and the grim efficiency of today's technologically-equipped fishing fleet has decimated its populations in these waters. This fact is revealed in National Marine Fisheries Service statistics reporting a 33 percent decline in cod landings between 1991 and 1992 (Howell, et al., 1995, from NMFS, 1993). Efforts to preserve this fishery through quotas, size restrictions, and a recent moratorium have not demonstrated success in protecting the sustainability of this fishery.

American and Norwegian efforts to enhance the wild populations through hatchery science released billions of cod larvae into the wild from the end of the nineteenth century through the 1950's (Øiestad, 1993). However, no methods were available for tagging the young animals to show that any had survived or that any survivors had succeeded in procreation. These programs lost support in America because of the lack of evidence demonstrating their cost-effectiveness in increasing the wild populations.

These early attempts at stock enhancement and subsequent studies of cod ecology and nutritional composition (summarized in Dahl, et al., 1984) formed a basis for current research in broodstock management and larval rearing. Researchers at the University of Maine, University of Rhode Island and the University of New Hampshire are working to establish culture techniques and specialized diets to allow captive larvae to develop (Howell, et al., 1995). Larval survival rates achieved recently by Kling at the University of Maine will make hatchery production of juvenile cod feasible once the techniques are proven in the laboratory

and applied at a commercial scale (*Atlantic Fish Farming*, 1996). Reports of successful rearing of cod larvae to a juvenile size in the hatchery facility of the Island Aquaculture Company of Swans Island, Maine are very encouraging (Jones, 1996). Manipulation of the spawning process is also being investigated through photoperiod adjustment, a technique which has been successfully applied to various salmonid species. Induced spawning allows hatchery managers to provide juvenile fish year round rather than waiting until late summer as dictated by the natural cycle. Assuming that reliable methods can be developed in the laboratory and in turn applied at a production scale, cod farmers will be able to purchase juvenile cod on a more convenient and practical schedule.

The deliberate culture of cod for market and stock enhancement is well established in Scandinavian countries, but intensive culture in land based systems has not received much attention because of the incredible availability of sheltered coastal sites in the region's fjords. It has been presumed that land-based culture of cod would be infeasible due to the additional cost of constructing and maintaining recirculating systems (Huse, 1991). However, this study can be declared worthwhile through two assumptions. The local popularity and historical connotation of cod should help to increase its marketability in New England. Advances in recirculating technology, development of affordable feeds, and the general growth of the industry from the time of Huse's commentary to the future date of a fish farm opening on Moon Island will go a long way towards reducing equipment and operating costs. In the event of the wild cod fishery's revival, cod aquaculture on Moon Island could continue by marketing younger cod which the fishermen cannot take legally. Assuming that the market will absorb the product without drastically depressing prices, the scale of production conceivable at Moon Island, increased efficiency of basic equipment, and reduction of risk

through sophistication of culture practices are assumed to be sufficient to make the culture of Atlantic cod worthwhile in the future.

4.2 GROWTH MODEL

In order to properly design a culture system for a specific animal it is necessary to have some estimate of how fast the fish are able to grow. Although this rate is certainly affected by many factors concerning the nutritional content of their feed, a simplified approach is sufficient for making a preliminary determination of growth trends.

Bioenergetics predict that maximum growth rates will occur at a temperature where food intake is maximum and energy required for maintenance metabolism does not inhibit energy conversion into additional growth. Since appetite peaks at some intermediate temperature in a fish's survivable range and maintenance metabolism increases with temperature, maximum growth rates will occur slightly before this peak in appetite (Jobling 1988). It has been shown that growth rates in fish decline with increasing body weight (Brett 1979) and this trend has also been investigated specifically in cod (Jobling 1983, Braaten 1984). A growth model presented by Jobling (1988) conveniently expresses percentage growth rates per day in terms of water temperature and animal weight. The expression stated in Figure 9 was derived from a regression analysis of laboratory data from Jobling's own work as well as earlier studies (Braaten 1984, Jobling 1983).

$$\ln G = (0.216 + 0.297 T - 0.000538 T^3) - 0.441 \ln W$$

G ≡ growth rate	[% body weight day ⁻¹]
T ≡ water temperature	[°C]
W ≡ body weight	[g]

Figure 9. Growth rate model for Atlantic cod.

This equation is based on a small sample size and the actual data is somewhat scattered ($n=11$, $R^2=0.71$) but allows a reasonable approximation. It should be noted however that large sexually mature cod have exhibited higher growth rates at temperatures below the optimum for smaller specimens (Pedersen & Jobling, 1989). Figure 10 shows a graph of the growth rates versus temperature for cod of three weights. For cod of any weight the value of G reaches a maximum value around 13.6°C. Investigation of this equation reveals important information concerning the development of the “typical” cod. While smaller cod exhibit the greatest daily relative growth rates, larger specimens are adding weight at a greater absolute rate. At the optimum temperature a 10g cod is adding 6.6% of its weight, 0.66g, while a 1000g cod is adding 0.9% by weight, or 9 grams of growth on that day.

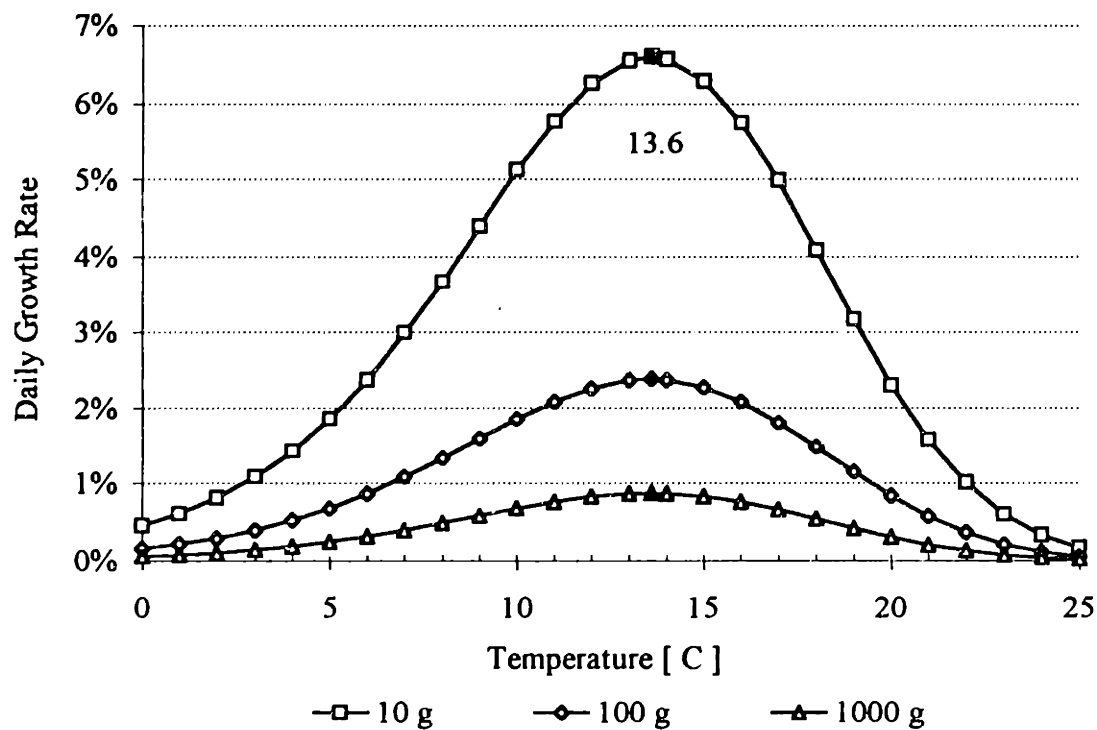


Figure 10. Growth rates for cod of three weights.

Temperature is not the sole parameter determining growth rates and this example is only limited to this variable for convenience. It is assumed that other factors such as feed content, feeding frequency, control of disease and parasites, and minimization of physiological stress caused by handling and sudden changes in water quality will contribute to the attainment of optimal growth rates, possibly beyond those predicted by this model. These effects have yet to be quantified and this example assumes that Jobling's model provides sufficient accuracy for a reasonable approximation of a cod's growth history when coupled with the temperature function that the animal will experience.

4.3 BOSTON HARBOR TEMPERATURE MODEL

Water temperature in Boston Harbor is monitored on a regular basis by the Massachusetts Water Resources Authority (MWRA) at a number of stations. For this model it is necessary to incorporate data that will be most characteristic of the water that the Moon Island facility would use. There is a sampling station on Moon Island itself called Station 48 by MWRA. This station is situated at the far end of the drainage works where the tunnel empties into the harbor. This outlet has functioned as a CSO since the shutdown of the Moon Island sewage reservoir system. The MWRA maintains a monitoring program to study the outputs of all CSO's in the metropolitan drainage system and how the current improvements to the system affect their performance. CSO's are primarily active during the rainy season since there is no distinction between storm drains and sewers in Boston. Therefore the data from Station 48 do not reveal any information from the colder months of the year and are insufficient to formulate a year-long growth model.

Station 139 of the MWRA sampling network is found nearby on Hangman's Island which is located at the mouth of Quincy Bay, just south of Moon Island. This station is close enough to Moon Island to assume that data recorded there will be representative of the water coming into the Moon Island facility. Station 139 provides data for a study of nutrient concentrations in the harbor that serve as an indicator of the progress of the harbor clean-up effort. The MWRA records measurements of water temperature, salinity, and dissolved oxygen concentrations from various depths in all seasons at numerous stations in order to fully characterize the water quality of the harbor.

The data employed in the formulation of the cod growth model are designated as bottom samples in the MWRA database. These samples are from an average depth of 4.9m, ranging from 3m to 8m. Water intakes for the Moon Island system will be located on the sea floor to preserve the navigability of these waters. Use of bottom water is advantageous to the management of the aquaculture system because of the relative stability of water quality relative to surface waters. Shallow coastal waters exhibit a strong tendency to stratify in summer because of differences in water density between surface and bottom water. Surface water absorbs the heat of the sun and is diluted by rainwater and freshwater run-off. These factors are sources of variability in temperature and salinity that would interfere with performance predictions for the system. At the same time it will be important to understand the behavior and composition of bottom sediments for the design and installation of the intake equipment. The machines should be able to exclude sediments from the water they draw and should not be placed in areas of the harbor where toxic substances that leach into the water or become re-suspended with fine sediments exist in unacceptable concentrations.

The graph shown in Figure 11 below plots the temperature data from the Hangman's Island station that are employed in this model along with the summertime data from Moon Island. The data that was available for the Moon Island station agrees with the trends in the Hangman's Island data, so it is assumed that the temperatures from Station 139 are representative of the water that would be used at Moon Island. These data are included in an appendix to this document along with the corresponding sampling depth, salinity, and dissolved oxygen concentration. The readings vary from -1.6°C (29.1°F) in February 1994 to 20.7°C (69.3°F) in August 1995. These data were used to find a mathematical representation of the water temperature trends over a "typical" year. To accomplish this the year fraction of

the date for each point was calculated and used as a sorting index for the set. That is to say that the data were sorted only by month and day, in effect compressing three actual years of samples into one nominal year. The set is then divided into three subsets so that the temperature trends could be captured by a series of quadratic functions. These curve fits are presented in Figure 12 as functions of the decimal year fraction of the dates represented.

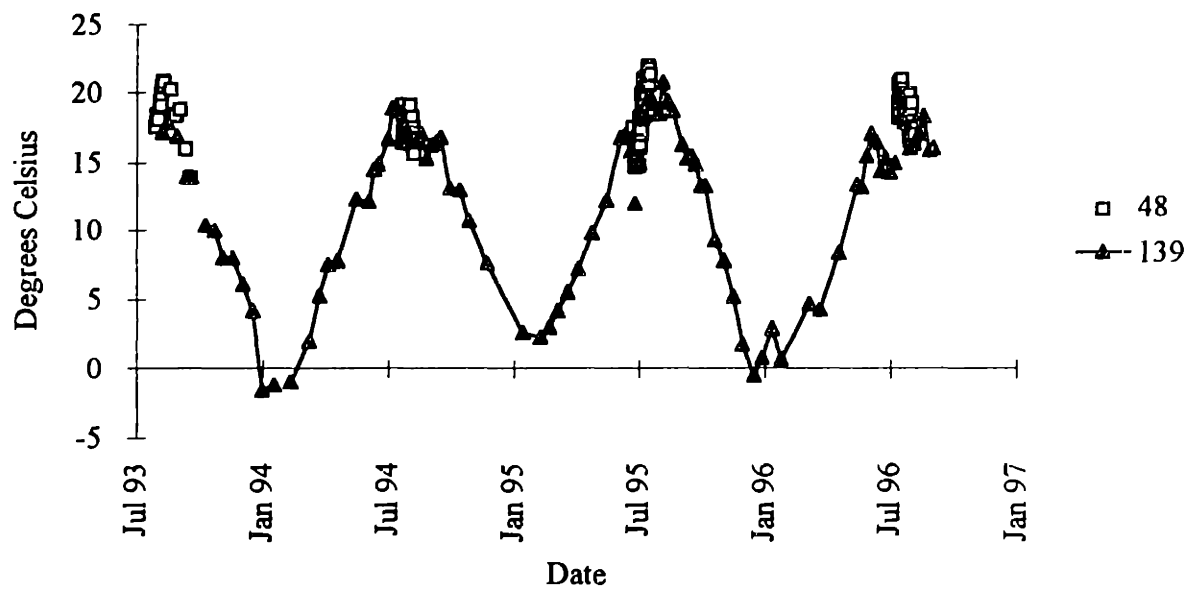


Figure 11. Boston Harbor water temperature history (MWRA, 1996).
Station 48 is Moon Island; Station 139 is Hangman's Island

This example does not claim that this set of curves is based on the best possible set of intervals or number of intervals, but the uncertainty of future temperature trends allows some liberty in the determination of a reasonable approximation. The March-June curve fits the data exceptionally well and the other two make-up for their relative inaccuracy by at least placing the peak temperature at the correct time, more or less. As later figures will show, the tails of these do not match very well, causing abrupt jumps in the overall temperature

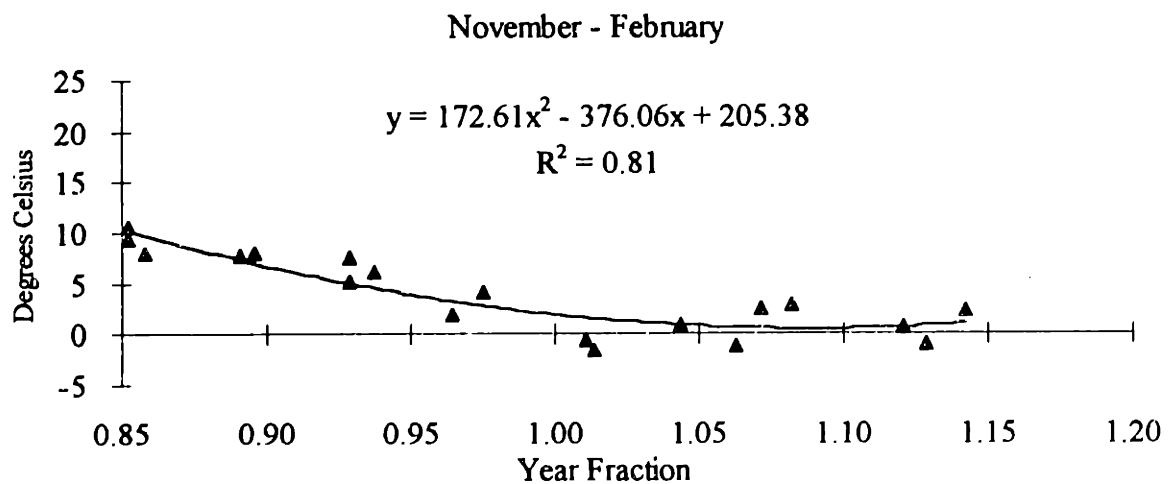
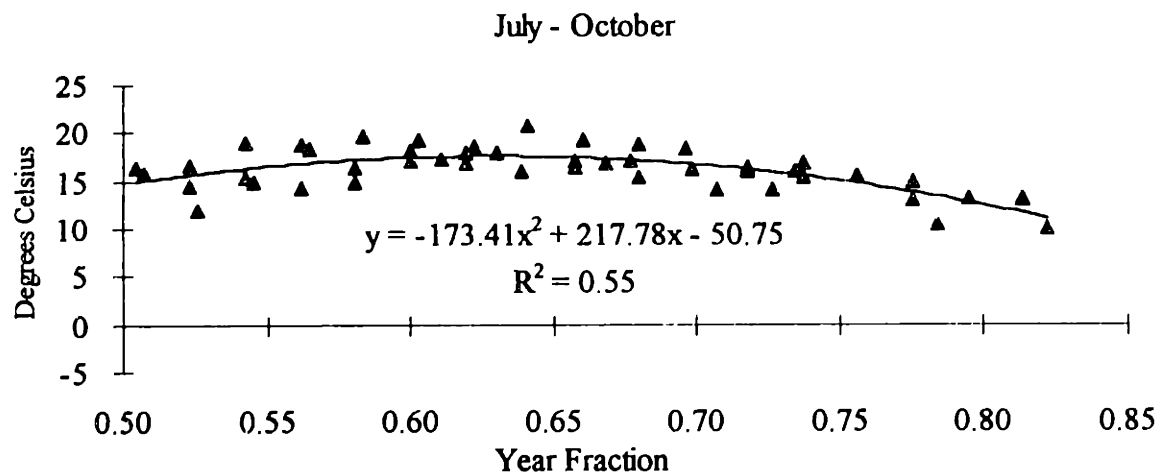
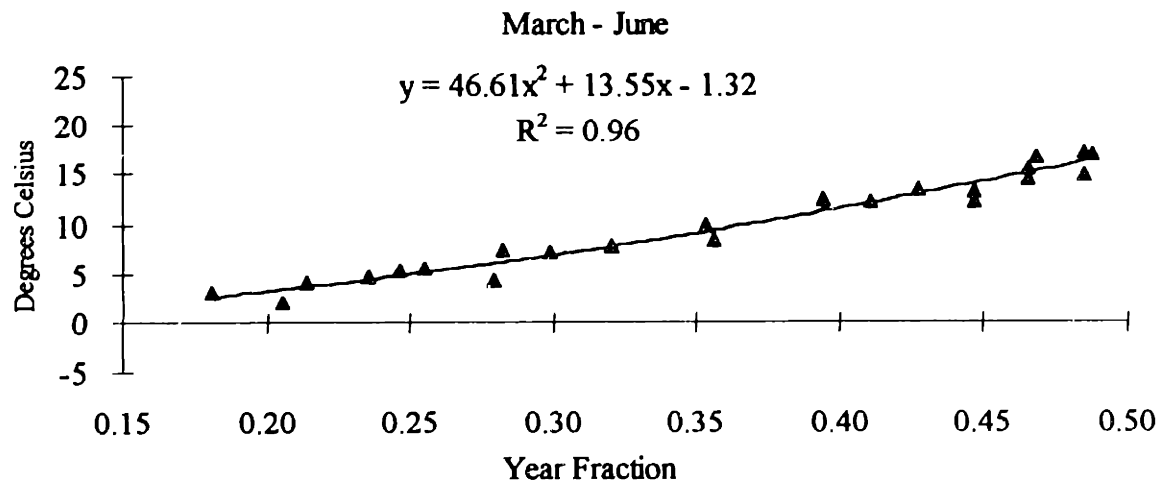


Figure 12. Temperature model using three quadratic curve fits.

function. It is more important to preserve the accuracy of each curve in relation to the data it represents rather than adjusting the constant offsets to get a smooth transition from one period to the next.

4.4 RESULTS

With Jobling's growth model and the temperature function for Boston Harbor waters in hand, it is a simple matter to formulate a spreadsheet model that tracks fish growth. Assuming that twenty-gram fingerlings could be delivered to the production facility on any day of the year, it is possible to simulate the growth of a fish from that day until the day it reaches a marketable size. The spreadsheet has a row for each day in the grow-out period which computes the water temperature for that date and the growth of the fish based on the temperature and the fish's cumulative weight from the day before.

In order to get a rough estimate of the marketability of a farmed cod the author arranged a personal interview with Mr Roger Berkowitz of Legal Sea Foods in August 1996. Mr. Berkowitz indicated in this meeting that a 1500g whole cod would be very appealing in his restaurant to be billed as a "scrod", or young cod (Berkowitz, 1996). This weight is used as that the target finishing weight for this model.

The first application of the spreadsheet model was to determine the number of days necessary to bring a cod to this final weight. Initially, before the development of the temperature model, the temperature input was held constant at its optimum value, 13.6°C. Under this condition the model predicts growth to 1500g within nine months. While this result is encouraging from the perspective of inventory turnover, it is important to keep in mind the increase in cost incurred by the installation of heating and chilling systems necessary

to maintain a constant temperature. With this in mind the temperature model was employed on a nine-month time scale to compare the effects of total temperature control versus no temperature control. Starting 20g cod on the first day of each calendar month and noting its predicted weight at the end of nine months reveals the extreme sensitivity of the nine-month growth cycle to the starting date. The model predicts weights from 377g to 796g under these conditions. This variability is unacceptable from the perspective of a farm manager working to establish a production schedule that utilizes the production system efficiently.

The elimination of this sensitivity is the next step in the refinement of the growth model. The author discovered that extending the growth period to a whole year drastically reduced the model's sensitivity to starting date. Regardless of the date of introduction to the production system, the final weights after one year fell within a six gram margin ranging from 886g to 893g.

In order to reach the desired weight of 1500g, the author hypothesized that setting a lower limit on the system water temperature would raise growth rates during the colder months. This modification represents the addition of water heaters to the facility's recirculation system. This hypothesis proved correct and calculations pegged this lower threshold at 8.5°C. The model maintained the insensitivity to starting date after this modification. These results are summarized in Table 1.

Plots of the growth trends calculated by this model give insight concerning these results. Figures 13, 14, 15, and 16 present graphs of four sets of grow-out conditions for

		Final Weight [g]											
Start Date		1 Jan	1 Feb	1 Mar	1 Apr	1 May	1 Jun	1 Jul	1 Aug	1 Sep	1 Oct	1 Nov	1 Dec
Grow-out Period													
		No Temperature Constraint											
9 months		508	679	792	796	725	578	445	377	395	413	395	405
12 months		887	886	887	888	890	893	891	891	891	893	893	889
		Temperature 8.5 C Minimum											
12 months		1504	1504	1504	1503	1503	1507	1505	1505	1504	1507	1508	1504

Table 1. Sensitivity of final weight to starting date, length of grow-out period, and temperature control (weight in grams).

investigation and comparison. The four cases form a matrix with two different starting dates and two different temperature functions. The two starting dates are the best and worst cases from the first row of Table 1, 1 April and 1 August. Figures 13 and 14 show the model results when the full range of temperatures predicted by the Boston Harbor model is experienced by the fish. The last two sets of graphs, Figures 15 and 16, incorporate the temperature constraint that brings the final weight above 1500g. The weight of the animal at the nine-month mark is indicated by a diamond on the graph for comparison with the results in Table 1. Each figure shows the curves of the temperature input, the daily growth rate, the absolute daily weight increase, and the cumulative growth curves for the case indicated in the caption.

As previously mentioned, the temperature function exhibits some jagged incontinuity in transition between the three regimes. This behavior is reflected in the graphs of growth rates and weight increase. Since the jumps are small and the rest of the temperature curve ignores higher-order variations, it is not necessary to smooth the temperature function.

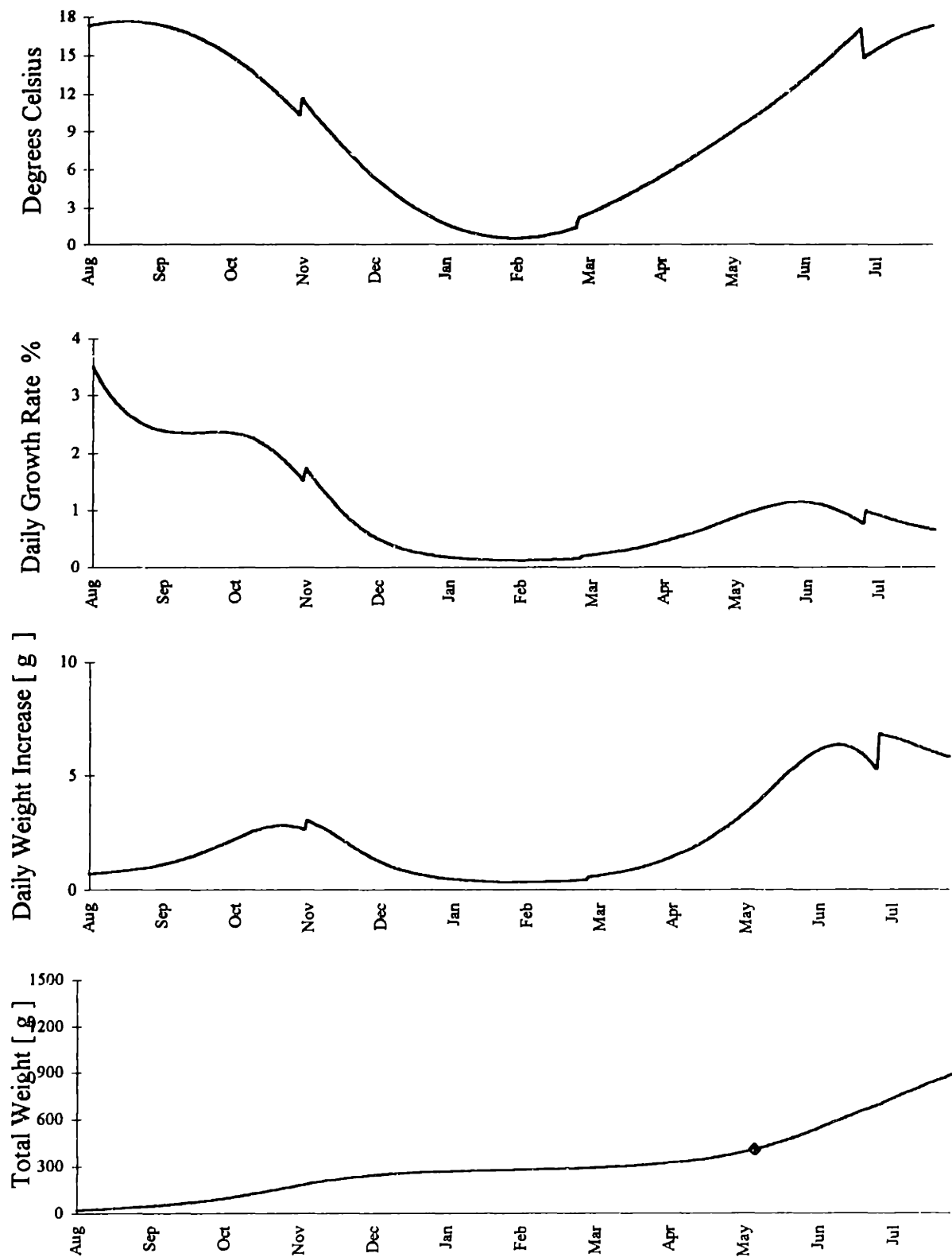


Figure 13. Growth history of 20g cod started on 1 August, no temperature constraint.

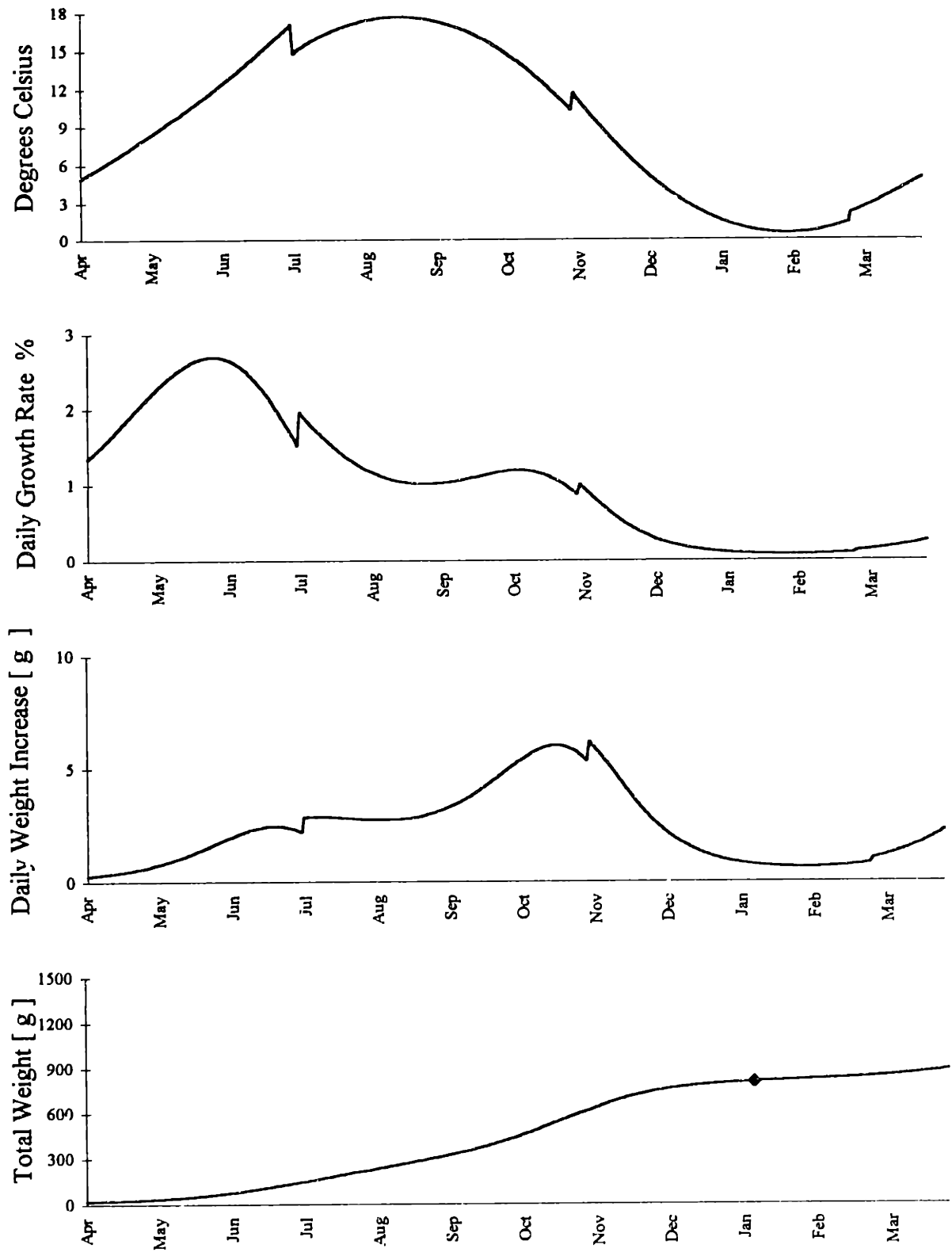


Figure 14. Growth history of 20g cod started on 1 April, no temperature constraint.

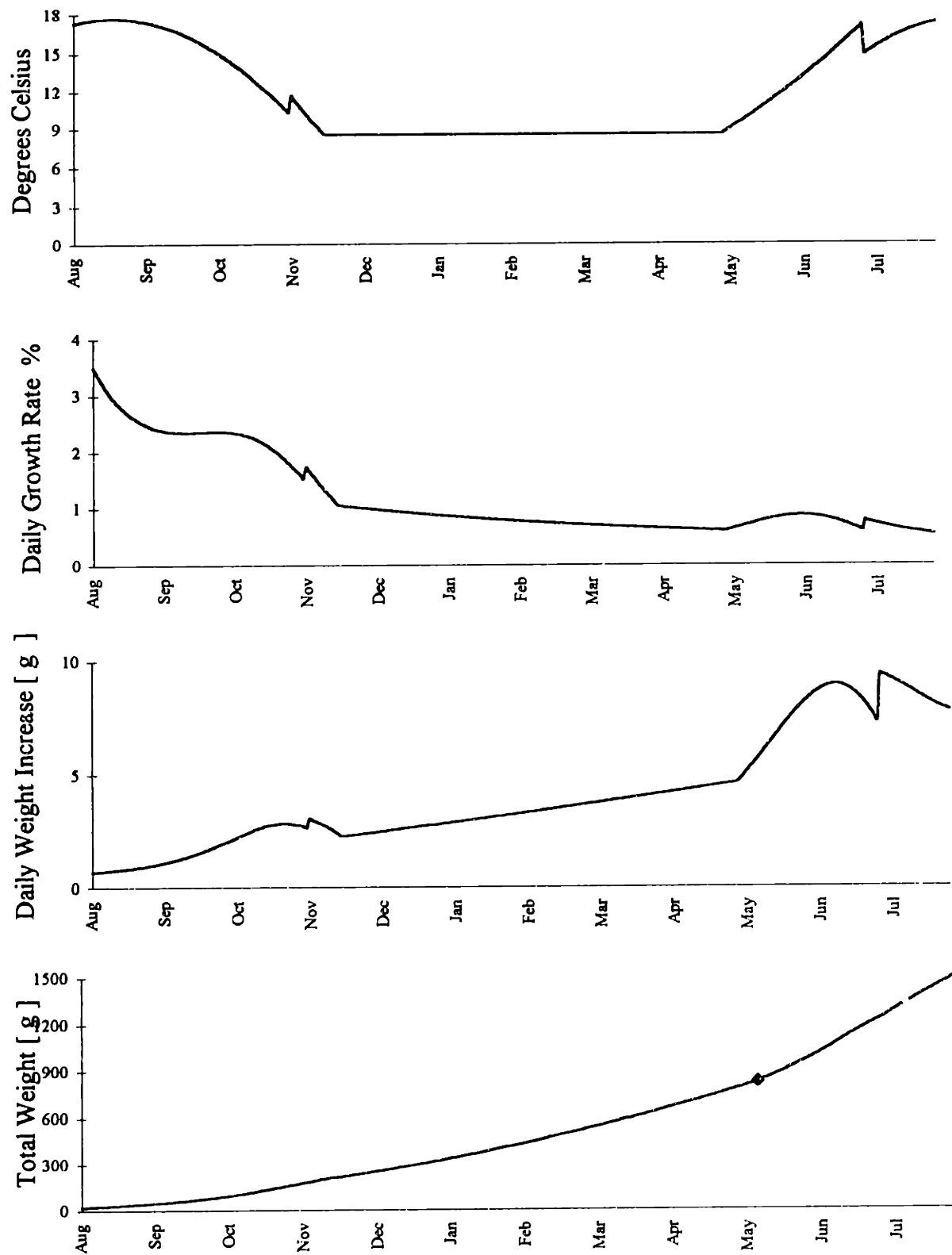


Figure 15. Growth history of 20g cod started on 1 August, 8.5°C minimum temperature.

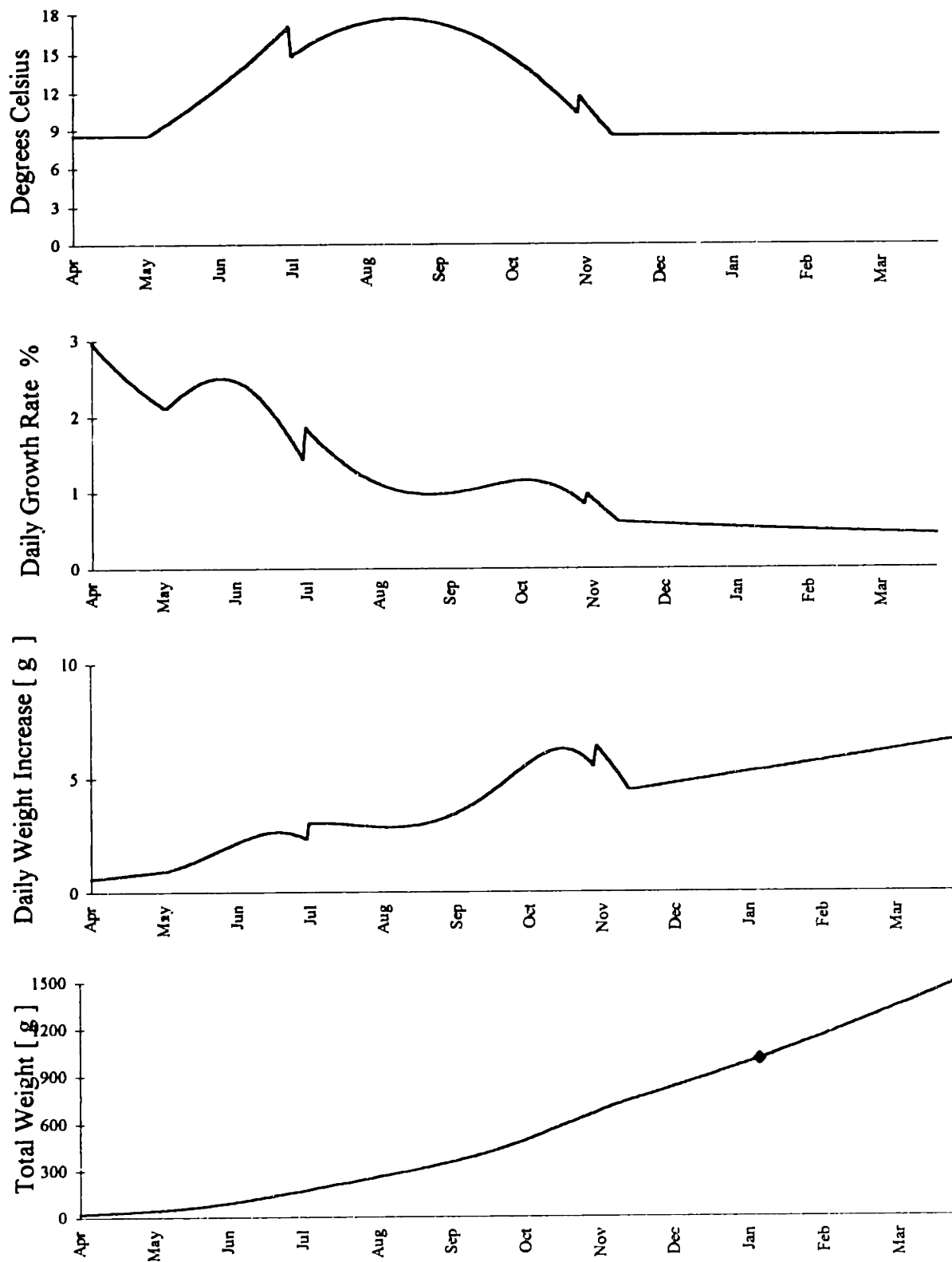


Figure 16. Growth history of 20g cod started on 1 April, 8.5°C minimum temperature.

Comparison of the first and second charts reveals the response of the model to the extension of the growth period. When a 20g cod is started on the first of August its growth performance is comparable to that of the fish started on 1 April through the first four months of growth. After this point the April starter experiences a peak in the amount of weight added each day while the temperatures it experiences pass through the optimum range. The August starter does not experience this explosion until the final months of a year-long period, hence its poor performance in the nine-month cycle.

The last two charts show the growth patterns exhibited by fish that start on the same dates but do not experience the extreme cold of the winter waters. The curves are identical up to the point where the temperature limit is reached and the heating system kicks in and the water temperature is constant at 8.5°C. This stretch of constant temperatures clarifies the effect of the weight feedback term in Jobling's growth rate equation. The only change over this period is the increasing weight of the animal which causes a proportional decrease in the logarithm of the growth rate. However the resulting weight increase is enough to translate the declining percentage growth rate into a steadily increasing weight increase.

In order to determine a rough production schedule it is necessary to identify a number of growth stages and their lengths. These stages correspond to a progression of tanks that grow larger along with the fish. For this study there are six growth stages, each two months in duration. The number of stages is arbitrary, but it makes sense to make them even so that each tank in the set is reaching its capacity about the same time as the others. It is important to keep cod of similar sizes together in order to prevent stress and mortalities caused by harassment, exclusion from feeding, and cannibalism. The qualification of these behaviors is beyond the expertise of the author, but it stands to reason that large carnivorous fish will tend

to pick on smaller individuals. Naturally every fish in a group will not achieve the exact same growth rates at each moment in their growth cycle so it is necessary to assume that the growth patterns described here represent an average fish with the remainder of the group falling in some statistical distribution centered on this average. Therefore some system of grading and sorting fish by size will have to be devised for the transfer process.

Another factor that is important in determining the production capacity of the Moon Island production system is the stocking density. A production manager will aim to maximize the mass of fish accommodated by each unit of production volume without causing physiological stress to the fish. Employing this strategy successfully will drive the output of the farm to a maximum, barring catastrophe. Stocking densities typically reported for cod raised in net pens are in the range of 30-35 kg m⁻³ of cage volume but the fish tend to congregate at the bottom of the cages leading to ineffective use of the available space (Jobling & Pedersen, 1995). It is reasonable to assume that this distribution problem can be overcome, perhaps by dimming the lights or limiting the depth of the tanks to simulate conditions to which a ground fish would be accustomed. Therefore the stocking density for this example is set at 70 kg m⁻³ by assuming that the fish in the previously-mentioned cages occupied the lower half of the cage volume.

Finally, it is important to remember that no matter how carefully the system is maintained, mortalities will occur. Since cod have not been raised in systems of this nature it is difficult to state the rate of mortality in the growth cycle. Another numerical model of a recirculating system for raising tilapia uses a 97.5% survival rate over the length of the growth cycle (Losordo & Westerman, 1991). The tilapia's 120-day grow-out period is markedly shorter than the cycle for these scrod, so it is reasonable to arbitrarily adopt a 90% survival

rate for this example in light of the lack of published guidelines. Over one year this survival rate translates into a daily mortality rate of 0.0289% for large numbers of fish. This fraction of fish is subtracted each day from the population tracked along with growth in the spreadsheet model. This assumption in conjunction with the stocking density assumption will be important in the determination of tank sizes.

Keeping these assumptions in mind, the development of this production model continues by tabulating the weight achieved at the end of six two-month stages by twelve groups of fish, started on the first day of each month. The choice of tank size for each stage depends on the maximum size of fish that it must have room for at the end of a two-month growth cycle. The intermediate weights achieved during the growth process are still extremely sensitive to the fishes' starting date despite the relative stability of the final weights. The weight progression predictions from this model are presented in Table 2.

Stage (after Start Date	I 2	II 4	III 6	IV 8	V 10	VI 12 months)
	[grams]					
1 Jan	73	173	393	672	1106	1504
1 Feb	73	193	429	719	1129	1504
1 Mar	73	227	441	793	1129	1504
1 Apr	83	254	476	813	1129	1503
1 May	106	263	537	813	1128	1503
1 Jun	110	266	520	770	1078	1507
1 Jul	92	268	463	699	991	1505
1 Aug	90	251	425	651	982	1505
1 Sep	109	242	412	635	1049	1504
1 Oct	101	218	380	633	1052	1507
1 Nov	78	181	329	629	981	1508
1 Dec	73	173	346	657	1015	1504
Maximum	110	268	537	813	1129	1508

Table 2. Six growth stages at two-month intervals, target final weight of 1500g.

The maximum weight achieved at each stage by any of the twelve growth groups appear in the bottom row of Table 2. As described above, these weights determine the sizes of the six tanks that will form a standard production unit. This method will insure the capacity needed for the fastest growing groups of fish regardless of the time of year. It is true that this will lead to under-utilization of the tank volume over time since there is a substantial margin between the maximum and minimum weights in the six stages, but this only means that the water levels in the tanks can be lowered, thereby reducing the water intake demand of the system.

Perusal of catalogs featuring commercially available steel tanks (Peabody TecTank, Inc. of Parsons, KS; Columbian Steel Tank Co. of Kansas City, KS) reveals some available sizes. A standard depth for these tanks is sixteen feet, which is convenient for installation in

the seventeen-foot-deep reservoirs on Moon Island. The process of choosing tank diameters begins with the largest tank, the site of the final growth stage. For this example the largest tanks are 65' in diameter simply because two of these can fit across three out of four of the Moon Island reservoirs (refer to dimensions in Table 5 below). Setting the water depth determines the volume in this tank. Dividing this volume by the stocking density yields the total mass of fish that this tank can hold. Dividing this mass by the maximum individual mass, 1508 g, gives the number of individuals in the tank at the end of that growth cycle. This number is 90% of the number of individuals introduced in the first growth stage. The determination of the remaining five tank sizes is an iterative, trial-and-error process from this point that uses the decreasing populations and increasing weights through the growth period. Table 3 shows a possible set of tanks based on this method, which incorporates the previously stated assumptions and results and the sizes listed in the catalogs. It is assumed that the tanks will be no deeper than sixteen feet and the depth of the sixth and final stage was adjusted so that the other tank depths meet this constraint. Each stage shows the status of the tank at the beginning and end of its two-month duration as the fish are transferred from one tank to the next and finally harvested at the target weight.

Stage	Tank Diameter		Water Depth		Volume		Maximum Population	Start Weight	Minimum Population	End Weight
	[ft]	[m]	[ft]	[m]	[m ³]	[gal]		[g]		[g]
VI	65	19.8	15.0	4.6	1409.5	372341			65446	1508
			11.4	3.5	1074.0	283710	66586	1129		
V	55	16.8	16.0	4.9	1074.0	283710			66586	1129
			11.7	3.6	786.9	207880	67772	813		
IV	48	14.6	15.4	4.7	786.9	207880			67772	813
			10.3	3.1	529.2	139787	68980	537		
III	42	12.8	13.5	4.1	529.1	139785			68979	537
			6.9	2.1	268.9	71047	70200	268		
II	29	8.8	14.4	4.4	268.9	71047			70200	268
			6.0	1.8	112.2	29642	71495	110		
I	18	5.5	15.6	4.7	112.2	29642			71495	110
			2.9	0.9	20.8	5489	72717	20		

Table 3. Choice of tank sizes based on stocking density of 70 kg m⁻³ (0.58 lbs gal⁻¹).

These six tank diameters determine the amount of floor space required for installation of a complete production unit. Each tank will be accompanied by the pumps, filters, and other equipment necessary for its operation, so providing a square footprint of a width equal to the diameter of the tank plus four feet is used for this estimate. Adding these areas together gives the floor space required for each production unit without specifying the geometric arrangement of these tanks and their supporting equipment. Table 4 presents these results.

Stage	Area [ft ²]
VI	4761
V	3481
IV	2704
III	2116
II	1089
I	484
Total	14635

Table 4. Floor space required for one six-stage production unit.

Reservoir		1	2	3	4	Overall
West wall	[ft]	873	782	678	576	576
East wall		950	873	782	678	950
Width		122	145	165	162	594
Area	[ft ²]	104833	114200	115331	97185	
Grow-out Units		7	7	7	6	27

(27 grow-out units)(65446 cod per unit)(1.5 kg per cod)(6 harvests per year)
= 15903 metric tons per year
= 35 million pounds per year.

Table 5. Available floor space at Moon Island, number of six-stage grow-out units, and total production.

The layout and arrangement of the tanks in the facility and the plumbing that will connect them all to the water distribution and treatment systems is a task of technical detail that cannot be included in this analysis. Ignoring the geometry of the tank placements and working with the floor space numbers is sufficient to obtain a rough estimate of the production capacity of the facility. The four reservoirs at Moon Island are each trapezoidal in shape but are sufficiently wider than the tank sizes used here to allow this approximation. The dimensions and areas of the reservoirs appear in Table 5. The reservoir areas are individually divided by the space requirement for a set of six tanks from Table 4. This calculation

indicates that twenty-seven production units would fit if the entire system were committed to cod production as described by this model. Multiplying the number of production units, the number of fish harvested, the target weight, and the number of harvests per year gives an estimate of the marketable annual output of the system. Based on the model that has been described in this section, the Moon Island facility would be capable of producing 35 million pounds of cod per year if its entire area were committed to this species. This amount would have made up for the decline in the American cod fishery between 1991 and 1992. The yields of these two years differ by 31.4 million pounds (Howell, et al., 1995, from NMFS, 1993).

5. CONCLUSION

The establishment of a commercial-scale aquaculture system on Moon Island in Boston Harbor is an attractive possibility from a marketing perspective, but the complex problems of environmental interaction and aquacultural engineering will have to be solved first.

- The details of the biological needs of the candidate species must be accurately quantified beforehand in order to design the systems that will perform optimally in both physical and economic terms.
- Reliable growth models for the animals are necessary for determining tank sizes, production schedules, and feed requirements. The method presented in this paper is only a beginning to this process. Further simulation of possible temperature conditions and refinement of the growth model equation will be necessary.
- The effluent quality of the facility must be predicted with confidence to allow the design of pre-discharge treatment systems. This requires study of the digestive response of the candidate species to different types of feed.

These issues would be explored in small-scale research projects that are designed to produce reliable data, not to make a profit. This information will be more valuable than the money that is expended to obtain it if it can be applied to a larger grow-out system. These projects will allow testing and refinement of equipment choices, sizing, and arrangement. No amount of simulation or calculation will benefit the designer of the large-scale system as much as small-scale experimentation.

Again, this thesis is only an initial step in making the concept of converting the Moon Island drainage facility for aquaculture, but the major ideas that need to be developed have been presented. A cohort of recirculating aquaculture components that have the potential of reducing the operating costs of a large-scale system through simplicity and reliability have been identified. An approach to sizing the grow-out volumes for a particular species has been outlined, and the output prediction is very promising.

Many other hurdles remain to hamper this effort, but the people who have the desire and diligence to solve them would not do so if they did not foresee rewards in the future. This discussion is not complete enough to advocate this project, and perhaps Boston Harbor will not become a cradle for aquaculture. However, if a successful aquaculture venture is established at Moon Island, it would have the opportunity play a major role in aquaculture research and public education to encourage further development in the region.

6. REFERENCES

- Atlantic Fish Farming*, 1996. "University of Maine professor makes advances in cod research." ed. P. MacNeill. p. 17, Vol. 9, No. 4, 26 August. Montague, Prince Edward Island, Canada.
- Berkowitz, Roger, August 1996. Personal communication. Legal Sea Foods; 33 Everett Street; Allston, Massachusetts 02134.
- Braaten, 1985. Growth of cod in relation to fish size and ration level. *Flodevigen Rapportser*, 1:677-710.
- Brett, J.R., 1979. Environmental factors and growth. In: W.S. Hoar, D.J. Randall and J.R. Brett (editors), Fish Physiology, Vol. VIII. Academic Press: London.
- Castro, W.E. and P.B. Zielinski, 1980. Pumping characteristics of small airlift pumps. *Proceedings of the World Mariculture Society*, 11.
- Chen, S., D. Stechey, and R.F. Malone, 1994. Chapter 3: Suspended Solids Control in Recirculating Aquaculture Systems, Aquaculture Water Reuse Systems: Engineering Design and Management, M.B. Timmons and T.M. Losordo, eds. Elsevier Science Publishers B.V.: Amsterdam.
- Chen, S., 1991. Theoretical and experimental investigation of foam separation applied to aquaculture. Ph.D. dissertation, Cornell University, Ithaca, NY.
- Clarke, E.C., 1888. Chapter 9: Reservoir and outlet, Main Drainage Works of the City of Boston, third edition. Rockwell and Churchill: Boston.
- Dahl, E., D.S. Danielssen, E. Moksness, and P. Solemdal (editors), 1984. The propagation of cod, *Gadus morhua* L. *Flodevigen Rapportser*.
- Dolin, E.J., 1990. Dirty Water/Clean Water: A Chronology of Events Surrounding the Degradation and Cleanup of Boston Harbor, MIT Sea Grant College Program: Cambridge, Massachusetts.
- Food and Agriculture Organization (FAO), 1990. FIDI/C:815 Revision 2. as reported in *Fish Farming International* 17(8): 12-13.
- FAO, 1994. Aquaculture production, 1986-1992. *Fisheries Circular* No. 815, Rev. 6.
- Forteach, N., L. Wee, and M. Frith; 1993. Chapter 1: Water quality, Recirculation Systems: Design, Construction, and Management. ed. P. Hart & D. O'Sullivan. Department of Aquaculture, University of Tasmania.

- Forteath, N., 1993. Chapter 3: Types of recirculating systems, Recirculation Systems: Design, Construction, and Management. ed. P. Hart & D. O'Sullivan. Department of Aquaculture, University of Tasmania.
- Goudey, C.A., 1996. Proposal for the development of Moon Island Aquaculture Center. Proposal submitted to the City of Boston Environmental Department, 2 August.
- Hardin, G., 1968. The tragedy of the commons. *Science*, 162(3859): 1243-1248.
- Hardy, D., 1991. Scallop Farming. Fishing News Books: Oxford, England.
- Howell, W.H., L.J. Kling, T.M. Bradley, and L.J. Buckley, 1995. Development of commercially viable aquaculture industries in New England based on cod and haddock. Submitted to University of New Hampshire/University of Maine Sea Grant College Program.
- Huguenin, J.E. and J. Colt, 1989. Design and Operating Guide for Aquaculture Seawater Systems, Developments in Aquaculture and Fisheries Science, Volume 20. Elsevier Science Publishers B.V.: Amsterdam.
- Huse, I., 1991. Culturing of cod (*Gadus morhua* L.). In: CRC Handbook of Mariculture: Volume II, Finfish Aquaculture, ed. J.P. McVey. CRC Press: Boston.
- Iversen, E.S., 1968. Farming the Edge of the Sea, Fishing News (Books) Ltd.: London.
- Jobling, M. 1983. Growth studies with fish—overcoming the problems of size variation. *J. Fish Biol.*, 22:153-157.
- Jobling, M., 1988. A review of the physiological and nutritional energetics of cod, *Gadus morhua* L., with particular reference to growth under farmed conditions. *Aquaculture*, 70:1-19.
- Jobling, M. and T. Pedersen, 1995. Chapter 19: Cultivation of the Atlantic Cod, Production of Aquatic Animals: Fishes, World Animal Science, volume C8. eds. C.E. Nash & A.J. Novotny. Elsevier Science B.V.: Amsterdam.
- Jones, S., 1996. "Maine hatchery raises Atlantic cod." *Fish Farming News*, Vol. 4, September/October 1996, p. 6.
- Kales, E. and D. Kales, 1976. All about the Boston Harbor Islands. Herman Publishing, Inc.: Boston.
- Lindell, Scott, Fall 1995. Personal communication. AquaFuture, Inc.; 15 Industrial Blvd.; Turners Falls, Massachusetts 01376.

- Losordo, T.M. and P. Westerman, 1991. An analysis of biological, economic, and engineering factors affecting the cost of fish production in recirculating aquacultural systems, Design of High-Density Recirculating Aquaculture Systems: A Workshop Proceeding. Louisiana Sea Grant College Program: Baton Rouge, Louisiana.
- Malone, R.F. and D.E. Coffin, 1991. Biofiltration and solids capture with low density bead filters, Design of High-Density Recirculating Aquaculture Systems: A Workshop Proceeding. Louisiana Sea Grant College Program: Baton Rouge, Louisiana.
- Massachusetts Water Resource Authority (MWRA), 1996. unpublished data.
- Metropolitan Area Planning Council (MAPC), 1972. Boston Harbor Islands Comprehensive Plan, prepared for Massachusetts Department of Natural Resources: Boston.
- National Marine Fisheries Service (NMFS), 1993. Status of fishery resources off the northeastern United States for 1993. Conservation and Utilization Division, Northeast Fisheries Science Center. NOAA Tech. Mem. NMFS-F/NEC-101.
- National Research Council (NRC), 1992. Marine Aquaculture: Opportunities for Growth. National Academy Press: Washington, D.C.
- National Oceanographic and Atmospheric Administration (NOAA), 1994. Chart 13267: Massachusetts Bay. U.S. Department of Commerce: Washington, D.C.
- NOAA, 1993. Chart 13270: Boston Harbor. U.S. Department of Commerce: Washington, D.C.
- Nicklin, D.J., 1963. The air-lift pump: theory and optimisation. *Trans. Instn Chem. Engrs.*, vol. 41.
- Ng, K.S. and J.C. Mueller, 1975. Foam separation—a technique for water pollution abatement. *Water Sew. Works*. 122(6): 48-55.
- Novotny, A.J. and C.E. Nash, 1995. Chapter 10: Production of the Salmonids, Production of Aquatic Animals: Fishes, World Animal Science, volume C8. eds. C.E. Nash & A.J. Novotny. Elsevier Science B.V.: Amsterdam.
- Odum, E.P., 1983. Basic Ecology. Saunders College Publishing: Philadelphia.
- Parker, N.C. and C.E. Nash, 1995. Chapter 4: The Catfishes, Production of Aquatic Animals: Fishes, World Animal Science, volume C8. eds. C.E. Nash & A.J. Novotny. Elsevier Science B.V.: Amsterdam.
- Pedersen T. and M. Jobling, 1989. Growth rates of large, sexually mature cod, *Gadus morhua*, in relation to condition and temperature during an annual cycle. *Aquaculture* 81:161-168.

- Pillay, T.V.R., 1992. Aquaculture and the Environment. Halsted Press: New York.
- Rakocy, J.E., T.M. Losordo, and M.P. Masser, 1992. Recirculating aquaculture tank production systems: integrating fish and plant culture. Southern Regional Aquaculture Center Publication No. 454, North Carolina Cooperative Extension Service: North Carolina State University.
- Rubin, E., R. Everett Jr., J.J. Weinstock, and H.M. Schoen, 1963. Contaminant removal from sewage plant effluents by foaming. PHS Publ. No. 999-WF-5, Pub. Health Serv., Cincinnati.
- Snow-Cotter, S., 1995. Massachusetts marine aquaculture white paper (draft). Coastal Zone Management Office, Executive Office of Environmental Affairs: Boston.
- Spotte, S., 1979. Fish and Invertebrate Culture: Water Management in Closed Systems, second edition. John Wiley & Sons: New York.
- Van Gorder, S., 1991. Optimizing production by continuous loading of recirculating systems. Design of High-Density Recirculating Aquaculture Systems: A Workshop Proceeding. Louisiana Sea Grant College Program: Baton Rouge, Louisiana.
- Wheaton, F.W., 1977. Aquacultural Engineering. John Wiley & Sons: New York.
- Wheaton, F.W., J.N. Hochheimer, G.E. Kaiser, M.J. Krones, G.S. Libey, and C.C. Easter, 1994. Chapter 4: Nitrification Filter Principles, Aquaculture Water Reuse Systems: Engineering Design and Management, M.B. Timmons and T.M. Losordo, eds. Elsevier Science Publishers B.V.: Amsterdam.
- Willis, S., 1993. Chapter 9: Alternative Methods of Filtration, Recirculation Systems: Design, Construction, and Management. ed. P. Hart & D. O'Sullivan. Department of Aquaculture, University of Tasmania.
- Øiestad, V., 1993. A century of cod farming. In: Manual for cod farming—breeding stock and fry production, eds. J.C. Holm, T. Svåsand & V. Wennevik. Ocean Res. Institute, Ctr. for Ocean Utilization: Bergen, Norway.

7. APPENDIX: MWRA WATER QUALITY DATA

The temperature data that form the basis for the cod growth model appear here. The corresponding readings of dissolved oxygen concentrations are included for the benefit of future researchers who are interested in developing additional models of system performance for Moon Island. These samples were made by the Massachusetts Water Resources Authority at Hangman's Island in Quincy Harbor which they have designated as Station 139 in their literature.

Date	Year Fraction	Depth [m]	Dissolved Oxygen [mg l ⁻¹]	Salinity [ppt]	Temperature [°C]
12 Aug 93	0.611	4.0		28.1	17.2
19 Aug 93	0.630	6.1	7.7	29.1	17.9
26 Aug 93	0.649	4.0			
02 Sep 93	0.668	6.1	6.7	29.9	16.9
09 Sep 93	0.688	5.0			
16 Sep 93	0.707	6.5	7.7	30.0	14.0
23 Sep 93	0.726	6.0		29.0	14.0
30 Sep 93	0.745	4.8			
14 Oct 93	0.784	6.2	8.5	28.6	10.4
28 Oct 93	0.822	6.3	7.9	28.7	10.0
10 Nov 93	0.858	4.0	7.5	29.5	8.0
24 Nov 93	0.896	4.8	8.8	29.9	8.0
09 Dec 93	0.937	4.0	6.6	29.0	6.1
23 Dec 93	0.975	4.6	10.3	27.0	4.2
06 Jan 94	0.014	3.0	12.9	27.2	-1.6
24 Jan 94	0.063	4.5	12.5	30.1	-1.2
03 Feb 94	0.090	4.0			
17 Feb 94	0.129	4.3	10.5	29.0	-1.0
17 Mar 94	0.205	6.0		31.0	2.0
01 Apr 94	0.247	4.0	14.0	27.2	5.3
14 Apr 94	0.282	5.0	11.0	27.0	7.5
28 Apr 94	0.321	6.4	10.6	28.1	7.8
25 May 94	0.395	6.4	9.1	23.6	12.3
13 Jun 94	0.447	4.0	8.6	22.8	12.1
20 Jun 94	0.466	5.1	8.1	31.3	14.5

27 Jun 94	0.485	5.2	8.9	29.9	14.9
11 Jul 94	0.523	6.1	9.2	29.5	16.7
18 Jul 94	0.542	4.0	6.7	30.5	18.9
25 Jul 94	0.562	5.5	8.0	31.0	18.7
01 Aug 94	0.581	4.4	8.8	30.6	16.5
08 Aug 94	0.600	6.4	7.1	30.7	17.0
15 Aug 94	0.619	3.5	6.8	30.6	16.9
29 Aug 94	0.658	3.9	7.8	30.9	17.1
06 Sep 94	0.679	4.9	7.2	31.1	15.3
13 Sep 94	0.699	4.4	6.4	31.6	16.3
20 Sep 94	0.718	6.4	6.9	31.5	16.5
27 Sep 94	0.737	3.9	5.8	30.8	16.8
11 Oct 94	0.775	3.8	8.2	31.4	13.1
25 Oct 94	0.814	4.4	7.3	31.6	13.0
08 Nov 94	0.852	3.3	8.0	31.9	10.7
06 Dec 94	0.929	5.5	8.9	31.4	7.6
27 Jan 95	0.071	3.2	10.8	30.5	2.6
22 Feb 95	0.142	3.7	11.5	31.5	2.3
08 Mar 95	0.181	4.0	10.9	31.5	3.0
20 Mar 95	0.214	6.2	10.4	31.4	4.2
04 Apr 95	0.255	5.0	10.4	31.0	5.5
20 Apr 95	0.299	3.7	9.7	31.1	7.2
10 May 95	0.353	5.3	8.8	31.2	9.8
31 May 95	0.411	4.8	8.2	31.4	12.2
21 Jun 95	0.468	3.0	9.4	30.6	16.8
28 Jun 95	0.488	6.0	8.0	30.9	17.0
05 Jul 95	0.507	3.5	8.3	31.2	15.8
12 Jul 95	0.526	6.3	9.1	31.4	12.0
19 Jul 95	0.545	3.6	7.9	31.5	15.0
26 Jul 95	0.564	4.9	6.5	31.5	18.4
02 Aug 95	0.584	3.5	7.7	31.4	19.7
09 Aug 95	0.603	6.3	6.5	30.8	19.2
16 Aug 95	0.622	4.7	7.3	31.1	18.5
23 Aug 95	0.641	4.8	6.8	31.0	20.7
30 Aug 95	0.660	4.7	7.9	31.1	19.3
06 Sep 95	0.679	6.0		31.2	18.7
20 Sep 95	0.718	5.3	6.7	30.8	16.3
27 Sep 95	0.737	5.1	6.6	30.9	15.3
04 Oct 95	0.756	5.5	8.4	31.1	15.5
11 Oct 95	0.775	5.5	6.5	30.6	14.9
18 Oct 95	0.795	5.6	7.0	30.9	13.3
25 Oct 95	0.814	5.3	7.3	31.1	13.3
08 Nov 95	0.852	5.7	7.9	31.0	9.3
22 Nov 95	0.890	7.3	7.8	30.2	7.8
06 Dec 95	0.929	6.1	9.0	30.6	5.2

19 Dec 95	0.964	5.9	9.3	30.7	1.8
05 Jan 96	0.011	3.8	10.2	31.1	-0.5
17 Jan 96	0.044	4.2	13.0	31.4	0.8
31 Jan 96	0.082	5.2	9.5	30.1	2.9
14 Feb 96	0.121	4.3	10.2	30.8	0.7
27 Mar 96	0.236	3.1	11.1	30.3	4.7
12 Apr 96	0.279	4.3	12.8	30.3	4.3
10 May 96	0.356	3.0	11.1	30.2	8.4
05 Jun 96	0.427	3.0	12.4		13.4
12 Jun 96	0.447	6.0	9.1	30.1	13.2
19 Jun 96	0.466	5.3	9.6	30.3	15.5
26 Jun 96	0.485	5.0	7.4	29.9	17.1
03 Jul 96	0.504	5.5	7.5	30.4	16.5
10 Jul 96	0.523	8.0	8.9	30.7	14.4
17 Jul 96	0.542	5.0	8.4	30.3	15.4
24 Jul 96	0.562	4.0	7.2	30.9	14.3
31 Jul 96	0.581	5.0	7.0	31.5	15.0
07 Aug 96	0.600	5.2	8.9	30.9	18.2
14 Aug 96	0.619	5.0	8.2	31.6	17.9
21 Aug 96	0.638	4.2	8.4	31.8	16.1
28 Aug 96	0.658	6.0	7.4	32.4	16.4
04 Sep 96	0.677	4.5	6.3	33.1	17.1
11 Sep 96	0.696	6.1	6.0	32.8	18.3
19 Sep 96	0.718	3.8	8.3	32.0	15.9
25 Sep 96	0.734	7.2	6.4	32.3	16.1
Minimum		3.0	5.8	22.8	-1.6
Average		4.9	8.6	30.4	12.0
Maximum		8.0	14.0	33.1	20.7

