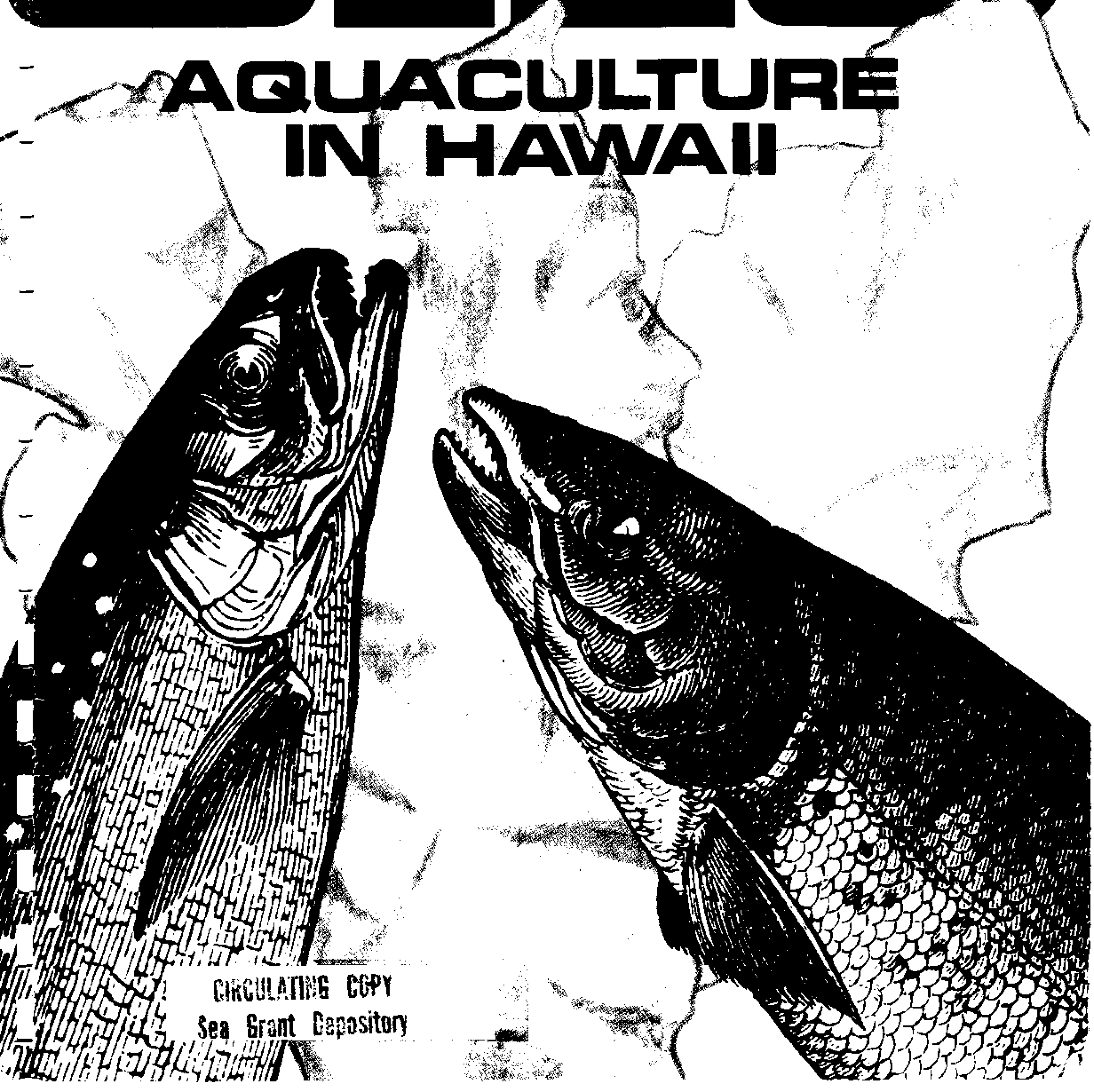
OTEC

AQUACULTURE IN HAWAII



OTEC AQUACULTURE IN HAWAII

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The National Sea Grant College Program is a network of institutions working together to promote the wise use, development, and conservation of the nation's coastal, marine, and Great Lake resources. Provisions of the National Sea Grant College and Program Act of 1966 called for the creation of Sea Grant Colleges, and in October 1972, the University of Hawaii was designated one of the first five Sea Grant Colleges in the nation. Locally, Sea Grant is a unique partnership of university, government, and industry focusing on marine research, education, and advisory/extension service.

FOREWORD

In retrospect, the significant discoveries of humankind have been simple and obvious. Watson and Crick uncovered the elegant simplicity of the double helix by first postulating that reproduction as an accident of nature had to be fundamentally simple. A similar philosophical approach to ocean resources has led to the conclusion that the greatest resource of the ocean is simply the ocean water itself and in particular the water of the deep ocean. Why so? Because it is clean, it is cold, and it is rich in nutrients.

The full implications of this simplicity have not been apparent to most investigators. Conventional wisdom has suggested that the greatest applied value of deep ocean water is as the cold source for the generation of energy through one or more of the ocean thermal energy conversion (OTEC) processes. To this end, the energy agencies of the state of Hawaii and of the United States supported the development of a laboratory at Keahole Point, Hawaii, which evaluates the use of deep ocean water as an energy-producing fluid.

There were those, such as Oswald Roels of Columbia University's Lamont Doherty Laboratory, however who suggested that the nutrients in deep ocean water would be valuable for use in mariculture. Roels' experiments with warmed, deep ocean water were promising. Efforts to obtain funding to further test this hypothesis were hampered by the prevailing focus on the energy value of this resource.

It remained for investigators like Arlo Fast and Rick Spencer to postulate that the three characteristics of deep ocean water — its purity, its coldness, and its nutrient content — made it an ideal medium for the aquaculture of marine organisms. It also remained for the University of Hawaii Sea Grant College Program to provide seed monies for research projects and then to join in partnership with agencies of the state of Hawaii, notably the Ocean Resources Branch of the Department of Business and Economic Department, to see these projects to their completion.

This publication presents the results of the initial Sea Grant-state of Hawaii projects which were funded to explore the biological productivity of the deep ocean water. The broader result of the work and investment of the investigators and their supporters was the establishment of "proof of concept" of the aquaculture and other extra-energy values of deep ocean water. The results have already manifested themselves in the successful aquaculture production of rapidly growing abalone; algae such as spirulina, *nori*, and *ogo*; salmon; trout; and oysters. In the future, the production of strawberries, alstymaria (an alpine ornamental flower), *opihi* (a Hawaiian gourmet shellfish), lobster, and an ever-growing range of marine algae may become established.

Sea Grant's initial partner was the Marine Affairs Coordinator's (MAC) office, and then its successor agency, the Ocean Resources Branch of the Department of Planning and Economic Development (renamed the Department of Business and Economic Development in mid-1987). Since the initial "proof-of-concept" work reported here, the Aquaculture Development Program of the Department of Land and Natural Resources and Sea Grant have continued the support for innovative scientific research and for entrepreneurial efforts to utilize the attributes of deep ocean water made available by the state's Natural Energy Laboratory of Hawaii at Keahole Point on the island of Hawaii.

As a total system, the UH Sea Grant College Program, the ocean agencies of the state of Hawaii, and the results reported herein represent a model of innovation that might well be replicated elsewhere as the United States seeks to regain its position as the world's most innovative and efficient producer.

John R. Craven
Jack R. Davidson
Craig MacDonald
John Corbin

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INTRODUCTION

Arlo W. Fast

Some 20 years ago, an interesting article appeared in the popular press about an imaginative project in the U.S. Virgin Islands. The project was led by a physicist, Dr. Oswald Roels of Lamont-Doherty Geological Observatory, Columbia University, and involved a host of actual and proposed uses for the upwelling of cold water from deep in the ocean. Roels was using nutrient-rich water pumped from the 870 m depth at St. Croix, to cultivate algae in an on-shore swimming pool. The algae were in turn fed to bivalves and crustaceans in a scheme to produce food through aquaculture practices. These experiments demonstrated the technical feasibility of culturing food and other organisms in upwelled water.

Around 1974, I came up with an idea for culturing coldwater fish in freshwater lakes and reservoirs. The idea was to upwell cold water from some depth in these water bodies, generally from less than 30 m deep, to the surface where the water could be used to mass culture coldwater fish such as trout. I patented my idea in 1977, but I did not extend it to large-scale practice.

In late 1978, there was a flurry of OTEC activity in Hawaii in response to the energy crises of the mid-1970s when the United States was frantically exploring a multitude of approaches for alternative energy generation and energy conservation. Upon learning about these activities, I became interested in adapting my fish culture concept, proposed for lakes, to the OTEC systems.

The intent was to test the feasibility of using cold seawater upwelled from the 600 m depth to raise fish such as salmon and trout. A number of people — including Dr. John Craven, the then Marine Affairs Coordinator for the state of Hawaii; Dr. John Caperon of the Hawaii Institute of Marine Biology (HIMB); and Dr. Craig MacDonald of the Ocean Resources Branch, Hawaii Department of Planning and Economic Development (DPED) — were consulted and funds were made available for a pilot-scale OTEC salmon culture project at HIMB. When first proposed, the experiments were to be conducted on the Mini-OTEC barge and/or on the OTEC-1 ship to prove the concept of raising salmonids in association with OTEC power plants. The idea was to produce food as well as energy through multiple use of upwelled water.

About the time that work on OTEC salmon culture began at HIMB, two colleagues, Richard Spencer and Fredrich Mencher, proposed to culture the seaweed *nori* under much the same conditions as I proposed to culture salmon. This idea was attractive to the University of Hawaii Sea Grant College Program, DPED, and other agencies that funded the project. Hence, with both projects funded, Spencer, Mencher, and I began collaboration during 1980. Our original plan was to conduct initial work at HIMB in preparation for work on either the Mini-OTEC barge or the OTEC-1 ship. In 1980, however, federal funds and interest in alternative energy began to wane in inverse proportion to the cost and availability of conventional petroleum energy. Funds for OTEC-related research were reduced and offshore OTEC experiments in Hawaii largely came to a halt. As a result of this and of the emergence of the Natural Energy Laboratory of Hawaii (NELH) at Keahole Point, Hawaii, as one of the principal OTEC research and development centers in the world, our plans were changed and we moved our OTEC salmon and nori projects to NELH in 1982. A 12-inch (0.3-m) coldwater pipe supplied seawater from the 600-m depth for the onshore experiments.

We successfully conducted the OTEC salmon and nori studies at NELH between 1982 and 1984. Perhaps as a partial result of our work, a host of other OTEC- and non-OTEC-related aquaculture projects have since evolved at NELH. These include the culturing of California abalone, American lobster, microalgae, giant clams and other bivalves, and *opihi* (limpets).

There are many aspects of OTEC water systems related to possible commercial applications and research opportunities for aquaculture. Some of these are:

1. Water volumes. Large volumes of both warm seawater and cold seawater can be pumped by even a small OTEC plant. An OTEC power plant roughly equivalent in capacity to the conventional fossil fuel plant that powers Oahu can pump a water volume equivalent to the mean flow of the Mississippi River at New Orleans. This is a lot of water. If the water, or even a small portion of it, can be used to culture plants and/or animals with little or no additional pumping costs, then it becomes a potentially valuable resource.
2. Water temperatures. OTEC plants can have two water streams: one stream of surface seawater at about 28 C and another stream of upwelled seawater at about 4 C. By appropriate blending of these streams, any water temperature between 4 C and 28 C can be achieved simply and inexpensively. Changing water temperatures by heating or chilling is, by comparison, very expensive and troublesome.
3. Water quality. OTEC deep water is biologically very clean. It contains few pathogens and is pristine. In most cases the same applies to surface waters, although even in the best case they are almost certainly biologically more active than deep waters.

The potential benefits of OTEC aquaculture are many but there are also challenges. One challenge involves the low level of oxygen in the deep water. Water drawn from the 600 m depth comes from near the base of the thermocline and from the oxygen minimum layer. In the Pacific Ocean, oxygen concentrations typically range between 1 mg/l and 2 mg/l at this depth. This low concentration of oxygen is not a problem for most algae, but it is lethal for many fish species. Steps must be taken to increase the dissolved oxygen concentrations for fishes.

Another challenge is how to divert the water from the OTEC plumbing circuit, use it for aquaculture, and then dispose of the waste water. Costs for establishing this water intake and disposal system include capital costs for the necessary hardware and, most likely, operating costs. The total cost can be substantial. In addition, provisions must be made to keep the aquaculture crop alive during generator shut-down and during periods when chlorine or some other chemical is being used for biofouling control.

At the experimental level on which we operated, these problems either did not exist or were easily dealt with. At a larger scale, or commercial level, they will be critical.

This publication on OTEC aquaculture in Hawaii is not an exhaustive treatment of the subject. Rather, it is a basic summary of the work conducted on projects largely from 1982 through 1984 and occassionally beyond. Some of this work has been reported in the scientific literature; some is reported here for the first time.

The feasibility of culturing salmonids under simulated OTEC conditions is evaluated in five related papers: four deal with technical feasibility and the fifth with economic feasibility. The feasibility of culturing seaweed also is evaluated. Two other papers, one each on abalone and lobster culture, are less detailed because the information is proprietary. (The lobster species involved was *Homarus americanus*, commonly known as the American, Maine, or northern lobster.)

This publication also includes a description of the Natural Energy Laboratory of Hawaii and aspects of the water used in these studies. With the development of the adjacent Hawaii Ocean Science and Technology (HOST) Park and continued interest in OTEC aquaculture at NELH, we feel that this information has value not only as a historical record but also as a guide for those interests that are contemplating future activities at these facilities.

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OCEAN THERMAL ENERGY CONVERSION AND THE NATURAL ENERGY LABORATORY OF HAWAII

Thomas Daniel

INTRODUCTION

The Natural Energy Laboratory of Hawaii (NELH) includes 322 acres of land at Keahole Point near Kailua-Kona on the island of Hawaii (Figure 1). Some of this land is set aside for aquaculture research and development using the large volumes of water which will be discharged from ocean thermal energy conversion (OTEC) plants. Aquaculture which can use the unique properties of the OTEC discharge water could have an important place in Hawaii's economic future.

OTEC effluents consist of cold, nutrient-rich waters pumped from depths of 600 m (2,000 ft) or more in addition to surface waters cooled only a few degrees during passage through the OTEC plant. Water temperatures ranging from 6°C to 25°C are easily produced by blending surface and deep waters in various proportions. Large water volumes will be discharged continuously, even from small OTEC plants.

OTEC aquaculture systems could produce as much seafood as some of today's capture-fisheries, which bring in millions of tons of product annually. Although OTEC aquaculture systems may eventually be assembled and maintained at great distances from land, the technology most likely will evolve through small-scale, land-based experiments such as those at NELH.

At present, the NELH laboratory includes both a unique, deep seawater system upwelling up to 4,300 l/min (1,100 gpm) from 600 m depth and a 6,000 l/min (1,600 gpm) surface seawater system. These systems, used for both energy and aquaculture research, can provide flowing seawater at any desired temperature between the coldwater temperature (always less than 10°C) and the warmwater temperature (24°C to 27°C) merely by adjusting a valve. In addition to existing office and laboratory buildings, land is available at NELH for construction of additional buildings as well as ponds, tanks, raceways, and other aquaculture facilities (see Appendix A).

An act of the 1984 Hawaii Legislature added "commercialization" to the original laboratory mandate of research and development. This allows the NELH Board of Directors to approve research proposals as well as to lease land for commercial developments at NELH. In keeping with its primary purpose of developing natural energy resources, the board has adopted a policy of encouraging projects which propose to use the unique resources of the facility and the site for research leading to commercialization.

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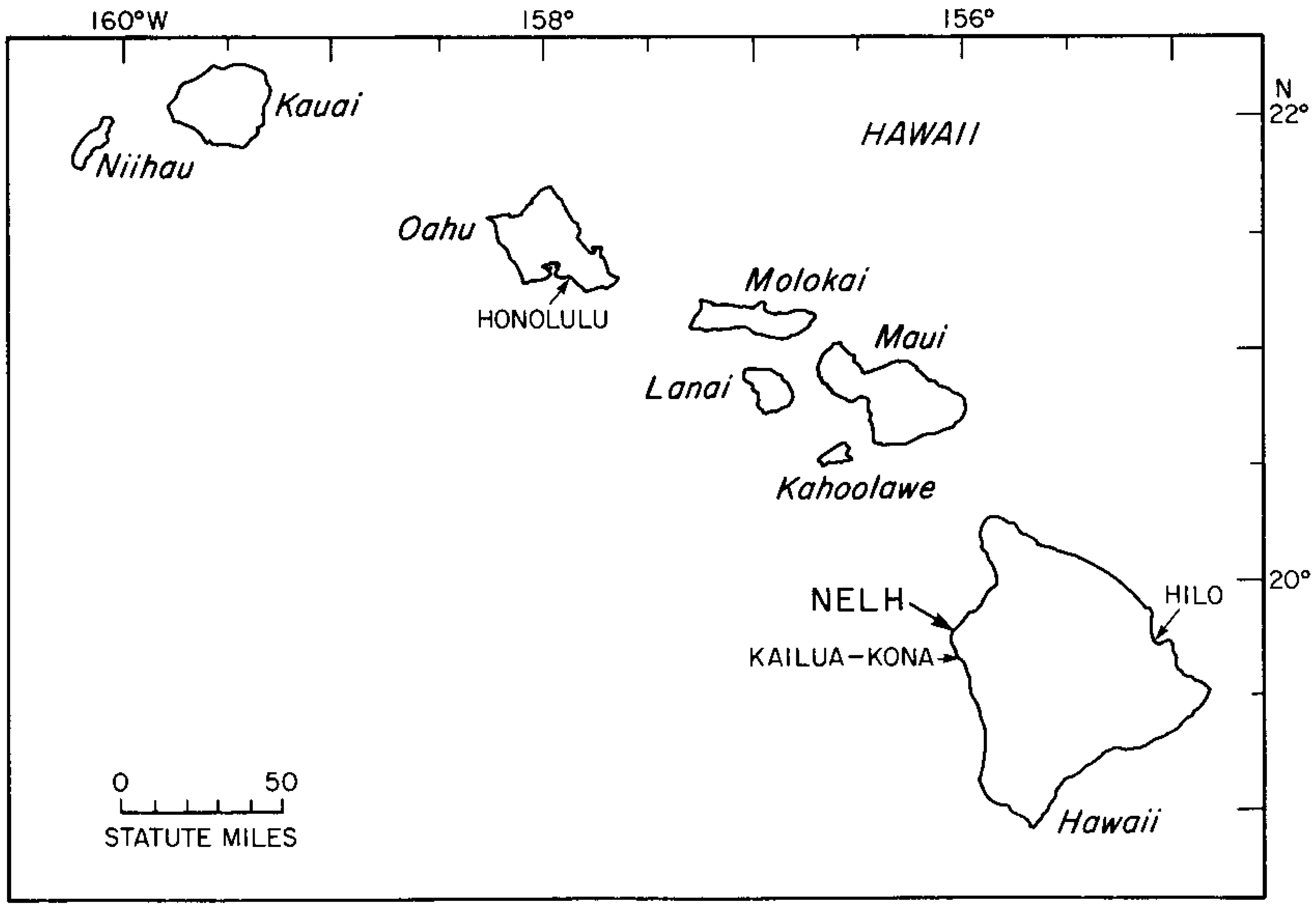

Figure 1. Location of the Natural Energy Laboratory of Hawaii at Keahole Point, Hawaii

Aquaculture research projects carried out at NELH include those involving nutrient exploitation (primary producers), temperature exploitation (aquaculture of coldwater species), and integrated systems (aquaculture combined with agriculture and energy production). Other projects stemming from interest in OTEC water for aquaculture development include research on the basic chemistry of deep ocean water and the biological responses of organisms to it, adaptation of existing aquaculture technology and development of new technologies which use OTEC water, and the treatment of OTEC aquaculture effluents both for mitigating potential environmental effects and for possible recovery of additional by-products.

OTEC aquaculture projects in progress or already concluded at NELH include the following:

1. Investigation of salmon and rainbow trout culture in OTEC water. This project has conducted a detailed study of environmental effects on smoltification of salmon and a successful demonstration of rainbow trout spawning in cold seawater. The results are reported elsewhere in this publication (see paper by Helms, Grau, and Fast on salmon smoltification and paper by Katase, Fast, and Barclay on rainbow trout spawning).
2. Evaluation of *nori* culture. Nori is the seaweed used for wrapping sushi. This project demonstrated nori growth rates exceeding 35% increase in weight per day. It appears that such culture would be economically attractive in conjunction with an OTEC plant. The results are reported elsewhere in this publication (see paper by Mencher and Katase).
3. Evaluation of a pilot plant demonstrating the feasibility of growing Maine lobster in Hawaii. A description of this project is reported elsewhere in this publication (see paper by Chapman, Guerra, and Thays).
4. A 2-year investigation by Hawaiian Abalone Farms on the feasibility of culturing abalone using the deep cold water. This has led to the initiation of a commercial development module for abalone production on 21 acres of land subleased by Hawaiian Abalone Farms from NELH. This project also involves culturing both giant kelp and diatoms to feed the abalone. A description of this venture is reported elsewhere in this publication (see paper by Barclay and Fast).
5. A strawberry culture project. Strawberries were successfully grown using "drip" irrigation. The drip comes from freshwater which condenses on pipes carrying cold seawater.
6. A commercial project by Cyanotech, Inc. using deep seawater that has been warmed to culture microalgae for both health food and pharmaceuticals.
7. A research project investigating the feasibility and parameters for culturing giant clams (*Tridacnidae* spp.) in Hawaii.

Appendix B contains a summary of the various OTEC aquaculture and energy research projects conducted at NELH since it was founded. Several new ventures will add to the present commercial operations for abalone and microalgae. These ventures include (1) commercial shellfish hatcheries for oysters, clams, and scallops; (2) another Maine lobster culture project using new technology; and (3) a commercial-scale nori culture project, partially sponsored by a large Japanese distributor of the seaweed.

So far, research has demonstrated the usefulness of three important properties of deep seawater for aquaculture:

1. Cold temperature. Deep seawater, which is colder than required for growing any of the species studied so far, can be used to maintain or change the temperature in the culture systems economically and reliably by regulating the water flow rate or by mixing deep seawater with surface seawater.
2. Nutrients. The deep seawater has high concentrations of dissolved inorganic nutrients (nitrates, phosphates, and silicates). The low concentrations of these nutrients in surface waters limit plant growth in tropical oceans. Deep-water nutrients contribute to the successful growth of nori, kelp, and diatoms in deep-water culture systems.
3. Cleanliness. Since deep seawater comes from below the photic zone and has been out of contact with the surface for centuries, it contains few living plants and very low levels of bacteria. This has proven useful in culturing larvae of various marine mollusks which are particularly susceptible to the pathogens usually present in surface waters. Also, the virtual absence of competing viable plant cells facilitates the growth of pure algae cultures.

THE OTEC RESOURCE

Tremendous amounts of heat energy are stored in the tropical oceans where the sun-warmed surface water averages over 20°C higher than the bulk of the water mass below. OTEC uses a heat engine principle to convert this stored heat energy to electrical energy and/or mechanical energy.

OTEC is an especially important renewable energy resource since it has the potential to satisfy a significant fraction of society's energy needs. Most other renewable energy resources — such as hydroelectric, geothermal, wind, and the waves, tides, and currents of the ocean — have considerably less potential (e.g., von Arx, 1974). In addition, OTEC can produce "base-load" power (i.e., 24 hours per day) since the ocean acts as a heat sink for the sun's energy. Base-load power production by OTEC is a significant advantage over direct solar conversion, the only other renewable energy resource with similar potential capacity. OTEC and other "renewables" use existing heat resources, so generation of electricity by these processes does not adversely affect the solar-terrestrial heat balance as do the burning of fossil fuels or the utilization of exothermic nuclear reactions (both fission and fusion).

OTEC PRINCIPLES

The literature on OTEC is not extensive and has received little circulation. However, in the following sections summaries are provided on how the process works, the extent of the resource, the history of its investigation, and its present status. Further details on these topics are contained in a comprehensive study by the U.S. Congress Office of Technology Assessment (1984) and in review papers by Cohen (1982), Richards et al. (1983), and Penney and Bharathan (1987).

Two types of system — closed cycle and open cycle — have been proposed for converting the ocean thermal resource into electrical energy. There are several similarities and several fundamental differences between these two systems.

Closed-Cycle System

French engineer Arsene D'Arsonval first proposed use of ocean thermal resources for electrical power generation in 1881. He adopted a closed-cycle system for energy conversion, and this remains a major design option for using the OTEC resource (Figure 2). Closed-cycle systems use a working fluid, such as freon or ammonia, which is vaporized by heat transferred from warm surface seawater. The expanding vapor turns a turbine attached to an electric generator. Cold seawater pumped from the depths then takes heat from the expanded vapor and condenses it back to a liquid. The condensed liquid then passes back to the evaporator where it is revaporized, and the process continues. The working fluid remains within the closed system, continuously vaporizing and recondensing. This system is similar to a very large refrigerator working in reverse: it takes "cold" from the ocean and turns it into electricity.

D'Arsonval recognized some of the major potential problems of OTEC systems. First, the relatively small available temperature difference means that large volumes of water are required to generate significant amounts of electricity. Second, for a closed-cycle system, the heat exchangers must be very large. Third, the heat exchangers must carry highly corrosive and biologically active seawater continuously for the lifetime of the OTEC plant, with the resulting potential for corrosion and biofouling of the heat exchanger surfaces.

Open-Cycle Systems

Claude cycle. In the late 1920s, another Frenchman, Professor Georges Claude of the University of Paris, first proposed the open-cycle OTEC concept which bears his name (Figure 3). The Claude cycle uses seawater as the working fluid. Warm surface seawater vaporizes when injected into a near-vacuum, and the expanding water vapor turns the turbine attached to an electrical generator. The water vapor condenses back to a liquid upon contact with cold seawater. Vapor condensation creates a vacuum into which warm seawater can again vaporize, thus continuing the cycle.

The Claude cycle has some significant potential advantages over closed-cycle systems: higher overall efficiencies are attainable; the material cost of system construction can be significantly lower; and, most important, freshwater can be a by-product since salt is left behind when the warm seawater vaporizes. A noncontact condenser, such as the shell-and-tube type described above for the closed-cycle process, condenses the vapor into fresh, potable water. This significantly reduces the efficiency of electricity production, but the scarcity of freshwater in most places where OTEC will work (i.e., the tropical oceans) makes freshwater an extremely valuable by-product.

There are two major problems with the Claude cycle. First, many uncertainties remain about the basic thermodynamics of seawater at the temperatures and pressures appropriate to open-cycle OTEC. In contrast with the well-understood dynamics of the closed-cycle process, much basic research remains before many of the parameters needed to optimize the design of an open-cycle plant can be defined. A more significant problem with the Claude cycle stems from the low pressures and the resultant requirement for a very large turbine to produce even a modest amount of electricity. A 5-MW turbine, for example, would have to be on the order of 10 m in diameter and enclosed in a vacuum chamber.

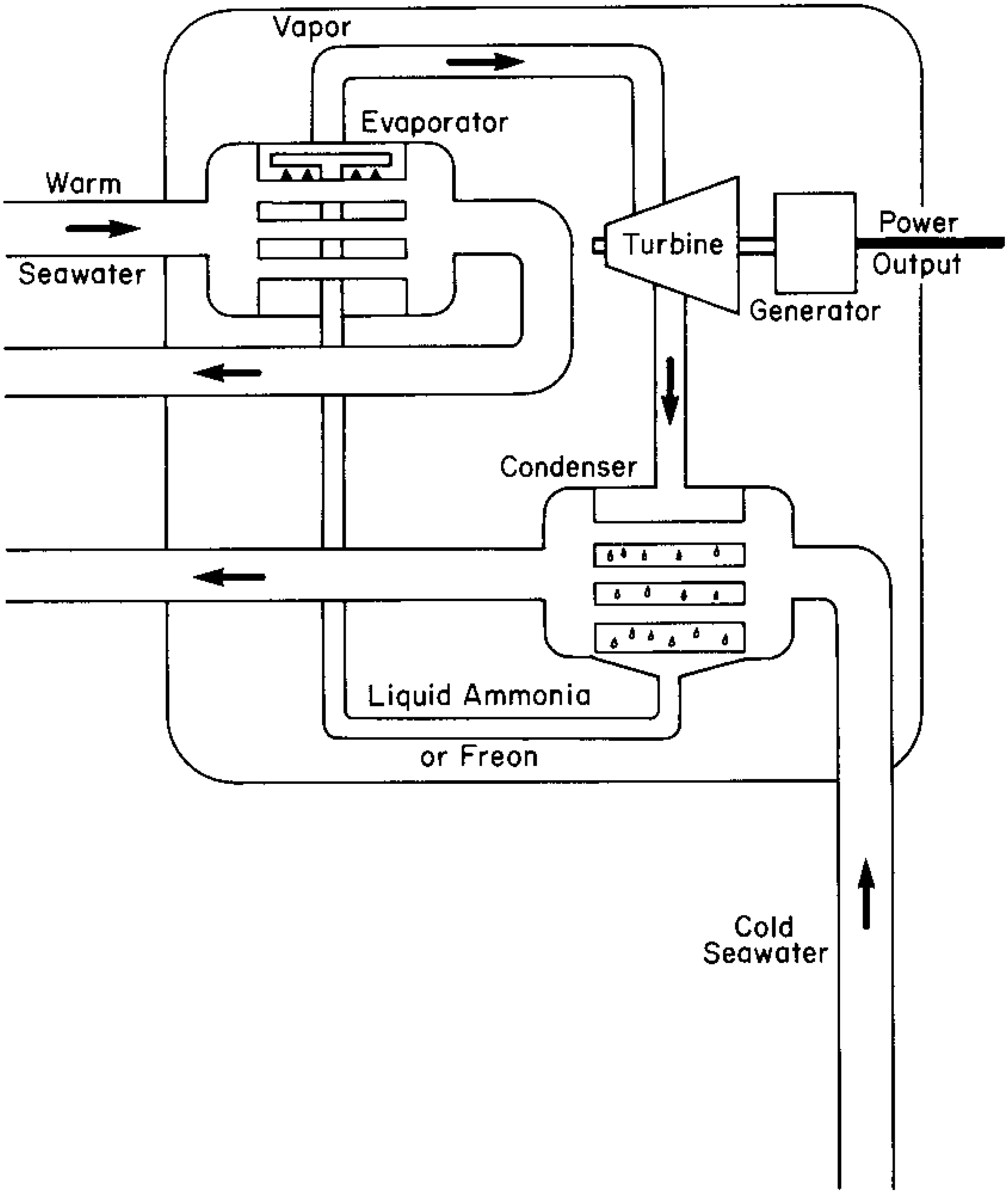

Figure 2. Closed-cycle OTEC schematic diagram

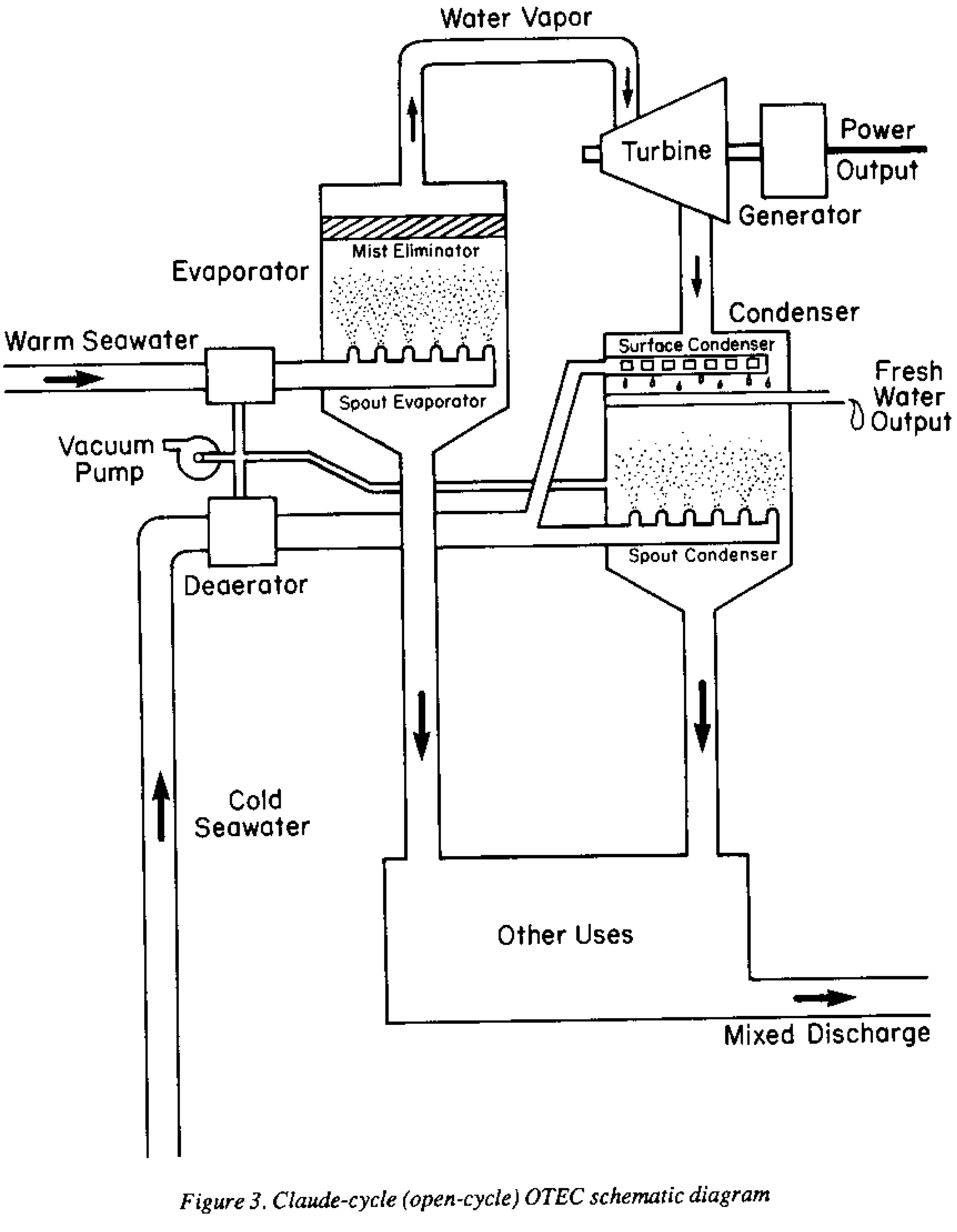

Figure 3. Claude-cycle (open-cycle) OTEC schematic diagram

Mist-lift cycle. The most promising of the proposed alternatives to the Claude cycle, removing its requirement for a very large turbine, is called the mist-lift cycle by its developer, Dr. Stuart Ridgway of R&D Associates in Marina del Rey, California (Ridgway, 1977). In this modified open-cycle system (Figure 4), the water vapor flowing from the evaporator to the condenser in an open-cycle process is constrained to rise in a vertical column. Some of the unvaporized warm seawater is then forced through a screen with small holes, and the resulting mist of liquid droplets is injected into the rising vapor stream. Ridgway drew upon his expertise in the theory of two-phase flow to predict that there would be sufficient coupling between the rising vapor and the mist to lift the liquid droplets high up in the column. His calculations show that 100 m of vertical lift of large volumes of liquid water can be obtained from the 20°C temperature differences available in OTEC systems. Since the potential energy of this elevated water is then available to turn a hydraulic turbine, which can be much smaller than the equivalent-output Claude-cycle vapor turbine, the mist-lift process avoids the size limitations inherent in the Claude cycle. However, unlike the Claude cycle, the mist-lift process can only produce freshwater as a by-product if a portion of the vapor is diverted for this purpose since the liquid seawater must be injected directly into the rising vapor stream.

OTEC Efficiency

Simple physics indicates that considerable energy is available in the world's oceans for the OTEC process. Calories and British thermal units (BTU) are measures of heat energy. A calorie is the amount of heat needed (or given off) when changing the temperature of 1 g of water 1°C; a BTU is the heat involved in changing 1 pound of water 1°F. J. P. Joule measured the mechanical equivalent of heat at 4.184 joules/calorie, 1 joule being the energy expended in accelerating a 1-kg mass at 1 m/s/s through 1 m. A watt is the corresponding unit of power, or rate of consuming energy, equal to 1 joule/s. Thus, the power available in watts can be determined by calculating the number of calories of heat transferred by the system per unit of time.

As an example, we can calculate the available power from Mini-OTEC, an experimental closed-cycle plant deployed with Hawaii DPED sponsorship in 1979 (see below). Mini-OTEC pumped up about 170 l/s (2,700 gpm) of about 6°C cold water and combined it with a similar flow of 27°C surface water. Since each liter weighs about 1 kg, the total mass input becomes 170 x 2 = 340 kg/s. The total amount of heat energy available is that given up in bringing the two fluids to a common equilibrium temperature. Thus, each would change through a 10°C temperature difference. If all this heat could actually be transferred to the working fluid, about 10 x 340 or 3,400 kcal of heat per second would be generated. Multiplying by Joule's constant gives approximately 14.2×10^6 joules/s or 14.2 MW of power input to the system.

All of this energy cannot be converted to electricity. Physical constraints on heat exchanger surface area and flow rates limit the actual temperature change to about 2°C or 3°C in each heat exchanger, and these provide the actual heat energy input to the system. For Mini-OTEC, a 2.5°C change in each heat exchanger yielded about 3.6 MW of power at the heat exchangers. The second law of thermodynamics provides a theoretical limit on the efficiency of a "Carnot-cycle" process such as OTEC, and practical considerations further limit the efficiency attainable from a real system. The Carnot limit, given by $(T_2 - T_1)/T_1$ where T_2 is the higher and T_1 the lower absolute temperature, comes to about 20/280, or 7%, for typical OTEC conditions. Real systems have additional losses such as heat exchanger inefficiencies, so that typical actual systems can provide 2–3% of the available

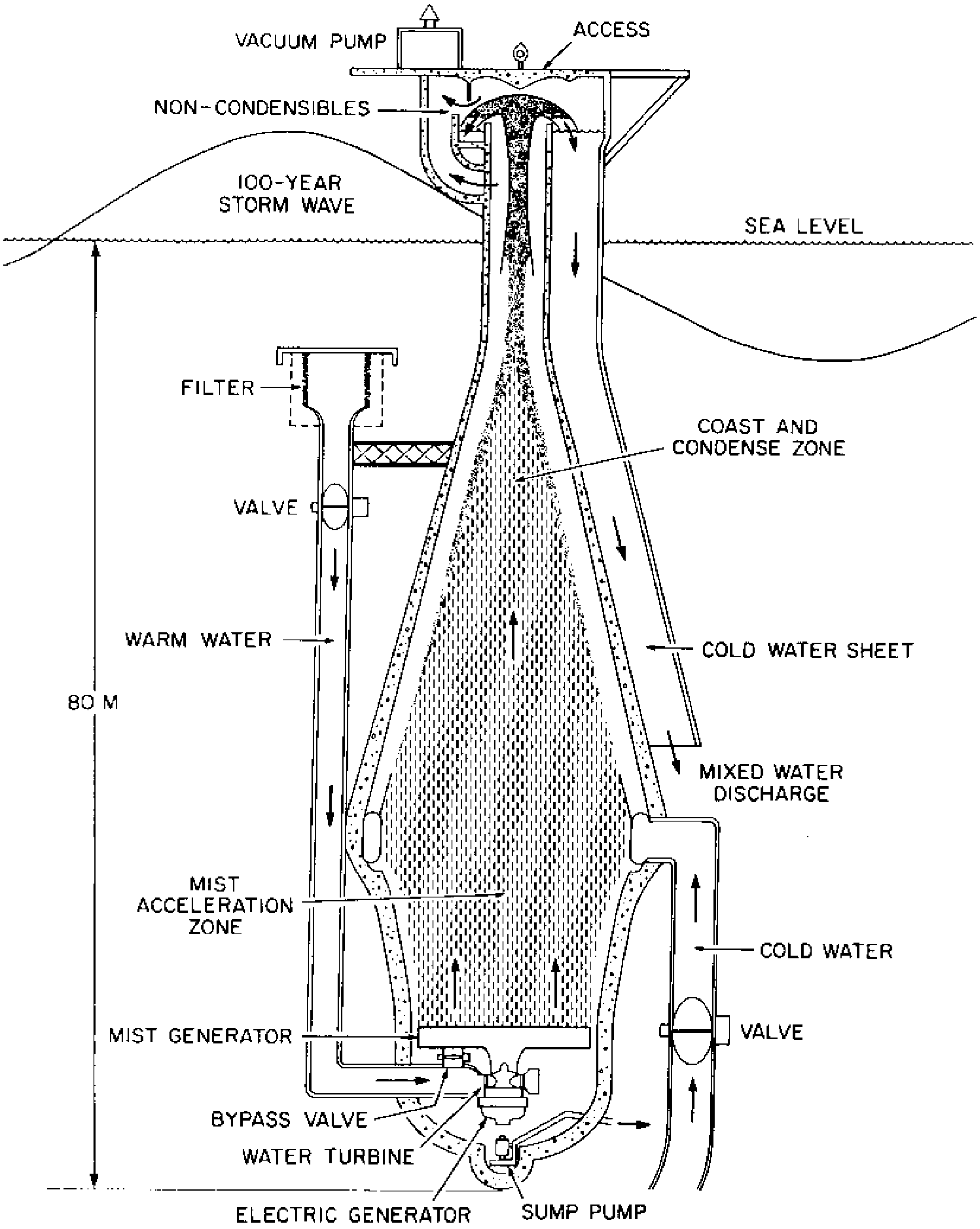

Figure 4. Mist-lift cycle OTEC schematic diagram (Ridgway, 1984)

input heat energy to the turbine. In the case of Mini-OTEC this was 2.7%, so that the energy input to the turbine was 96 kW. Losses due to inefficiency in the turbine and generator reduced this further to approximately 50 kW of actual measured generator output.

For small systems, parasitic losses such as power for water pumping can represent a sizable fraction of the gross electrical output. For Mini-OTEC, these parasitic functions required about 40 kW, leaving only 10 kW of net electrical output. Larger systems have proportionally smaller parasitic losses. For example, the OTEC plant designed for Kahe Point on Oahu (see below) produces a net electrical output of 40 MW from a gross turbine output of 52 MW. Larger plants provide even better net to gross ratios.

In discussing these efficiencies, which are low when compared with those of conventional power systems, it is important to remember that tremendous resources of warm and cold ocean waters are available for use and re-use. There is no fuel cost for OTEC. As noted on page 4, tremendous amounts of OTEC energy can be withdrawn without significantly altering the oceanic temperature structure. The sun, which continues to reheat the ocean surface, replaces the energy removed by OTEC.

OTEC ECONOMICS

Since OTEC has great potential to satisfy our future energy needs at minimal environmental expense, it warrants development even in the face of significant implementation difficulties. Such difficulties fall into two major classes. First, the fact that the temperature difference available for OTEC is considerably smaller than that used by other energy conversion processes leads to large water requirements and, consequently, to large systems to supply and handle the water. The need for such systems results in major materials selection and pipe construction difficulties. The second group of difficulties results because the thermal resource exists in the tropical oceans at locations generally remote from the population centers where energy is required (Figure 5). Direct transmission of electrical energy from these remote locations to population centers is impossible with present technology and would probably be inefficient even if it could be done.

Partial solutions have already been found for both of the above classes of difficulties faced by OTEC designers. Work at NELH has gone a long way toward solving some of the materials and construction problems resulting from the need for such large volumes of water. It now appears, for example, that aluminum may be used for OTEC heat exchanges in place of scarce and expensive titanium. Also, mechanisms have been proposed for using OTEC-produced electricity for energy-intensive processes *in situ* on OTEC platforms at sea, thus eliminating the need for direct transmission of the electricity to populated areas.

OTEC Plant Life Expectancy

Since OTEC plants use the solar energy stored in the ocean's surface layer, they require no fuel for producing electricity. This makes the economics of OTEC power production significantly different from the economics of more traditional fossil fuel and fission power systems. A much larger

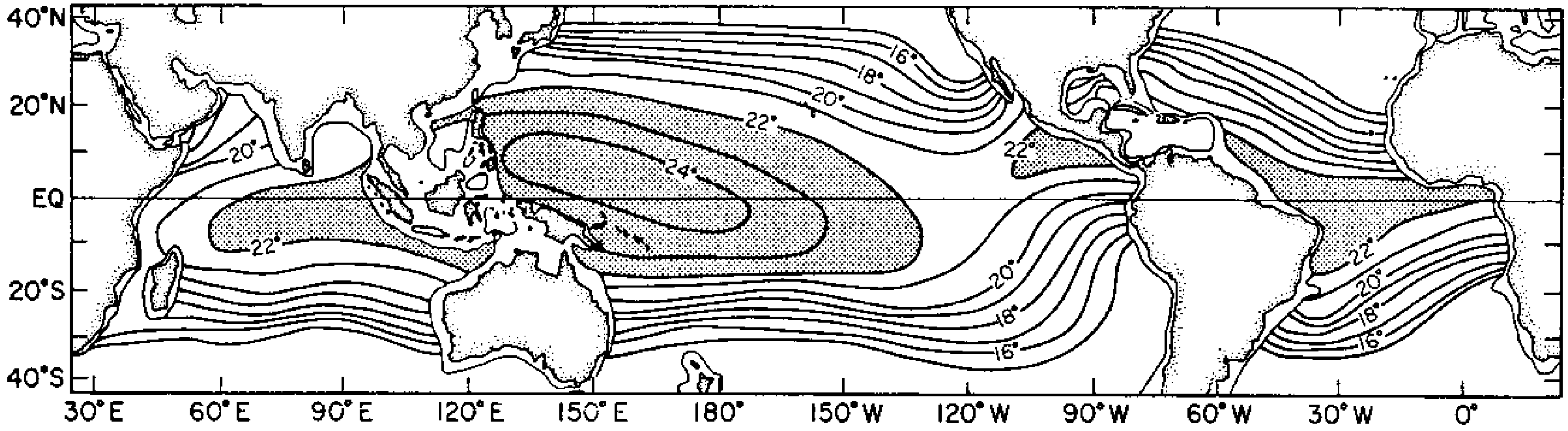

Figure 5. Map showing the extent of the OTEC resource. Contours are of the average temperature difference between the sea surface and 1,000 m depth. The shaded areas represent the zones of greatest OTEC efficiencies.

proportion of the total cost of OTEC power production is required for the initial capital investment. The only costs during production are for operation and maintenance.

The large initial capital outlay required for OTEC plants makes analysis of their overall economics difficult. Instead of the assumptions about the future trends in fuel costs which are essential ingredients for economic projections of traditional power plants, OTEC economics revolve largely around the plant's life expectancy. If, for example, designers could guarantee a plant lifetime of 40 years without significant overhaul costs, the overall economics would be significantly better than for a plant which would last only between 20 and 30 years.

This dependence upon plant life expectancy is unfortunate for a new technology, since it is especially difficult to produce believable estimates of lifetime for a large plant when it has yet to be built. This problem is compounded by the uncertain nature of engineering systems in and around the ocean. Although the offshore oil industry has amassed a large base of engineering experience at sea, prediction of the vagaries and extremes of oceanic weather and their effect upon structures remains difficult. Join this problem with the corrosive nature of seawater, and one can see how difficult accurate life-expectancy prediction becomes. These uncertainties force economists to use conservative estimates of plant life cycle, making the overall economics of OTEC appear unfavorable. This is especially true when compared with making economic projections for fossil fuel plants at times like the present when fuel prices are lower. Thus, the eventual economics of OTEC depend upon future changes in the cost of traditional fuels and upon the achievable lifetimes for OTEC plants.

Required OTEC Plant Sizes and Water Volumes

As noted earlier, a primary reason for interest in OTEC stems from its potential to satisfy most of humankind's energy needs. Since large numbers of small plants are unlikely to be economical, large plants are essential for the development of a viable technology. The relatively small temperature difference available in the OTEC resource means that large volumes of water must flow through even small plants. These requirements present severe difficulties for plant designers, especially in the areas of plant cost and component size. The large volumes of effluent water potentially available, however, make the possibility of adjunct aquacultural enterprises particularly attractive.

Straightforward calculations indicate a need for approximately 3.8 million l/min (1 million gpm) each of warm surface seawater and cold deep seawater for each 10 MW of electrical output. Design alternatives, such as open- or closed-cycle systems, do not significantly affect these total water requirements as long as the plant's output is larger than about 10 MW.

Large water volumes require large heat exchangers for closed-cycle systems. A 100-MW plant, for example, would require nearly 11,000 km (7,000 miles) of 3-cm (1.5-in) diameter tubing in the evaporator and condenser. Heat exchangers this large are feasible mechanically, but the requirement that they be made of corrosion-resistant materials makes them very expensive.

OTEC By-products

Coldwater aquaculture research was initiated at NELH largely as an effort to develop economically viable by-products of the OTEC process. Investigators felt that the value of such by-products might be great enough to improve significantly the economic competitiveness of OTEC in comparison with alternative energy sources. Although OTEC designers have been slow to recognize and/or develop the potential, it now appears clear that significant economic benefit would accrue from the development of such by-products. In addition, work at NELH indicates that some coldwater aquaculture ventures might be economically viable on their own, i.e., independent of an OTEC plant. The value of the products may be sufficient to justify the capital and operating costs for the required coldwater supply system.

BRIEF HISTORY OF OTEC

D'Arsonval proposed a closed-cycle system for using the ocean thermal resource for electrical power generation (see above). He recognized potential problems with both corrosion and biofouling as well as with the size of the required pipes and heat exchangers. Claude invented the idea of open-cycle OTEC. He raised sufficient capital to build a small plant at Matanzas Bay, Cuba, in 1930. That plant actually generated more than 20 kW of electricity for a short time before a hurricane destroyed the coldwater pipe. After the loss of the Cuba plant, Claude returned to France and raised enough money to install a floating plant off Brazil the following year. Although he was unsuccessful in two attempts at deploying a floating coldwater pipe, Claude's work remains an example of innovation and resourcefulness.

The next major push for OTEC development followed the oil crisis in the fall of 1973. The U.S. Energy Research and Development Administration (ERDA) — predecessor to the Department of Energy (DOE) — instituted several programs to develop alternate energy resources including OTEC. It funded studies in which various large U.S. companies developed conceptual designs for both open- and closed-cycle OTEC plants. These studies identified several engineering problems which required solutions, such as coldwater pipe materials, construction techniques, and dynamics in the ocean; corrosion and biofouling of candidate heat exchanger materials; and seawater thermodynamics under open-cycle conditions. For example, although titanium is an ideal heat exchanger material from the corrosion standpoint, its scarcity and cost dictate that alternative materials be used, especially if we ever hope to utilize the large OTEC energy resource. As noted above, a single 100-MW closed-cycle plant would require nearly 11,000 km of 3-cm diameter titanium tubing. This represents approximately one-fourth of the present U.S. annual titanium consumption. The scarcity of the metal would preclude economical construction of more than a few such plants.

The ERDA studies led the Department of Energy to begin a two-pronged investigation aimed at solving some of the OTEC design problems. The first part of the program, called OTEC-1, used a floating platform and the second part involved the development of the Seacoast Test Facility (STF). Both are discussed below.

OTEC-1

OTEC-1 involved the installation of two 1-MW heat exchangers in a converted 170-m (560-ft) Navy tanker which was moored off Kawaihae on the island of Hawaii where the water depth was about 1,280 m (4,200 ft) (Figure 6). Cold seawater was pumped through three 1.2-m (4-ft) diameter polyethylene pipes, each 670 m (2,200 ft) long, which were bound together and suspended beneath the ship. This cold seawater and warm surface seawater flowed through heat exchangers and evaporated and condensed ammonia in a closed-cycle OTEC system. The OTEC-1 experiment was devised to test and evaluate heat exchanger and other component designs under dynamic, at-sea operational conditions. No attempt was made to generate electricity.

Several large U.S. corporations responded to the DOE request for proposal for the OTEC-1 project, which was planned to be a $50 million venture. A partnership between TRW, a California aerospace engineering contractor, and Global Marine Development, an oil exploration firm which at the time was operating the *Glomar Challenger* for the National Science Foundation's Deep Sea Drilling Project, won the contract in 1978. Engineering and management difficulties caused project delays and significant cost overruns, but the system finally began full operation at sea in January of 1981. The Reagan administration, inaugurated that same month with the avowed goal of reducing Department of Energy programs, ended the experiment less than 4 months later. The ship was placed in mothballs at Pearl Harbor and eventually turned over to the state of Hawaii to be sold as scrap.

One of the major goals of the OTEC-1 project was to study the long-term operational behavior of the system components. Some information was obtained on heat exchanger efficiencies and on techniques for deploying large pipes and mooring a ship in the deep ocean, but the early termination of the project precluded much of the planned data collection on long-term biofouling and corrosion.

Seacoast Test Facility

The second part of the Department of Energy's OTEC program involved construction of a shore-based laboratory for longer-term research that could not be done conveniently at sea. The Research Corporation of the University of Hawaii (RCUH), representing Hawaii researchers, contracted with the internationally known firm of Parsons, Brinckerhoff, Quade and Douglass for the design of a laboratory to meet DOE specifications for OTEC research. A joint federal-state agreement was worked out for construction of the Seacoast Test Facility (STF) at the NELH site at Keahole Point. Of the projected $16 million facility cost, the state, through RCUH, agreed to clear the land and install the access road and utilities at a cost of about $5 million (exclusive of the land), and the DOE agreed to provide the remaining $11 million to construct experimental facilities and buildings. When laboratory construction began in late 1979, the OTEC-1 project was experiencing large cost overruns, with the result that the actual federal funding for STF construction amounted to only about $2 million. The state DPED increased its contribution to about $6 million, so that the actual capital expenditures during construction amounted to approximately $8 million. NELH has since met or exceeded all of the goals proposed for the STF, with a facility costing half the projected amount.

In 1981, RCUH, acting for the state of Hawaii, installed a 30-cm (12-in) diameter pipeline which brings seawater from 600 m deep in the ocean to the onshore laboratory at NELH. This remains the only deep seawater system operating in the world, and it has made the laboratory a center for research

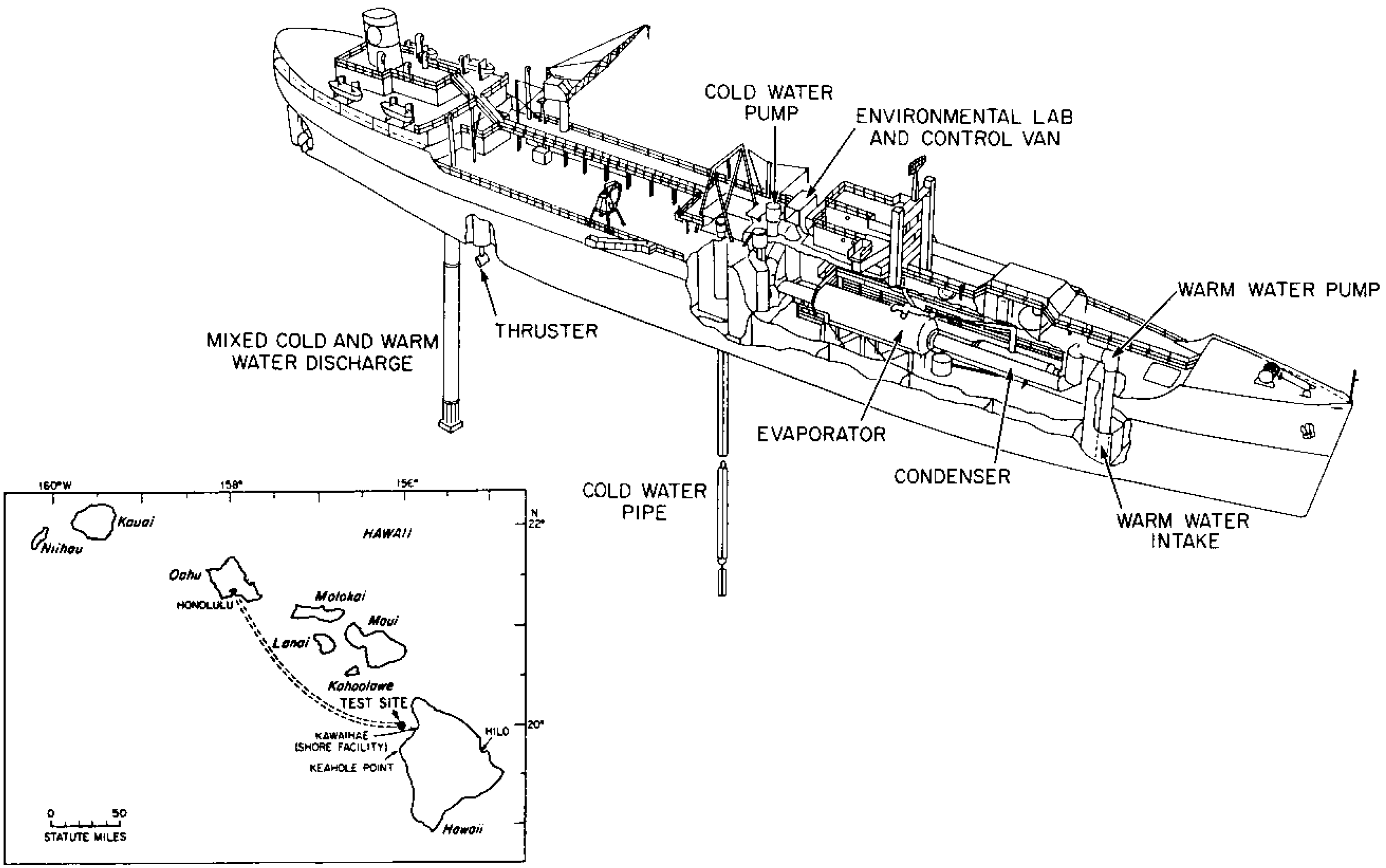

Figure 6. OTEC-1 location map and MV Ocean Energy Converter system diagram

in OTEC, aquaculture, and oceanography (Figure 7). DOE has funded research on biofouling and corrosion of candidate closed-cycle OTEC heat exchanger materials, heat and mass transfer and noncondensible gas removal in open-cycle OTEC systems, and the variability of the quality of both the surface and deep water. The encouraging results of these experiments are discussed briefly below, whereas the various aquaculture and oceanographic projects conducted at NELH are discussed more fully in subsequent chapters. Appendix B presents a tabular summary of the research at NELH.

Mini-OTEC

A highly successful OTEC project resulted indirectly from the OTEC-1 program. Several engineers who worked on the unsuccessful OTEC-1 proposal effort at Lockheed Missiles and Space Co. (LMSC) in Sunnyvale, California, developed an alternative called Mini-OTEC. They planned the smallest system which they were certain would generate net energy; that is, a system which would generate more electricity than the seawater pumps and other ancillary equipment would consume. The design used only "off-the-shelf" components already available from other technologies and operated on an isolated platform at sea to demonstrate its self-sufficiency.

The Hawaii Department of Planning and Economic Development agreed to fund Mini-OTEC in cooperation with LMSC and several other companies, many of which loaned or donated components to the project. Hawaiian Dredging & Construction Company, a subsidiary of Dillingham Corporation, designed and built the platform modifications and mooring system for deploying Mini-OTEC at sea off Keahole Point. The platform was a barge rented from the U.S. Navy. Alfa-Laval of Sweden loaned the project two of their titanium heat exchangers and helped to design and monitor the instrumentation system. Worthington Pumps donated used pumps for both the seawater and ammonia systems. Rotoflow Corp. provided a low-pressure water vapor turbine which was modified to work with ammonia.

Although it was an outgrowth of the OTEC-1 project, Mini-OTEC began operation first. It was moored in the offshore research corridor which had just been established for NELH. It first operated successfully on August 2, 1979, producing 50-kW gross and 10-kW net electricity. When the warm and cold water pumps were turned on, the turbine started turning and the auxiliary generator was turned off — and all the lights, TVs, and appliances kept working. The system operated for 48 uninterrupted hours the first time it was started. In all, it operated for slightly longer than the planned 3 months, producing electricity approximately 50% of the time. Although designed primarily as a demonstration project and not for data collection, Mini-OTEC produced much useful information for designers of future OTEC systems.

Mini-OTEC received a National Academy of Engineering award as the best engineering project of 1979. It was built at minimal cost in a very short time and exceeded its design goals.

The "PON" or "10-40" OTEC project

The Department of Energy initiated an OTEC project for the design of a 40-MW pilot plant. It was announced via a proposal opportunity notice (PON). Initial concepts involved the use of four 10-MW modules. This project has, therefore, been referred to as either the "PON" or the "10-40" OTEC project. Although DOE initially expected to award 6 conceptual design contracts, it found that only

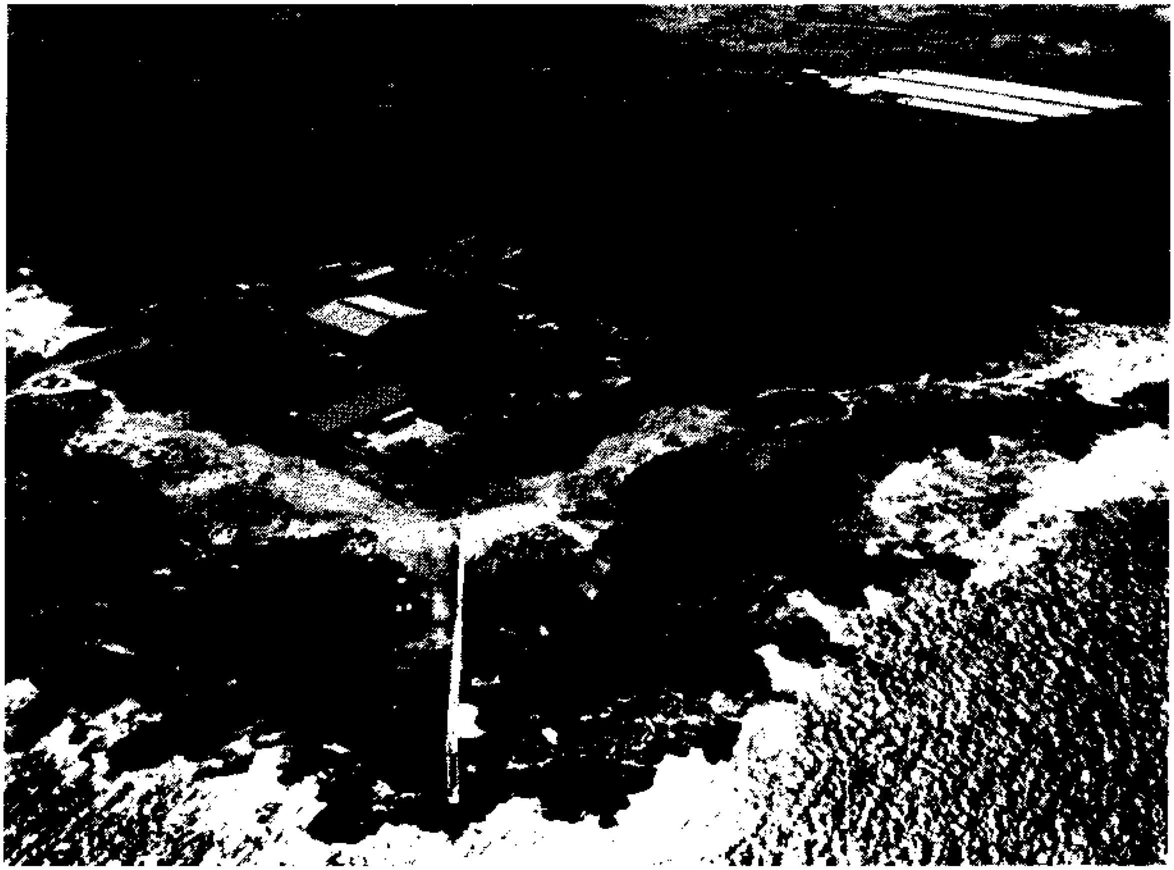

Figure 7. Aerial photograph of NELH. Cyanotech Corporation's microalgae raceways (upper right), Hawaiian Abalone Farms' 4-acre kelp pond (upper center), shade cloth covering abalone tanks next to two million-gallon kelp tanks (upper left), laboratory buildings and facilities (left center), and seawater pipelines (lower left).

2 out of 11 proposals received in response to the notice met the criterion of immediate commercial viability. Both of these — one from General Electric Co. (GE) and the other from Ocean Thermal Corporation (OTC), a consortium including Alfa-Laval and TRW — proposed plants that would operate in conjunction with Hawaiian Electric Company's conventional power plant at Kahe Point on Oahu. These designs appeared to be more economically attractive than other options because of the component size reductions achievable by using the warmwater effluent from the existing plant to increase the temperature difference across the OTEC heat exchangers. An additional criterion requiring no significant extensions of existing technology dictated that both successful proposals used closed-cycle systems with titanium heat exchangers. GE proposed a tall, offshore oil platform-type structure in 200 m (600 ft) of water, whereas OTC planned a shallower, bottom-mounted structure connected to shore by a causeway. Many people in the OTEC design community felt it was unfortunate that the PON project resulted in only two funded efforts, both necessarily site-specific to Kahe Point. It appears unlikely that the project will produce results applicable to other sites or to the offshore plants needed for eventual significant utilization of the OTEC resource.

Following the 1-year conceptual design effort, a DOE design review led to the elimination of GE from the program. OTC was funded for an additional 2-year preliminary design phase with the understanding that, in keeping with the goal of turning development projects over to the private sector, federal funding would cease with the conclusion of that contract in October 1984. Since that time OTC has been working on getting environmental approvals and private sector funding for the final design and construction of the 40-MW plant at Kahe Point.

The 1/3 Scale OTEC Coldwater Pipe Experiments

Another DOE program addressed the engineering problems associated with the design and construction of the large pipes required to bring up the cold deep water for OTEC. Sized to support the PON effort, this program planned to test scale models of the pipes that would be required for a 40-MW plant. The initial request for proposals issued in 1979 called for designs of a 1/3 scale pipe about 3 m (10 ft) in diameter and 300 m (1,000 ft) long, constructed from fiberglass-reinforced plastic (FRP). It was to be deployed instrumented from a floating platform. Hawaiian Dredging & Construction Company won the proposal effort and negotiated a contract, reduced by budgetary constraints, for assembling a 2-m (8-ft) diameter and 120-m (400-ft) long pipe. The pipe was fabricated more easily than the subcontractor, Ershigs, had anticipated, leading their manufacturing experts to project straightforward FRP construction of much larger pipes in the near future. The 120-m long pipe was emplaced for several weeks in April 1983 off Waikiki Beach, suspended underneath the Mini-OTEC barge. An extensive data acquisition system measured forces and moments on the pipe under varying wind, wave, and current conditions so well that all expected data were collected and the test pipe was removed ahead of schedule.

In keeping with the shift of OTEC program emphasis away from floating platforms and toward shore-based plants, DOE instituted a follow-on program which resulted in HD&C deploying a 24-m (80-ft) section of the 2-m diameter FRP pipe on the bottom, down the steep slope off NELH. A large part of this project involved the design and implementation of a mooring system to hold the heavy pipe in position on the 40° slope. Data from instruments measuring the forces, moments, and pressures on the pipe under varying environmental conditions were transmitted via electrical conduit to a data acquisition system installed at NELH. Deployment was successfully performed off NELH in April 1984; data acquisition began in June.

Water leakage into the housing of the multiplexer caused failure of the data acquisition system in August before any large wave effects had been measured. In addition, an electrical storm seriously damaged the electronics in the remaining instrumentation in January 1985, just before the repaired multiplexer was to be reinstalled. As a result, no data were obtained when large waves arrived the following week.

After funding for the 1-year data acquisition program expired in April 1985, all removable instrumentation was recovered. Since then, DOE funding renewal has never materialized, so the large pipe remains installed without instrumentation off NELH. However, the pipe and instrumentation from this experiment have recently been transferred to NELH so that further data collection may soon be conducted during high wave action.

The 1.2-m (48-inch) OTEC Pipe

After the OTEC-1 experiment ended in April 1981, its coldwater pipe, consisting of three 670-m long by 1.2-m diameter (48 in) polyethylene tubes, was left anchored at the 1,280 m water depth off Kawahae. The state, trough DPED, later proposed to deploy this pipe downslope along the bottom off Keahole Point to supply larger water volumes for DOE and other experiments at NELH. DOE eventually recovered the pipe using the submersible *Turtle* (which also performed inspections of both the NELH coldwater pipe and the Mini-OTEC pipe and mooring system) and towed it to Kawaihae Harbor where it was moored and turned over to RCUH, representing the state in October 1982. Anticipating its use of the pipe, DOE contributed funds toward the design and implementation of its redeployment. After several delays, an initial redeployment effort failed in September 1983 when one of the flanges left from the OTEC-1 deployment parted. After infusion of increased funds from both federal and state DPED sources to cover the large additional costs caused by this failure, and the resultant delay and remobilization, redeployment was again attempted in October 1983. This time the pipe flotation broke loose during the tow from Kawaihae to NELH, and most of the pipe was lost in about 100 m (350 ft) of water 6 km (4 miles) north of NELH. The heavy concrete anchors attached to the pipe caused it to break while sinking, thereby precluding any possibility of recovery.

International OTEC Developments

The United States has not been alone in researching OTEC possibilities. Several nations have similar projects. Ever since Claude's pioneering work, the French have maintained a strong interest in OTEC. They are now planning a 5-MW open- or closed-cycle plant in Tahiti. Swedish investigators are working on designs for an open-cycle plant in Jamaica, while Dutch and Indonesian engineers are designing a closed-cycle demonstration plant for the island of Bali. The Japanese have initiated a strong OTEC research program, including the construction of a 100-kW plant which operated on the island of Nauru for a short period before its coldwater pipe was destroyed by a typhoon in August 1982. Although the Japanese decided not to rebuild that system, it is rumored that they are constructing a larger closed-cycle plant on Nauru. The Japanese government has also announced its intention to support the development of an open-cycle pilot plant now being planned by Hawaii's Pacific International Center for High Technology Research.

RESULTS OF OTEC RESEARCH AT NELH

The U.S. Department of Energy has sponsored OTEC research at NELH since 1976. Initial projects used a buoy offshore in the NELH research corridor for biofouling measurements. These experiments, conducted by researchers from The Johns Hopkins University Applied Physics Laboratory and from the University of Hawaii at Manoa, demonstrated that high biofouling rates could be expected in the surface water. A temporary seawater system was installed in 1979 to pump surface water onshore for further biofouling and corrosion experiments, but this system was demolished by large waves during a January 1980 storm.

Closed-Cycle OTEC Research

Experimental apparatus. Since the construction and initiation of the NELH warm seawater supply system in July 1981, the Department of Energy has supported nearly continuous experimentation on biofouling and corrosion of heat exchange elements. Supplemental funds from the state DPED covered periods between federal Department of Energy contracts. Researchers from the Argonne National Laboratory (ANL) provided a set of three test racks, each of which supported six "loops" of plumbing through which seawater flows continuously at speeds of up to 2 m/s (6 ft/s). Each of the six test loops contains a heat transfer monitor (HTM) constructed by ANL using a modification of a design developed by Fetkovich (1976). These devices contain a copper block which is tightly clamped to a tube of the material through which the seawater flows. The PDP-11 computer controlling the experiment turns on a heater which warms the copper block to about 2°C above the temperature of the water. A sensitive thermopile imbedded in the copper block then provides the temperature decay coefficient, from which an estimate of the heat transfer through the tube can be calculated. Values of resistance to heat transfer due to fouling (R_f) can thus be measured accurately. To accommodate OTEC's small delta-T and consequent requirement for extremely efficient heat transfer, these devices are approximately 10 times more sensitive than similar instruments used for other measurements. They provide repeatable R_f measurements down to $1 \times 10^{-5} \times F \times ft^2 \times hr/btu = 3 \times 10^{-4} \times C \times m^2/watt$. OTEC plants can be designed to work with fouling resistance up to about $3 \times 10^{-4} \times F \times ft^2 \times hr/btu$, so it is important to be able to measure lower fouling values accurately.

Following these heat transfer monitors in each loop, there are "coupons," or sample tubes of various materials, through which the water also flows. The sample tubes are analyzed periodically for corrosion and biofouling. Two of the racks of six loops each carry warm seawater flowing at about 2 m/s. The remaining rack of six loops has carried cold water since initiation of the coldwater pipeline and pumping system in July 1982.

Heat transfer results. Figures 8, 9, and 10 present representative results of heat transfer studies. Figure 8 shows the results of a titanium tube that was allowed to foul freely as warm seawater flowed through it at 2 m/sec. After the fouling level exceeded 5 R_f units, the tube was brushed with 5 passes of a bottle brush, which invariably brought the R_f level down to the zero, or clean tube level. Unfortunately, no one has yet devised a straightforward mechanism for thus brushing the 7,000 miles

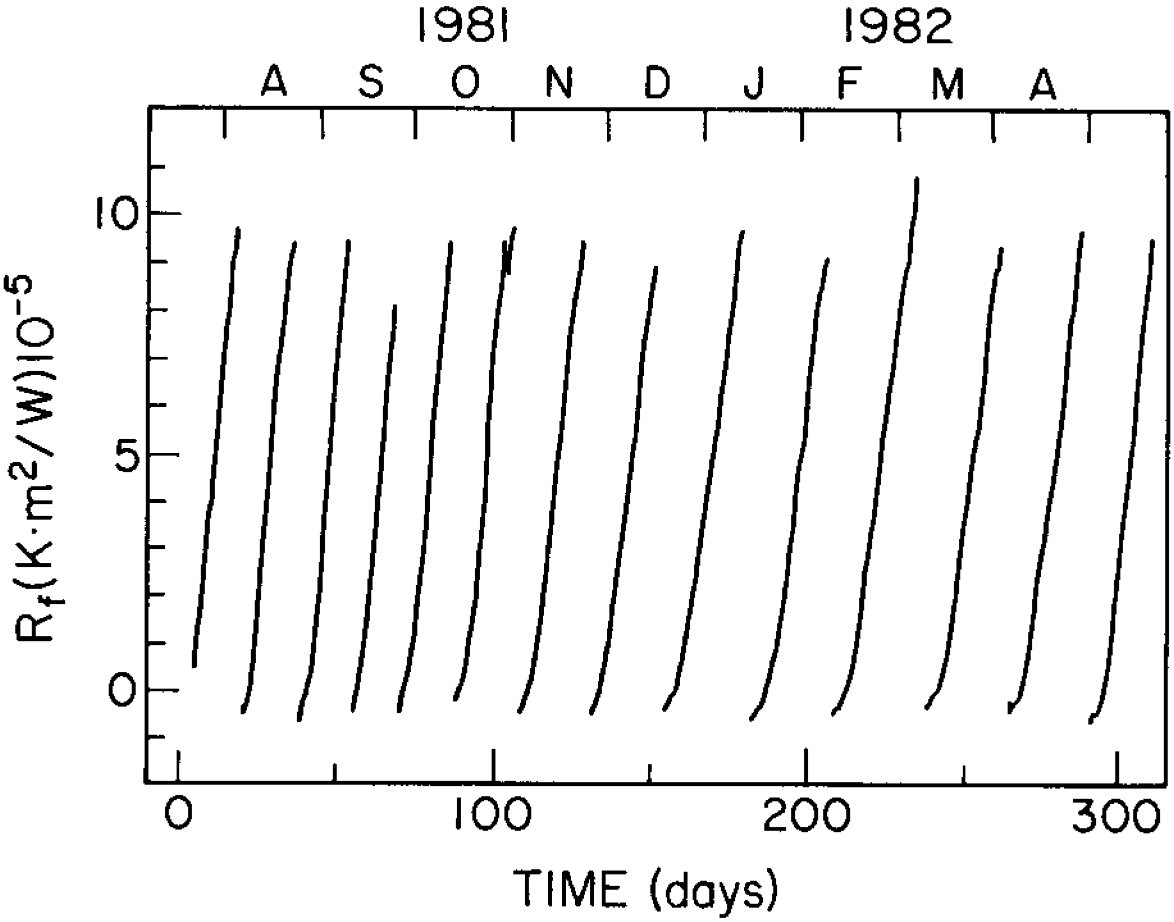

Figure 8. R_f vs time curves for free-fouling titanium in surface water. R_f units are 10^{-5} x °C•m²/watt

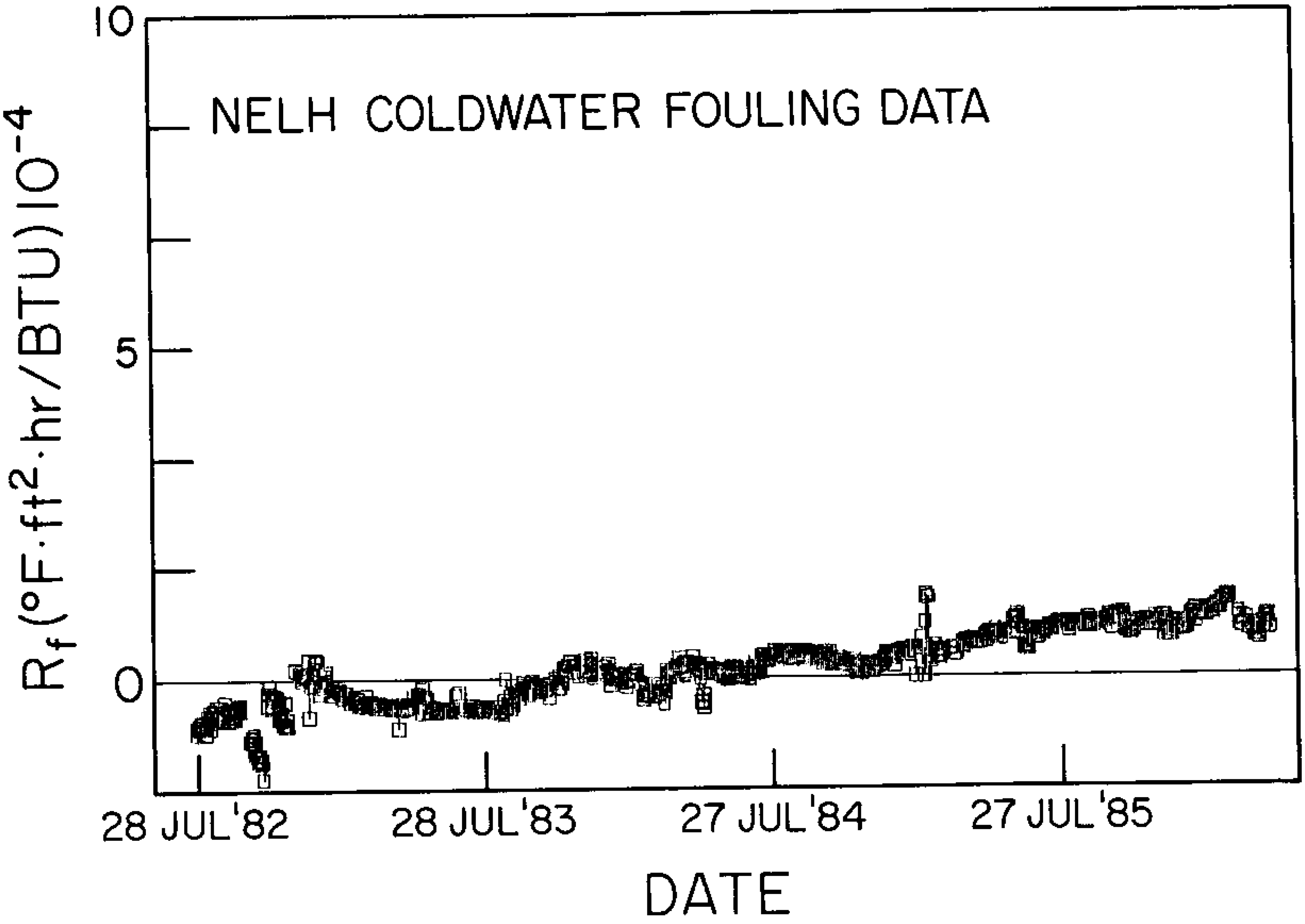

Figure 9. R_f vs time curves for free-fouling titanium in deep coldwater. Rf units are in 10^{-5} x °C•m^2/watt.

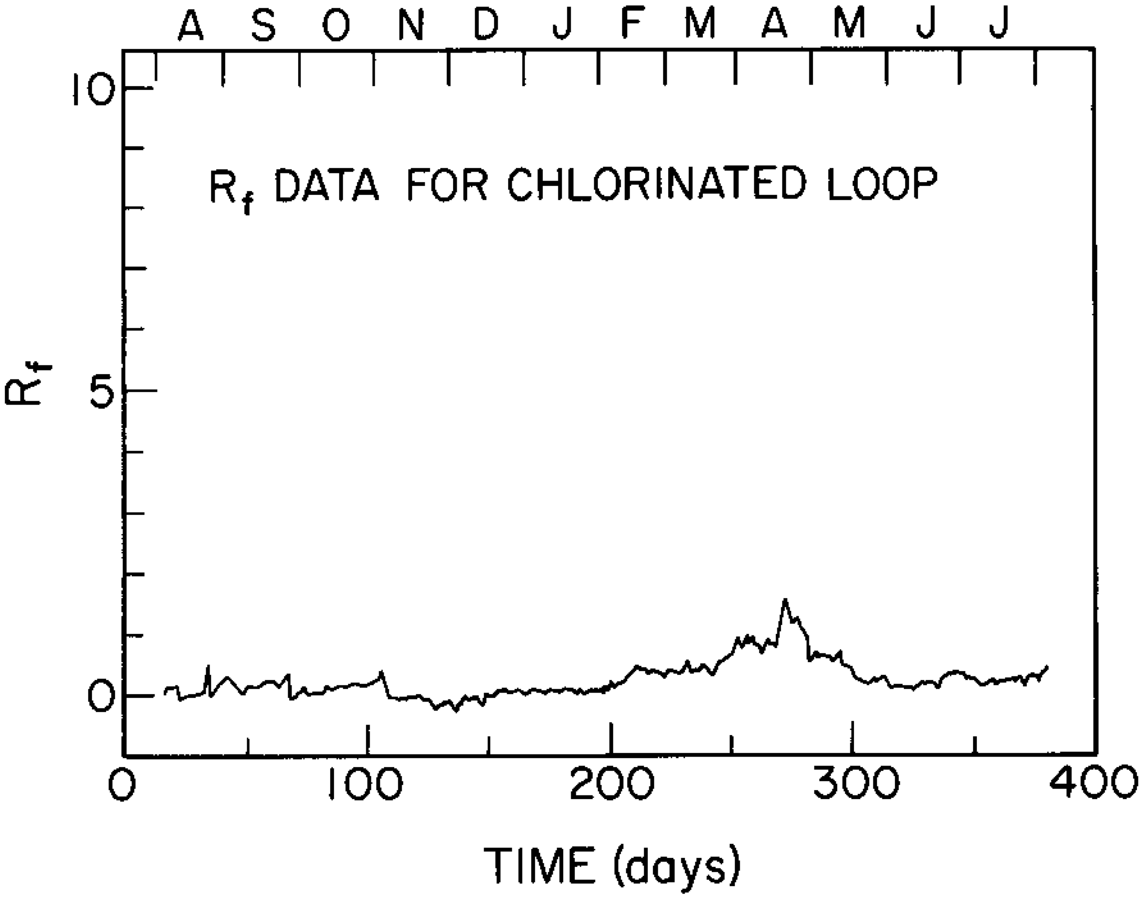

Figure 10. R_f vs time curves for titanium in surface seawater chlorinated at .05 ppm chlorine for one hour per day. Rf unit are 10^{-5} x °C•m^2/watt.

of tubing which would be employed in a moderately sized (100-MW) OTEC plant. As shown, these free-fouling curves are repeatable, and we have now collected more than 5 years of consistent data of this type. Although these fouling rates are similar to those observed at other sites and in the previously mentioned buoy experiments at NELH, the fouling began more rapidly than in those studies. In all cases, the data indicate that uncontrolled biofouling would effectively shut down an OTEC plant after 25 to 30 days.

Figure 9 shows that practically no biofouling occurs in the cold deep seawater. Although researchers had expected lower values for deep water than for surface water, the absence of fouling was a pleasant surprise. The result still holds after more than 4 years of continuous coldwater flow. It appears that biofouling will not be a problem on the condenser side of OTEC systems.

Biofouling countermeasures results. Several experiments conducted at NELH have focused on investigation of potential methods for controlling biofouling in candidate OTEC heat exchanger materials. Mechanical treatments, such as passing slurries and sponge rubber balls through the tubes, reduce the fouling rate, but they do not appear to control the fouling adequately — and they cause unacceptable corrosion or erosion of aluminum, a prime candidate material. Recent experiments on nonchemical biofouling control have indicated that ultraviolet control requires unacceptably high energy levels and that ultrasonic energy is only partially effective.

Ongoing experiments over the past several years have shown, however, that extremely low levels of electrolytically generated chlorine will control biofouling and that chlorination will have negligible environmental impact. Experimenters have found that a concentration of less than 0.1 mg/l of hypochlorite applied for only 1 hour per day will effectively control the biofouling of several candidate heat exchanger materials (Figure 10). In addition, it appears that chlorination of the oligotrophic tropical seawater at NELH does not produce the carcinogenic halogenated organic compounds which are known to form when seawater is chlorinated in other locales. Although mechanisms are poorly understood, it appears that both the low chlorine concentration requirements and the absence of halogenated organic production result from the low level of organic material in the tropical seawater. In any event, both results make the OTEC future appear brighter since they reduce or solve some major potential problems with the heart of the OTEC systems: the heat exchangers.

Corrosion results. The corrosion results have been equally encouraging. University of Hawaii researchers at NELH have found that, following the initial formation of an inorganic aluminum hydroxide corrosion layer, practically no pitting corrosion has occurred in a wide variety of aluminum alloys through which warm seawater has flowed continuously since July 1981 (Figure 11). This contrasts sharply with the results from similar experiments elsewhere and with those from samples in the cold deep seawater at NELH, where significant pitting corrosion occurs in all but one of the alloys tested. Although the results were initially surprising to corrosion experts, they now believe that the warmer temperature increases the rate and completeness of the formation of the hydroxide layer, which protects the aluminum from pitting. These results indicate that most aluminum alloys should work well for closed-cycle OTEC evaporators and that at least one alloy (bare 5052) will work in the condensers. Use of aluminum in the heat exchangers can reduce the initial capital cost of a closed-cycle OTEC plant by one-third, as compared with the cost using titanium. Alcan International, one of the world's largest producers of aluminum, has begun

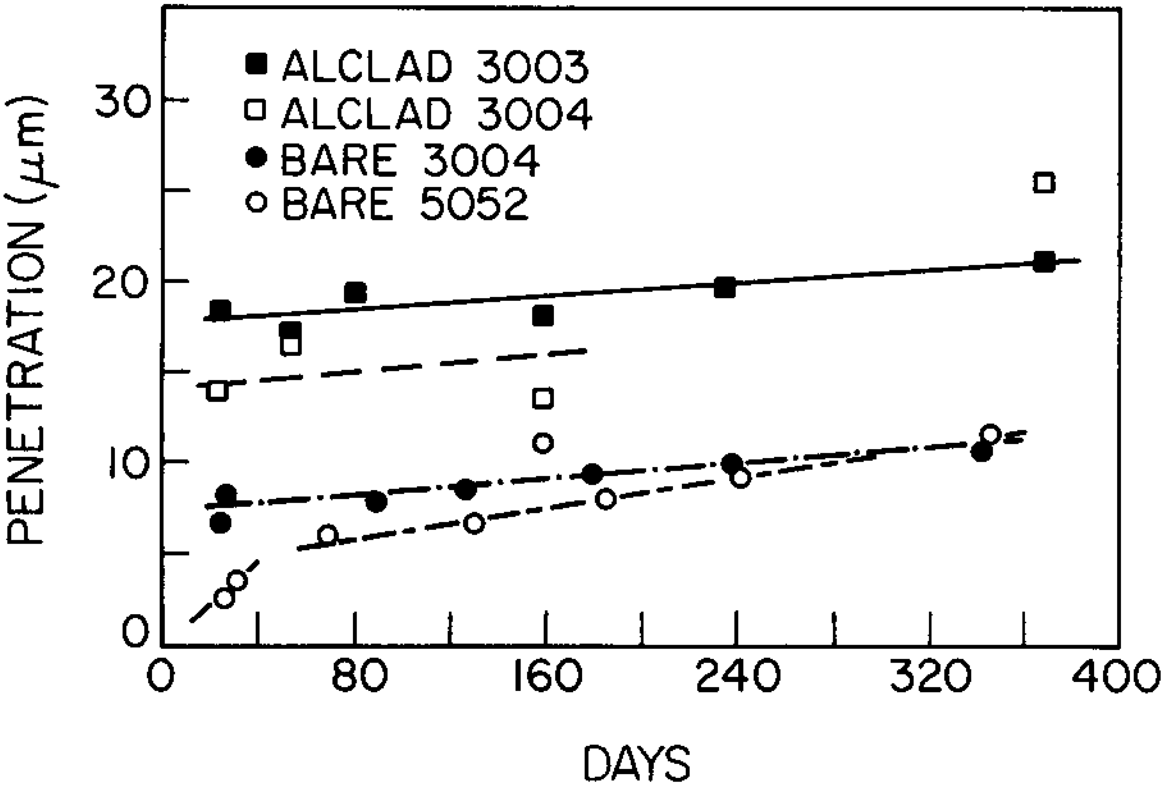

Figure 11. Corrosion data plots for four aluminum alloys used in surface seawater at NELH

experiments in both the warm seawater and cold seawater at NELH to study biofouling and corrosion of various alloys using a variety of multitubed heat exchanger configurations and fabrication techniques.

Open-Cycle OTEC Research

Experimental apparatus. Initial open-cycle experiments were conducted using evaporator and condenser chambers constructed by University of Hawaii researchers from 1.2 m long sections of 60-cm diameter Mini-OTEC polyethylene coldwater pipe. These chambers, mounted on top of the NELH coldwater header tank tower, are evacuated by a 25-HP vacuum pump mounted under the tower. The pump was provided by DOE's Solar Energy Research Institute (SERI). A 5-m (15-ft) deep hole drilled beneath the tower provided about 10 m (35 ft) of head to the drain, so that gravity maintained the vacuum. A packed column transported from Oak Ridge National Laboratory (ORNL) allows measurements to be made of the dissolved gas content of the seawater streams at various temperatures and pressures, and additional apparatus constructed on top of the tower permits investigation of techniques for removing those gases from the seawater. In the spring of 1987, DOE began installation of a new expanded apparatus for experimentation on Claude-cycle OTEC.

A mist-lift test apparatus was installed at NELH with DOE funding in September 1983 by Stuart Ridgway of R&D Associates, the developer of the mist-lift cycle. This apparatus included an additional 15-HP vacuum pump, an evaporator, a condenser, and a 5-m high mist-lift column.

Heat and mass transfer results. Experiments with seawater at NELH have generally confirmed earlier freshwater results on heat and mass transfer and on spout evaporator efficiency. The spout evaporators developed at SERI appear to offer an attractive alternative to traditionally proposed trough evaporator configurations.

Gas desorption results. SERI has funded research by investigators from the University of Hawaii, SERI, and ORNL on the dissolved gas contents of warm and cold seawater and on mechanisms for removing the gases. Although dissolved gas concentrations were as expected based on previous research, investigators found that the energy required to remove these gases from the seawater, measured in "height-of-transfer units," is about one-half of that required to remove similar gas concentrations from freshwater under similar conditions. This unexpected result, although still preliminary, will reduce significantly the parasitic losses required for noncondensible gas removal in open-cycle OTEC systems. Follow-on research has demonstrated an effective "pre-deaeration" system which utilizes these results.

Mist-lift cycle results. Critics have pointed out two major potential difficulties with the mist-lift process. First, seawater may quickly clog the small holes through which it must pass to generate the required mist of liquid water droplets. The second difficulty concerns uncertainties about the thermodynamics of two-phase flow, specifically the amount of coupling that will actually occur between the rising vapor and the liquid water droplets. Both questions have been answered favorably by the results from mist-lift experiments performed by R&D Associates at NELH with SERI sponsorship. Although preliminary studies showed that clogging times of less than 6 hours can be dealt with by appropriate screen changes and backflushing, a prototype mist generator consisting of a stainless steel sheet perforated with 100-micron diameter holes did not clog significantly during over

48 hours of operation. Likewise, the predictions for the volumes of liquid water available at two elevations in the experimental mist-lift column were verified over a range of delta-T values in actual experiments with seawater. Although these encouraging results were obtained in late 1983, DOE has not funded follow-on proposals. Therefore, the apparatus remains assembled but unused at NELH.

Water Quality Analyses on NELH Source Waters

With DOE support, NELH has maintained a water quality sampling program in which both the warm surface seawater and the cold deep seawater have been sampled at regular intervals since experimentation began in 1981. The analyses of the samples have been made as an essential part of the OTEC research program, but the importance and the implications of the data collected extend far beyond the OTEC arena. The values of the basic parameters of salinity, pH, alkalinity, dissolved oxygen, nutrients, and dissolved and particulate organic and inorganic carbon and nitrogen were well known for Hawaiian waters, but their variability at one point over extended time periods was heretofore unknown.

Table 1 contains a summary of the average values of the parameters measured weekly since 1981. The significant scatter observed in these weekly analyses led to more frequent sampling for specific experiments in 1985 and 1986. These increased sampling efforts were funded by Hawaii Natural Energy Institute and the University of Hawaii Foundation. The variability observed at several sampling frequencies in the deep water was particularly surprising and interesting. Strong, approximately diurnal signals are highly correlated between the nutrient concentrations and the salinity, quite surprising in water from 600 m deep. Longer sampling times have indicated a discernible period of 120 hours, in addition to annual cycles, and an apparent 3-year period which is beginning to develop from the long-term weekly data. Although the *in situ* temperature variations at 600 m are not now available (since the water has warmed up some unknown amount in traveling to shore through the pipeline), vertical (or possibly horizontal) advection of water masses past the end of the pipe is the only explanation thus far proposed which accounts for the observed variations. Thus, these data appear to represent the first measurements of internal waves in the ocean using variations of properties other than temperature. (Some aspects of these observations are discussed in detail by Smith and Walsh in this publication.)

TABLE 1. RESULTS OF WEEKLY WATER QUALITY ANALYSES AT NELH, 1982–86

Parameter	Warm Seawater	Cold Seawater
Temperature (°C)	25.99 ± 0.93	8.91 ± 0.95
Temperature (°F)	78.79 ± 2.82	48.04 ± 5.12
Salinity (°/00)	34.816 ± 0.172	34.298 ± 0.033
pH	8.227 ± 0.049	7.563 ± 0.040
Alkalinity (meq/l)	2.318 ± 0.020	2.354 ± 0.021
$NO_3 + NO_2$ (micromolar)	0.20 ± 0.08	38.97 ± 1.19
PO_4 (micromolar)	0.16 ± 0.04	2.96 ± 0.08
Si (micromolar)	2.98 ± 1.53	74.59 ± 4.36
NH_4 (micromolar)	0.36 ± 0.21	0.19 ± 0.20
Dissolved Organic N (micromolar)	4.34 ± 0.71	1.78 ± 0.61
Dissolved Organic P (micromolar)	0.24 ± 0.05	0.05 ± 0.06
Dissolved Oxygen (mg/l)*	6.98 ± 0.33	1.21 ± 0.19
Total Organic C (mg/l)	0.77 ± 0.33	0.36 ± 0.14
Particulate Organic C (micromolar)	2.88 ± 0.85	0.96 ± 0.35
Total Suspended Solids (mg/l)	0.61 ± 0.52	0.25 ± 0.13

Values shown are averages ± standard deviation
*Dissolved O_2 data from 1985 only (most reliable data)

PRESENT STATUS OF OTEC RESEARCH AT NELH

As of spring 1988, the DOE-sponsored closed-cycle OTEC experiments at NELH have been discontinued, following collection of six years of heat transfer data. The mist-lift apparatus remains assembled but unused. SERI, with DOE funding, has constructed the Heat and Mass Transfer Scoping Test Apparatus (HMTSTA) for open-cycle work. Experimentation continues on this apparatus, which in August 1987, produced the first freshwater ever from an open-cycle OTEC process. They are now designing a net power producing open-cycle experimental apparatus, sized to take full advantage of the cold water available to NELH from the new 100-cm (40-inch) diameter coldwater pipe which the Hawaii Ocean Science and Technology (HOST) Park and DOE installed in late 1987. It will be large enough to produce approximately 165 kW (gross) of electricity. The Pacific International Center for High Technology Research is working with SERI on turbine design and other aspects of this project.

NELH FACILITIES

The 30-cm surface water pipe for the NELH interim seawater supply system was installed as part of the phase 1 construction of the Seacoast Test Facility in 1980. The pipeline runs up at a 35° angle from the 6 m (20 ft) depth at the base of the seacliff to the approximate 3-m (10-ft) elevation of the shoreline and from there over 160 m (535 ft) to the pump station inside the laboratory compound. The station's four onshore 1,900 l/min (500 gpm) pumps can water at a rate of 6,000 l/min into the two 3,800-liter (1,000-gal) header tanks. Since July 3, 1981, water has been pumped through the system continuously. In August 1982, a new surface water intake was installed; it now extends 92 m (303 ft) offshore and rises 6 m above the 20-m (65-ft) deep bottom. Total pipe length from intake to pumps is now 270 m (887 ft). Water from this extended intake has a significantly lower concentration of suspended solids than that from the nearshore intake located at the base of the cliff. The latter intake is still available when needed for backup.

Figure 12 shows the placement of the 30-cm diameter NELH interim coldwater pipeline, as prepared by J. van Ryzin of Makai Ocean Engineering, Waimanalo, Hawaii. The offshore portion — made from slightly buoyant, high-density polyethylene — is held on the bottom with concrete anchors down to the 150 m (500 ft) depth, below which the bottom drops off more steeply. From that 150-m transition point, the pipe floats in a buoyant catenary down to the 610 m depth where naval surplus battleship anchors hold the intake about 30 m (100 ft) off the bottom. The intake is located 1,400 m (4,650 ft) offshore. The pump station, located in about 10 m (30 ft) of water approximately 30 m offshore, contains three horizontally mounted, in-line submersible pumps arranged in parallel. Power to run the pumps comes through armored cables from shore. The pipeline extends 1,720 m (5,638 ft) from the intake to the pump station, 50 m (156 ft) from the pump station to shore, and another 170 m (562 ft) from the shoreline to the header tank inside the laboratory compound — for a total length of 1,940 m (6,356 ft).

RCUH contracted for the installation of the interim coldwater supply system in December 1981, using capital improvement project funds earmarked for aquaculture via DPED. The system began pumping in February 1982, and cold deep seawater has flowed onshore continuously since initial pumping problems were rectified in August 1982.

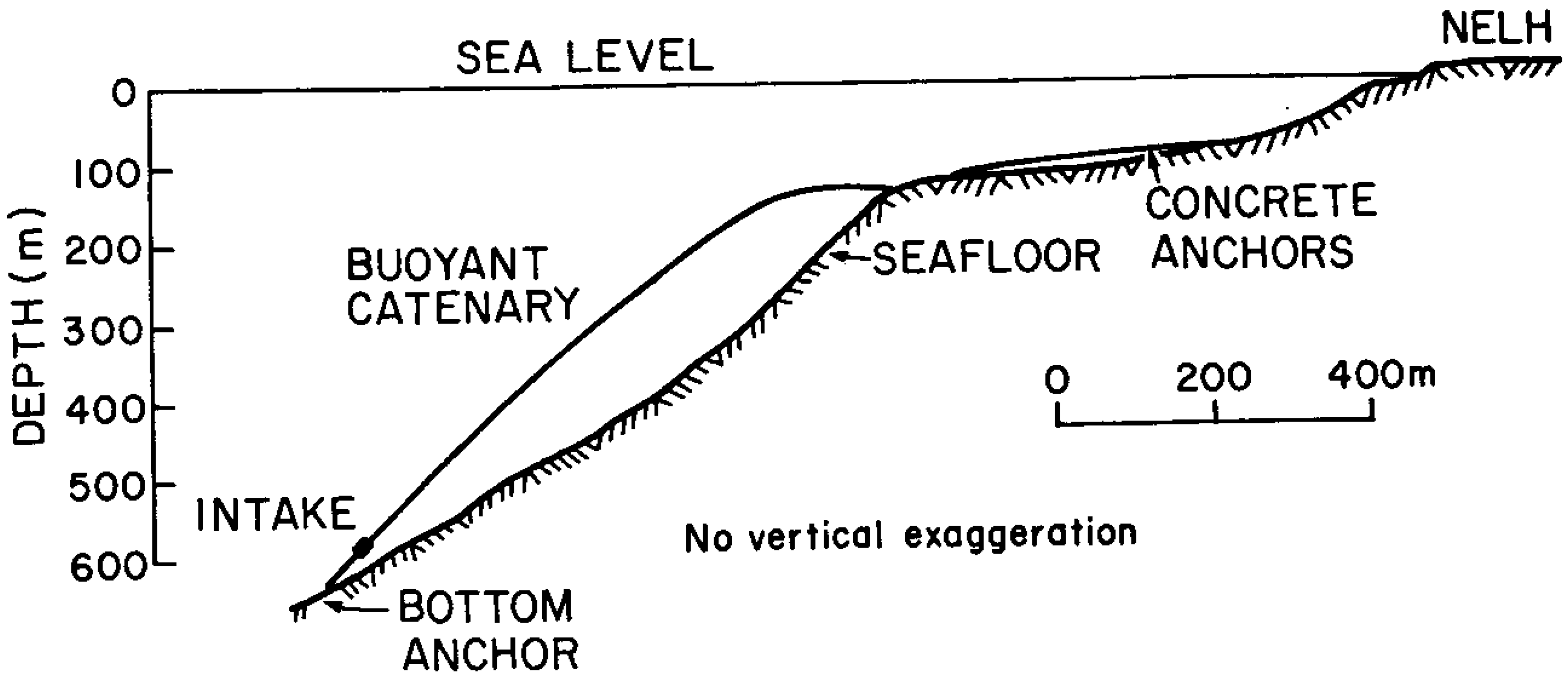

Figure 12. Elevation diagram of NELH interim coldwater pipeline

DOE OTEC experiments required that the coldwater pumps not dissolve iron ions into the water so standard steel pumps were unacceptable. Since fiberglass or plastic-lined submersible pumps were unavailable, 316 stainless steel alloy was used for all wetted components. With the three pumps now installed, the system produces 2,300 l/min (600 gpm), 3,400 l/min (900 gpm), and 4,200 l/min (1,100 gpm) with one, two, and three pumps operating, respectively.

The NELH cold seawater system is believed to be the only one in the world which continuously brings pure ocean water from the 610 m depth to shore for experimentation and commercial ventures. As noted below, plans are being formulated by both industry and government for additional pipelines to be installed at NELH.

NELH PROJECT ACCEPTANCE POLICY

NELH welcomes proposals from both the public and private sectors. With the approval of the board, users may arrange to share existing facilities or construct their own. Areas of planned expansion are closed- and open-cycle OTEC; coldwater aquaculture and agriculture; desalination; solar ponds; direct solar energy applications; and marine materials and equipment testing. Inquiries concerning NELH should be addressed to the Executive Director at 220 South King Street, Suite 1280, Honolulu, HI 96813.

According to the NELH Board of Directors, the criteria for acceptance of projects at the Keahole Point site shall be based upon each project's relation to the development of natural energy resources and upon their utilization of those resources that are available at Keahole Point. Projects that are only tenuously related to alternate energy development and/or do not require the resources that are available shall be referred to the appropriate governmental agency for action and recommendations. Illustrative examples include:

- OTEC research. High priority; alternate energy development plus utilizes available NELH resource (deep cold seawater).
- Solar pond power systems. High priority, alternate energy development plus utilizes available NELH resource (high solar radiation).
- Coldwater aquaculture. Medium priority, may be an adjunct to OTEC research plus utilizes available NELH resource (deep cold seawater).
- Solar desalination. Medium priority, indirectly energy related and utilizes available NELH resource (high solar radiation).
- DUMAND. Medium priority, tenuous relation to energy but requires proximity to undisturbed deep ocean.

NELH FUTURE PLANS

HOST Park. The High Technology Development Corporation (HTDC) was formed by the Hawaii Legislature in 1983 and began planning in November 1984 for the Hawaii Ocean Science and Technology Park. This facility, being developed on 547 acres of state-owned land adjacent to NELH along the access road, will provide space and infrastructure for the large-scale commercialization of projects which have performed successful research and pilot-scale development at the laboratory.

NELH has cooperated with HTDC in the joint funding of an environmental impact statement (EIS) for the proposed HOST Park, and the planned expansion of NELH. The EIS, along with related updates of existing NELH permits, will help to ensure the orderly development of both facilities. NELH has also contracted for preparation of an updated master plan to serve for the coming years of site development.

Initial infrastructure of the HOST Park includes the large diameter, cold seawater pipeline and supply systems. Current plans call for installation of the pipeline near the existing NELH cold seawater system so that cross-connections can be included which will provide redundancy and enhanced reliability of the NELH seawater supplies.

New pipelines. In January 1986, budget constraints forced the DOE to cancel plans to install a 76-cm (30-inch) OTEC research pipeline off NELH. DOE officials then approached the designers of the HOST Park about the possibility of federal contributions to expand the scope of the HOST Park coldwater pipe so that it would include capacity and facilities to support DOE experiments at NELH. Negotiations led to an agreement for joint sponsorship of a 100-cm diameter deepwater pipeline which was deployed just north of the existing 30-cm coldwater pipe in July 1987. Dual pumping and delivery systems now provide water for OTEC experiments at NELH and to HOST Park users at higher elevations along the NELH access road.

Following a prolonged period of large waves in February 1986, the NELH coldwater pipeline separated, causing a flow interruption for nearly 62 hours. This demonstrated the need for redundancy in this system, and the state legislature responded by appropriating $1 million for installation of a back-up pipeline. NELH's 45-cm (18-inch) pipeline, located about 0.4 mile south of the 30-cm coldwater pipe became operational for emergency backup in March 1988. This system provides not only the required back up, but also an additional 9,800 1/min (2,600-gpm) pumping capacity.

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APPENDIXES

APPENDIX A. OPERATIONAL SUPPORT CAPABILITIES AVAILABLE AT THE NATURAL ENERGY LABORATORY OF HAWAII

Warm Seawater Supply

*2,000 gpm
*24 C to 28 C

Cold Seawater Supply

*1,100 gpm (three 640 gpm pumps)
*Expandable to 1,300 gpm
*7.5 C to 10.5 C (constant, depends on total flow)

Water Chemistry Laboratory

Measurements:

*Flow
*Temperature
*Salinity
*Suspended solids
*pH and alkalinity
*Nutrients
*Dissolved oxygen
*Biochemical oxygen demand (BOD)
*Residual chlorine
*Analytical weights

Equipment:

*Balances and scales
*Microscopes
*Particle counter
*Auto-analyzer
*Salinometers
*Amperometric titrators
*pH meters
*Sampling nets, bottles, etc.
*Fume hood
*Glassware

Technical Support

*Mechanical
*Electronic/instrumentation/electrical
*Laboratory
*Diving

APPENDIX A—*Continued*

Facilities

*Laboratory space (indoor/outdoor)
*Warehouse space
*Office space
*Shops: electronics, machine
*Large vacuum pumps and open-cycle experimental chambers
*Aquaculture tanks (all plumbed with warm and cold seawater):

10 ea.	600 gal	fiberglass tanks
5 ea.	1,000 gal	plastic-lined steel tanks
10 ea.	$3m^3$ (800 gal)	rectangular tanks, each divided into 1 m^3 sections

*Various tanks, larval basins, and growout baskets
*A 20-ft x 50-ft inflatable building (currently in storage)
*Offshore research corridor
*24-ft workboat with trailer
*Trailer-mounted 100-kw 440-volt three-phase generator
*3 automatically started 125-kw diesel generators for facility backup
*Electrical distribution panels for experimental areas
*2 trailer-mounted 10-kw generators for field work
*7.5-ton Pettibone 4-wheel drive hydraulic crane
*3 trailer-mounted compressors: 1@ 375 cfm and 2 each @ 600 cfm
*2 PDP/11-23 computers for on-line heat transfer processing
*IBM-PC, IBM-PC/XT, and Epson Equity II microcomputers with 2 graphics printers, letter-quality printer, 2 color monitors, modem, data logger interfaces; and word processing, spreadsheet, communications and high-level language software

Vehicles

*2 fork lifts
*3 trucks
*Electric utility vehicle
*Station wagon

Communications

*Private VHF system with all vehicles, boats, and handheld units
*NEC 1648 phone system with 6 CO lines and 16 extensions
*Computer-based modem for electronic mail communications
*Telephone facsimile

Environmental Monitoring

*Wind, temperature, rainfall
*Solar insolation
*Multi-channel data loggers

Permits in Place

*Approved offshore research corridor
*Conservation district use permit for coastal and submerged land
*Special management area use permit for coastal lands
*Department of Transportation Harbors Division shore waters construction permit
*Environmental impact statement/environmental assessment for the whole facility
*NPDES discharge permit for seawater effluents
*United States Army Corps of Engineers permits

Public Information

*Tours available
*Public lectures
*Brochures and information packets

Security

*Fenced research compound
*Guard service off hours and holidays

APPENDIX B. SUMMARY OF RESEARCH PROJECTS AT THE NATURAL ENERGY LABORATORY OF HAWAII

Project Name	Objectives	Sponsor(s) Institution(s)	Funding Source(s)	Investigator(s)	Dates	Results	Status 1/87
Buoy Fouling and Corrosion Studies	Study fouling and corrosion of OTEC heat exchanger materials	UHM, HNEI JHU/APL	HNEI, DOE, NSF/ERDA	J. Larsen-Basse, F. Munchmeyer	'76–'79	Biofouling became significant after an initial incubation period of several weeks.	Completed
Mini-OTEC	Demonstrate net power production from OTEC	DPED, LMSC Dillingham Corporation	State of Hawaii, various companies	E. Grabbe	1/79–12/79	First successful production of net power from OTEC. Generated more than 10-Kw net on a floating platform moored in the NELH offshore research corridor.	Completed
Argonne Test Project	Monitor heat transfer and biofouling control Study Mircofouling Study corrosion Study macrofouling Analyze water quality	UHM/ANL UHM/ANL UHM/ANL UHM/ANL NELH/ANL	DOE/DPED DOE funding via SERI since 7/83	J. Larsen-Basse L. R. Berger J. Larsen-Basse E. A. Kay T. Daniel	7/81–present	1. Biofouling in warm surface water repeatably reduces heat transfer to unacceptable level within 20 days. 2. Only 70 ppb chlorine applied for 1hr/day controls the biofouling. 3. No reduction in heat transfer (i.e., biofouling) has occured over 4 years of continuous cold water flow. 4. Aluminum alloys do not show pitting corrosion in surface water, but do in deep water.	Continuing
Simplex Corrosion	Measure corrosion of samples installed on offshore buoy	UHM	Simplex Wire & Cable Co.	J. Larsen-Basse	7/81–3/82	Measured corrosion on several alloys installed on offshore buoy.	Completed
UH Atmospheric Corrosion Project	Monitor and analyze corrosion of samples in NELH marine atmosphere.	HNEI	UH Foundation	J. Larsen-Basse	7/81–3/83	Collected corrosion data on several aluminum alloys.	Completed

APPENDIX B—*Continued*

Project Name	Objectives	Sponsor(s) Institution(s)	Funding Source(s)	Investigator(s)	Dates	Results	Status 1/87
OTEC Aquaculture (Fish)	Investigate parameters of growing salmon and trout in deep cold water	HIMB	UHSG, MAC, DPED	A. Fast	1/82–11/84	1. Grew more than 1/2 pound of fish per gallon of deep water. 2. Found optimum temperatures, photoperiods and flow rates. 3. Studied smoltification parameters. 4. Spawned trout successfully in seawater.	Completed
OTEC Aquaculture (Macroalgae)	Demonstrate culture of nori (*Porphyra tenera*) and ogo (*Gracilaria* spp.)	HIMB	UHSG, MAC DPED	F. Mencher, R. Spencer	1/82–3/83	1. High nori growth rates (35% mass increase per day) initially and 40–60 $gm/m^3/day$ in high density (2–3 kg/m^3) tanks. 2. Optimum photoperiods and temperatures were determined.	Completed
Abalone Culture	Investigate feasibility of commercial abalone culture in Hawaii	Monterey Abalone Farms	Monterey Abalone Farms	G. Lockwood	2/82–present	1. Abalone and kelp (*Macrocystis*) to feed them can be grown in the deep cold water. 2. The high nutrient content in the deep water results in high protein in kelp. 3. The lack of pathogens in the deep water permits its use without filtration. 4. A commercial development module has been initiated.	Continuing
OTEC Chlorination	Study the effects of low level chlorination on the marine food chain	UHM	HNEI	F. J. Sansone	6/82–6/83	1. Chlorine kinetics in tropical seawater differ markedly from results with other seawater. 2. Reaction of the chlorine with the water takes much longer than in temperature water. 3. Only trace levels of halogenated organics are produced in chlorinated NELH water.	Completed

APPENDIX B—*Continued*

Project Name	Objectives	Sponsor(s) Institution(s)	Funding Source(s)	Investigator(s)	Dates	Results	Status 1/87
Maine Lobster Culture	Validate Hawaii as site for northern lobster (*Homarus americanus*) culture	Sanders Associates	Sanders Associates DPED	M. Thays	9/82–10/83	1. Maine lobster grow well in the Sanders culture system using temperature control obtained by mixing surface and deep waters. 2. Present economics indicated this culture would be unprofitable.	Completed
Cable Corrosion	Investigate corrosion of candidate materials for deep-sea cables	Parson's Hawaii	DOE/HECO	J. Larsen-Basse	1/83–present	Various candidate cable materials show expected corrosion in seawater.	Continuing
ASTM Corrosion	Monitor corrosion of metals in the ocean offshore of Keahole Point	ASTM	NELH	J. Larsen-Basse	6/83–6/89	First samples submitted to ASTM.	Continuing
Alcoa Corrosion	Study the corrosion of various aluminum alloys in flowing seawater	Alcoa	Alcoa	B. Liebert	1/83–1/85	Analysis of proprietary samples completed. Effects of brushing in warm and cold waters are being studied.	Completed
Open-cycle OTEC							
Heat and Mass Transfer Research	Study efficiency of spout evaporators and condensers by measuring heat and mass transfer in seawater system	UHM/HNEI	SERI/DOE	J. Larsen-Basse	6/83–present	1. Seawater results are similar to those with freshwater in Colorado. 2. Spout evaporators and condensers promise high efficiency for OC-OTEC	Continuing
Gas Desorption Research	Use a packed column to study composition of dissolved gases in seawater at various temperatures and pressures	UHM/ Look Lab	SERI/DOE	H-J. Krock	6/83–6/84	1. Dissolved gas compositions confirm predictions. 2. The "height of transfer units" which measure the power required to remove dissolved gases are about 50 % less with NELH seawater than predicted from freshwater data.	Continuing

APPENDIX B—*Continued*

Project Name	Objectives	Sponsor(s) Institution(s)	Funding Source(s)	Investigator(s)	Dates	Results	Status 1/87
Mist-Lift Process	Demonstrate operation of the mist-lift cycle with seawater	R&D Associates Marina del Rey, Calif.)	SERI/DOE	S. L. Ridgway	6/83–12/83	1. Mist generator works well without clogging. 2. Vapor-mist coupling approximates predictions — up to 100 m of lift may be available from 20 C.	On Hold
CWP/AST Phase III	Deploy and monitor 1/3 scale FRP CWP down slope off Keahole Point	HD&C/NOAA	NOAA/DOE	I. Sandison	4/83–5/85	Deployment successful. Data collection completed.	Completed
OTEC Agriculture	Grow strawberries in fresh-water condensing on pipes carrying cold seawater	UHM	UHSG	S. Siegel, M. Vitousek	1/84–6/84	Strawberries and various vegetables grow well. Seasonal cycling can be controlled by water flow rate.	On Hold
Microalgae Culture	Develop commercial micro-algae culture techniques in seawater	Cyanotech Corporation	Cyanotech Corporation	G. Cysewski	7/84–present	*Spirulina* grows well in seawater. Commercial production on going.	Continuing
Macroalgae Study	Study growth of macroalgae in surface and deep water	UHM	HNEI	F. Mackenzie, C. Agegian	1/85–6/85	Macroalgae efficiently utilize high deep water nutrient concentrations.	Completed
Giant Clam Culture	Study effects of Hawaiian environment on giant clam growth	Marine Animal Associates/ Waikiki Aquarium	Private	M. Dailey	8/85–8/86	Preliminary: Clams grow well in Hawaii.	On Hold
Nori Culture	Develop commercial nori culture techniques for Hawaii	Aquaculture Concepts	Private	S. Katase	8/85–present	Preliminary: Nori spores will germinate and grow in NELH seawater.	Beginning
ALCAN OTEC	Investigate corrosion behavior of various alloys and heat exchanger configurations	ALCAN Int'l	ALCAN	D. Goad	3/86–present	Apparatus erected; experiments in progress	Operating
Opihi Culture	Investigate and demonstrate growth of opihi (Hawaiian limpets)	W. H. Magruder	Private	W. H. Magruder	10/86–present	Preliminary: Opihi reproduce and grow well in sprays of the deep water.	Operating

APPENDIX B—*Continued*

Project Name	Objectives	Sponsor(s) Institution(s)	Funding Source(s)	Investigator(s)	Dates	Results	Status 1/87
Macroalgae Investigation	Investigate potential of macroalgae for removing excess nutrients from seawater return	UH Dept. Tropical Agriculture	HNEI, ADP	D. Robichaux	5/86–1/87	Preliminary: Algae can remove most of the excess nutrients from water flowing past them.	Completed

SURFACE AND DEEP WATER COMPOSITION AT THE NATURAL ENERGY LABORATORY OF HAWAII

S. V. Smith
T. W. Walsh

INTRODUCTION

Keahole Point, the westernmost point on the island of Hawaii (Figure 1), is in the climatic and oceanic shadow of the largest land mass in the Hawaiian Archipelago. There is no significant island shelf and little coral reef development at the point; the bottom plunges to abyssal depths. The coastline is apparently directly bathed by oceanic water. Relatively long-lived eddies develop along this coastline, exchanging nearshore water with more oceanic water offshore (Patzert, 1969; Lobel and Robinson, 1983). No streams enter the sea in this region to alter seawater composition along the West Hawaii coast, but groundwater from the watershed enters the sea along this coastline and can have some localized influence (Lau, 1977). There are thus reasons to suppose, but with some hesitation, that the composition of seawater at Keahole Point closely approaches open oceanic composition.

In a broader context, island-mass effects have been responsible for biologically interesting water properties (nutrients, primary productivity) in the vicinity of the Hawaiian Islands (Gilmartin and Relevante, 1974; Bienfang et al., 1984). One might therefore anticipate some composition gradient from immediately onshore water through nearshore transitional water to water of open ocean composition. If the island-mass effects involve quantitatively significant alteration of nearshore water composition, these effects could arise from either: a) enhanced upward turbulent or advective flux of nutrients associated with the barrier of the islands; or b) input of land-derived nutrients from the islands. Because of the considerations mentioned above, Keahole Point might be expected to maximize these effects.

In the context of these considerations, we address two closely related questions: 1) How does the water composition at Keahole Point compare with the composition of more clearly offshore local ocean water? 2) What are the characteristics and causes of variation in water composition at Keahole Point?

The Natural Energy Laboratory of Hawaii (NELH) at Keahole Point provides a unique operational advantage for comparing nearshore surface and deep waters to open oceanic waters.

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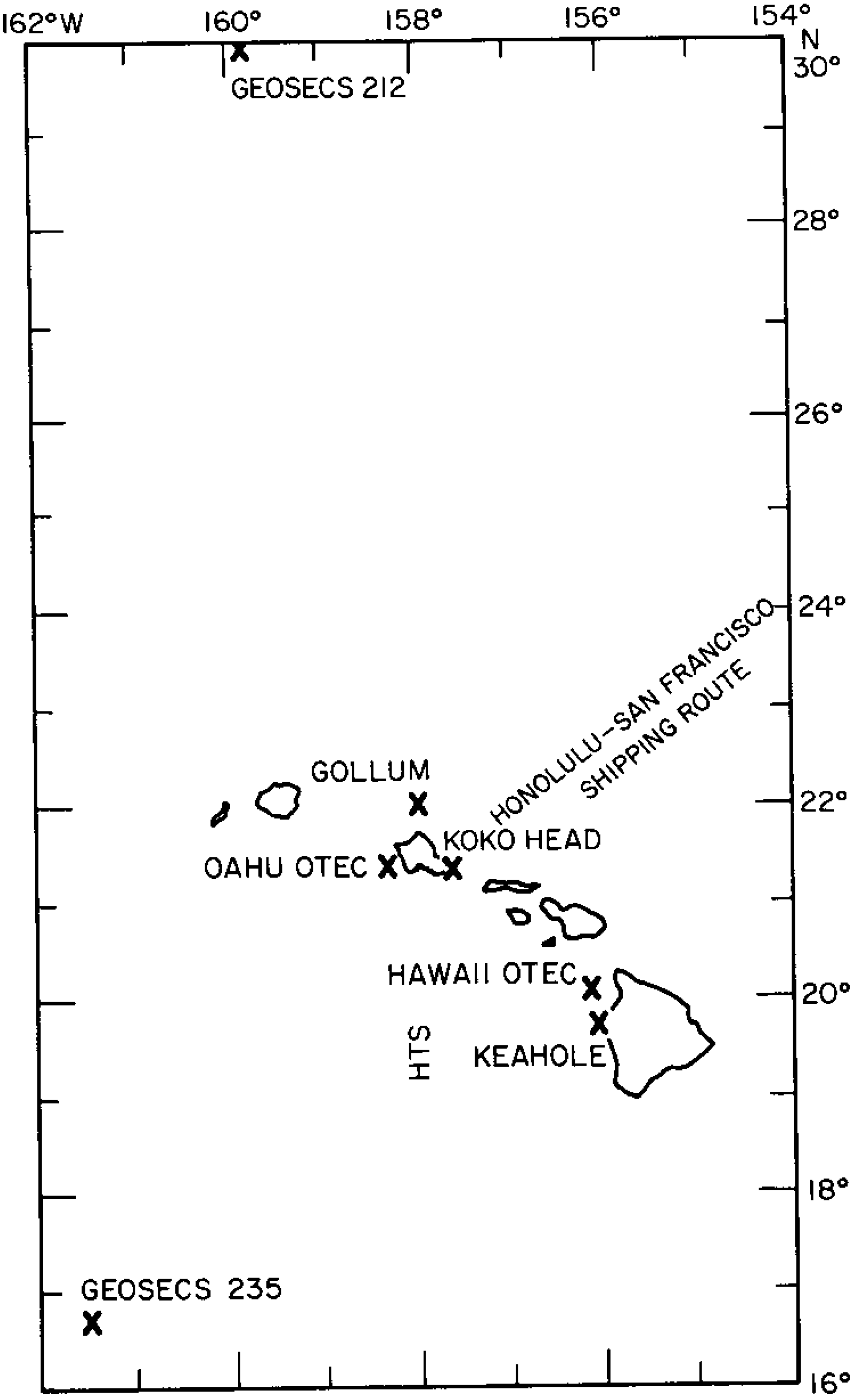


Figure 1. Map of the Hawaiian Islands, showing location of Keahole Point and other sample sites discussed here

Water from near the sea surface and from near the core of the oxygen minimum has been pumped continuously at NELH since 1982. Water composition has been monitored regularly. This pumping and monitoring have been undertaken as part of an ocean thermal energy conversion (OTEC) test facility. Especially for the deep-water intake, there is no location in the central ocean gyres with a comparable temporal intensity of sampling for water composition. The question of water quality is also important from the vantages of aquacultural utilization of the water and potential impact of OTEC-type discharges on the surrounding environment.

METHODS

NELH surface water is presently drawn from an inlet approximately 100 m offshore and from a water depth of approximately 8 m. The intake pipe is approximately 20 m above the sea floor at this location. This intake replaces an earlier one (operated until August 1982) which was only 6 m offshore and 4 m deep. The deep water is drawn from an intake approximately 1,700 m from the shoreline and from a depth of 586 m. This intake is approximately 30 m above the sea floor. The water residence time in the deep-water pipe varies with pumping rate, but ranges between about 60 and 90 minutes. Further details are given by Daniel (this volume).

Water composition has been measured at roughly 1-week intervals since mid 1982; some earlier data were collected as well, but with some interruptions. Because of various initial analytical problems, we restrict our discussion here to the 1983 and 1984 weekly sampling, as well as to data collected during a 24-hour experiment conducted in April 1985.

Sample collections and analyses have been supervised by the Hawaii Institute of Marine Biology (HIMB) analytical services facility, under contract from NELH. Temperature, salinity, oxygen, and pH measurements are made on site; samples are returned to the University of Hawaii for analysis of alkalinity, dissolved organic carbon, particulate organic and inorganic carbon and organic nitrogen, and dissolved nutrients. Details of the analytical procedures generally follow those summarized by Smith et al. (1981) as modified by Noda et al. (1981), Smith et al. (1986), and Walsh (unpublished). Calculations of the CO_2 parameters at *in situ* temperature, but without compensation for hydrostatic pressure, have used dissociation constants from Mehrbach et al. (1973), the solubility constants for CO_2 from Weiss (1974), and an iteration procedure adapted from Ben-Yaakov (1970).

There are some holes in the data set. Some samples have been lost or were otherwise not collected. Sampling for particulate materials has only been undertaken once a month (with a few lost samples), and neither particulate materials nor dissolved organic carbon were sampled during the 24-hour experiment. Clear analytical outliers have been discarded; in the case of oxygen, there were obvious problems with a large number of the samples, resulting in a loss of much of the oxygen data. We attribute these problems to sample storage before analysis. Some suspect analyses remain, but cannot be objectively discarded.

Data from Keahole Point have been compared with temporally more limited data sets from several other locations (Figure 1). Two surveys have been conducted in the Hawaiian Islands to consider sites for possible commercial OTEC operation. One of these was approximately 50 km northwest of Keahole Point (Noda et al., 1981a). Data from two cruises during that survey are summarized here. The dissolved organic nitrogen data from those cruises are clearly erroneous and are not reported.

The second such survey was approximately 10 km west of Oahu, and consisted of triplicate casts at each of two sites, six times over the course of an annual cycle (Noda et al., 1981b). Aspects of those data are also discussed by Bienfang et al. (1984) and Smith et al. (1986). Analyses discussed here for both of these OTEC surveys were undertaken by the HIMB analytical services facility and largely followed the same procedures as used at Keahole Point. Three clear outlier points for Si were discarded from the Oahu OTEC data.

Cross sections derived from Hawaii-to-Tahiti Shuttle Experiment (HTS) (Wyrtki and Kilonski, 1982) have been used to extract mean and standard deviations of temperature, salinity, nutrients, oxygen, total alkalinity, and total CO_2 between 19 and 20°N, 158°W over a one-year period. GEOSECS station 235 (Broecker et al., 1982), southwest of the Hawaiian Islands (16°45'N, 161°23'W), provides another clearly oceanic station with high-accuracy temperature, salinity, nutrient, oxygen, alkalinity and CO_2 data. Data were only collected once at this site. Station GOLLUM (Gordon, 1970; summarized in Gordon, 1971) north of Oahu (22°10'N, 158°W) was an oceanic station sampled repeatedly over an 18-month period; GOLLUM provides a reliable record of oceanic particulate materials. Williams et al. (1980) provide DOC data from GEOSECS station 212 (30°0'N, 159°50'W). This station is sufficiently far north of the Hawaiian Islands that we do not use it for other, more locally available data.

There are, in addition, long-term records of surface temperature and salinity at Koko Head, Oahu (Seckel and Yong, 1977; National Marine Fisheries Service unpublished). Saur et al. (1979) present surface temperature data from the Honolulu-San Francisco merchant shipping route. These data are discussed, as appropriate, but they are not tabulated.

RESULTS AND DISCUSSION

Tables 1 and 2 summarize the data for surface water and deep water from Keahole Point (1983–1984 data) and the comparison sites. So that we can examine variability as well as mean composition, the standard deviations for the 9-m Oahu OTEC data, the average standard deviations of the 456 m and 679 m Oahu OTEC data, the graphically present standard deviations from HTS, and the particulate-load standard deviations from GOLLUM have also been included.

There is no consistent difference between the clearly offshore data and the more nearshore OTEC stations, except for a regional surface salinity gradient which elevates the salinity of the two OTEC sites relative to the more southerly, offshore sites. We therefore simply compare data from all of the offshore stations with the immediately onshore Keahole data.

The Keahole surface-water temperature shows an annual oscillation between about 25 and 27°C (Figure 2), with some inter-annual variation. September-October is the warmest period, and February-May is the coolest period. Surface water temperature in and around the Hawaiian Islands shows a similar annual oscillation, between about 23 and 26°C (Seckel and Yong, 1977; Saur et al.,

TABLE 1. COMPARISON OF KEAHOLE SURFACE-WATER DATA WITH OTHER DATA SOURCES. VALUES REPORTED ARE MEAN ± STANDARD DEVIATION (NO. OBS.).

	Keahole 8 m		Hawaii OTEC[3]	Oahu OTEC[4]	GEOSECS 235[5]	HTS[6]	GOLLUM[7]
	1983-84[1]	1985[2]	9 m	9 m	3, 17 m ave.	surf.	0 — 100 m ave.
Temperature (°C)	25.97 ± 0.74 (98)	23.77 ± 0.17 (24)	25.60	25.86 ± 0.78 (36)	25.84	25.5 ± 1	—
Salinity (0/00)	34.89 ± 0.12 (103)	35.00 ± 0.01 (12)	34.97	34.84 ± 0.17 (36)	34.26	34.65 ± 0.2	—
Oxygen (µmol/l)	253 ± 30 (55)	212 ± 3 (14)	219	215 ± 1 (36)	211	215 ± 3	—
pH	8.23 ± 0.05 (97)	8.23 ± 0.01 (24)	8.31	8.31 ± 0.02 (36)	8.28	8.26	—
Alkalinity (µeq/l)	2322 ± 19 (99)	2367 ± 6 (12)	2306	2300 ± 19 (36)	2301	2340	—
Total CO_2 (µmol/l)	1995 ± 26 (97)	2052 ± 7 (12)	1933	1928 ± 20 (36)	1953	2000	—
P_{co_2} (µatm)	370 ± 57 (97)	372 ± 13 (12)	290	291 ± 21 (36)	320	344	—
Diss. Org. C (µmol/l)	63 ± 16 (100)	—	—	—	—	—	—
Part. Org. C (µmol/l)	2.8 ± 1.3 (9)	—	—	—	—	—	1.5 ± 0.4 (27)
Part. Inorg. C (µmol/l)	0.08 ± 0.07 (9)	—	—	—	—	—	0.1 ± 0.03 (27)
Nitrate + Nitrite (µmol/l)	0.17 ± 0.06 (103)	0.22 ± 0.05 (24)	0.09	0.14 ± 0.19 (36)	0.0	0.0 ± 0.3	—
Ammonium (µmol/l)	0.40 ± 0.14 (103)	0.13 ± 0.02 (24)	0.44	0.33 ± 0.20 (36)	—	—	—

[1] Approximately weekly sampling
[2] One or two hour sampling intervals, 9–10 April 1985
[3] Noda et al. (1981a); triplicate casts, 2 stations, 2 times
[4] Noda et al. (1981b); triplicate casts, 2 stations, 6 times over 1 year
[5] Broecker et al. (1982); single cast
[6] Wyrtki and Kilonski (1982); Hawaii-to-Tahiti Shuttle (19-20°N, 158°W); 1-year data summarized in sections; data picked from figures or calculated from those figures
[7] Gordon (1970); average of data collected between 0 and 100 m over 18 months

TABLE 1 — *Continued*

	Keahole 8 m		Hawaii OTEC[3]	Oahu OTEC[4]	GEOSECS 235[5]	HTS[6]	GOLLUM[7]
	1983-84[1]	1985[2]	9 m	9 m	3, 17 m ave.	surf.	0 — 100 m ave.
Diss. Org. N (μmol/l)	4.0 ± 1.4 (103)	4.8 ± 0.4 (24)	—	3.4 ± 0.9 (36)	—	—	—
Part. N (μmol/l)	0.33 ± 0.11 (9)	—	—	—	—	—	0.18 ± 0.04 (27)
Phosphate (μmol/l)	0.16 ± 0.03 (103)	0.15 ± 0.01 (24)	0.12	0.12 ± 0.05 (36)	0.19	0.2 ± 0.03	—
Diss. Org. P (μmol/l)	0.22 ± 0.05 (103)	0.19 ± 0.03 (24)	0.24	0.20 ± 0.07 (36)	—	—	—
Silicate (μmol/l)	3.0 ± 0.9 (102)	1.9 ± 0.4 (24)	2.2	1.9 ± 1.0 (36)	2.2	2 ± 0.3	—

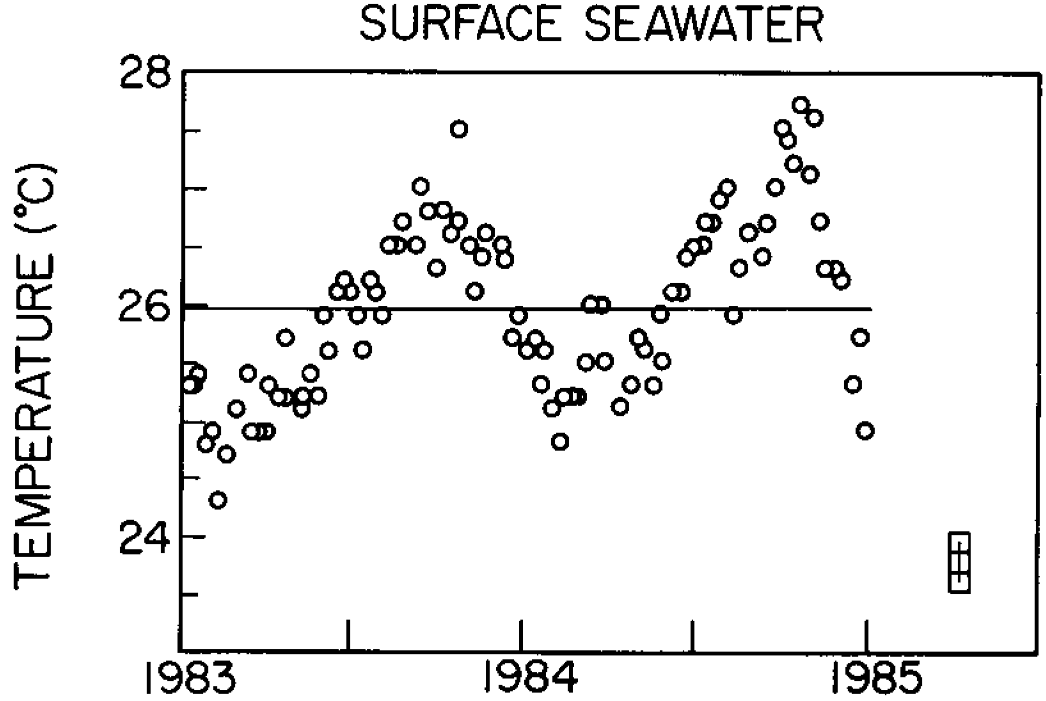
TABLE 2. COMPARISON OF KEAHOLE DEEP-WATER DATA WITH OTHER DATA SOURCES. VALUES REPORTED ARE MEAN ± STANDARD DEVIATION (NO. OBS.). THE BRACKETED VALUES UNDER THE OTEC SITES REPRESENT LINEAR INTERPOLATIONS TO 586 m.

	Keahole 586 m		Hawaii OTEC[3]			Oahu OTEC[4]			GEOSECS 235[5]	HTS[6]	GOLLUM[7]
	1983-84[1]	1985[2]	453 m	[586 m]	679 m	456 m	[586 m]	679 m	598 m	590 m	400–700 m ave.
Temperature (°C)	9.26 ± 0.67 (97)	7.54 ± 0.18 (24)	7.37	(6.14)	5.29	7.26	(5.96 ± 0.19)	5.03	6.32	6.0 ± 0.2	—
Salinity (0/00)	34.29 ± 0.03 (103)	34.31 ± 0.02 (24)	34.18	(34.30)	34.39	34.15	(34.28 ± 0.03)	34.38	34.46	34.30 ± 0.02	—
Oxygen (µmol/l)	56 ± 15 (21)	37 ± 3 (14)	79	(54)	36	98	(64 ± 1)	39	29	50 ± 5	—
pH (6°C)	7.70 ± 0.05 (97)	7.72 ± 0.02 (24)	7.83	(7.78)	7.74	7.87	(7.80 ± 0.03)	7.75	7.75	7.77	—
Alkalinity (µeq/l)	2356 ± 16 (94)	2412 ± 5 (12)	2295	(2324)	2345	2288	(2324 ± 15)	2349	2395	2380	—
Total CO_2 (µmol/l)	2350 ± 20 (97)	2397 ± 9 (12)	2243	(2292)	2327	2225	(2287 ± 19)	2330	2370	2350	—
P_{CO_2} (µatm)	1227 ± 113 (97)	1254 ± 62 (12)	877	(1002)	1089	795	(955 ± 77)	1070	1098	1032	—
Diss. Org. C (µmol/l)	30 ± 13 (97)	—	—		—	—		—	—	—	—
Part. Org. C (µmol/l)	0.6 ± 0.3 (9)	—	—		—	—		—	—	—	0.3 ± 0.2 (32)
Part. Inorg. C (µmol/l)	0.01 ± 0.02 (9)	—	—		—	—		—	—	—	0.02 ± 0.01 (32)
Nitrate + Nitrite (µmol/l)	38.9 ± 1.1 (102)	38.7 ± 0.5 (24)	33.5	(38.4)	41.9	30.9	(35.7 ± 4.8)	39.1	41.3	37 ± 0.7	—

[1] Approximately weekly sampling
[2] One or two hour sampling intervals, 9-10 April 1985
[3] Noda et al. (1981a); triplicate casts, 2 stations, 2 times. Linear interpolation to 586 m reported in brackets.
[4] Noda et al. (1981b); triplicate casts, 2 stations, 6 times over 1 year. Linear interpolation to 586 m and average standard deviation at 456 and 679 m reported in brackets (36 samples at each depth).
[5] Broecker et al. (1982); single station. Depth reported is close to Keahole deep station.
[6] Wyrtki and Kilonski (1982); Hawaii-to-Tahiti Shuttle (19-20°N, 158°W); 1-year data summarized in sections; data picked from figures or calculated from these figures.
[7] Gordon (1970); average of data collected between 400 and 700 m over 18 months

TABLE 2 — *Continued*

	Keahole 586 m		Hawaii OTEC[3]			Oahu OTEC[4]			GEOSECS 235[5]	HTS[6]	GOLLUM[7]
	1983-84[1]	1985[2]	453 m	[586 m]	679 m	456 m	[586 m]	679 m	598 m	590 m	400–700 m ave.
Ammonium (μmol/l)	0.23 ± 0.13 (102)	0.06 ± 0.02 (24)	0.47	(0.47)	0.47	0.32	(0.33 ± 0.19)	0.33	—	—	—
Diss. Org. N (μmol/l)	1.5 ± 1.0 (102)	2.5 ± 0.4 (24)	—		—	1.5	(1.4 ± 2.9)	1.3	—	—	—
Part. N (μmol/l)	0.05 ± 0.01 (9)	—	—		—	—		—	—	—	0.03 ± 0.01 (32)
Phosphate (μmol/l)	2.96 ± 0.08 (102)	2.92 ± 0.03 (24)	2.52	(2.88)	3.13	2.28	(2.66 ± 0.28)	2.94	2.86	2.9 ± 0.7	—
Diss. Org. P (μmol/l)	0.05 ± 0.04 (102)	0.06 ± 0.02 (24)	0.08	(0.04)	0.02	0.03	(0.01 ± 0.18)	0.00	—	—	—
Silicate (μmol/l)	74.2 ± 3.4 (102)	76.8 ± 2.6 (24)	57.2	(78.3)	93.0	53.0	(74.5 ± 9.8)	89.9	73.1	75 ± 4	—



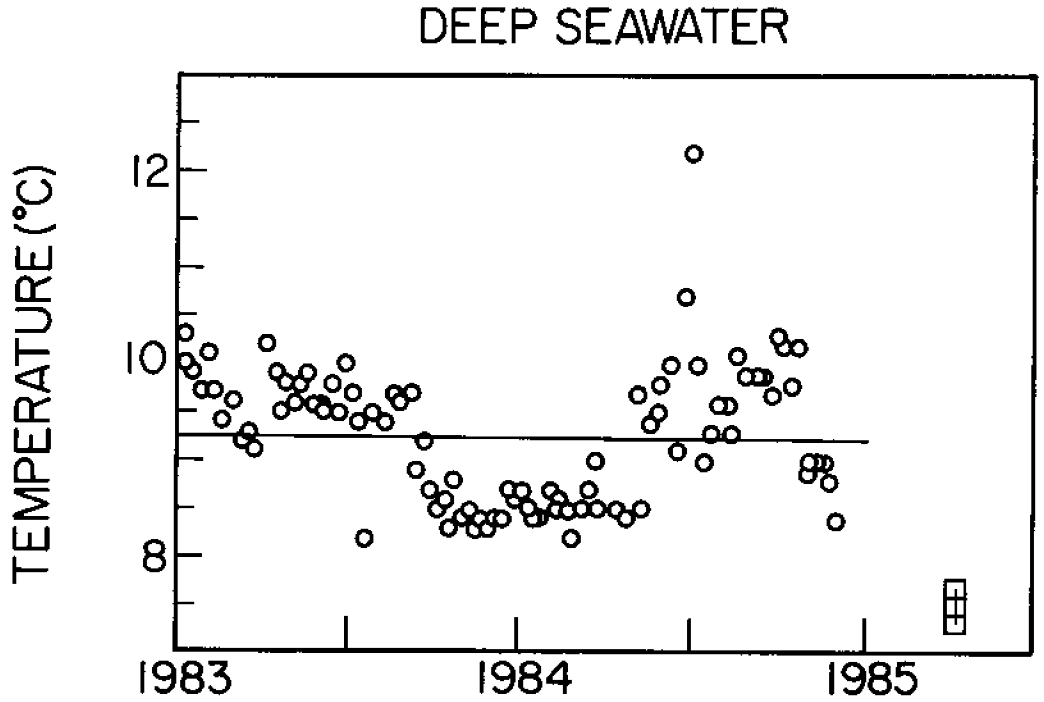


Figure 2. 1983-84 distribution of surface and deepwater temperature at Keahole Point. The 2-year means of surface and deep properties are shown as a horizontal line. Also shown (with three boxes connected with a vertical line) are the mean and standard deviations of analyses conducted over a 24-hour period in April 1985.

1979). It appears that Keahole surface water is marginally warmer than more offshore water, presumably due to nearshore net heating.

Deep water at the Keahole discharge is warmer than more oceanic water (9.3 vs 6.0°C). This difference is an artifact related to pumping rate and to the temperature of the overlying water through which the deep water pipe extends; the pipe acts as a heat exchanger. The best estimate of deep water *in situ* temperature at Keahole is 6 ± 0.8°C (Daniel, this volume).

Both the mean and standard deviation of surface-water salinity at Keahole are comparable to offshore surface salinity (34.9 ± 0.1%.) (see also Seckel and Yong, 1977). There is an annual oscillation in surface salinity, and there was a general surface salinity increase from early 1983 through the end of 1984 (Figure 3). Such interannual variations largely reflect the characteristics of regional surface circulation. Deep-water data, both at Keahole and offshore, average about 34.3 ± 0.03%, with no long-term trend (Figure 3).

The mean oxygen concentration in both surface and deep water at Keahole is similar to offshore water; we attribute the much higher standard deviation of the Keahole data to analytical problems with the on-site analyses.

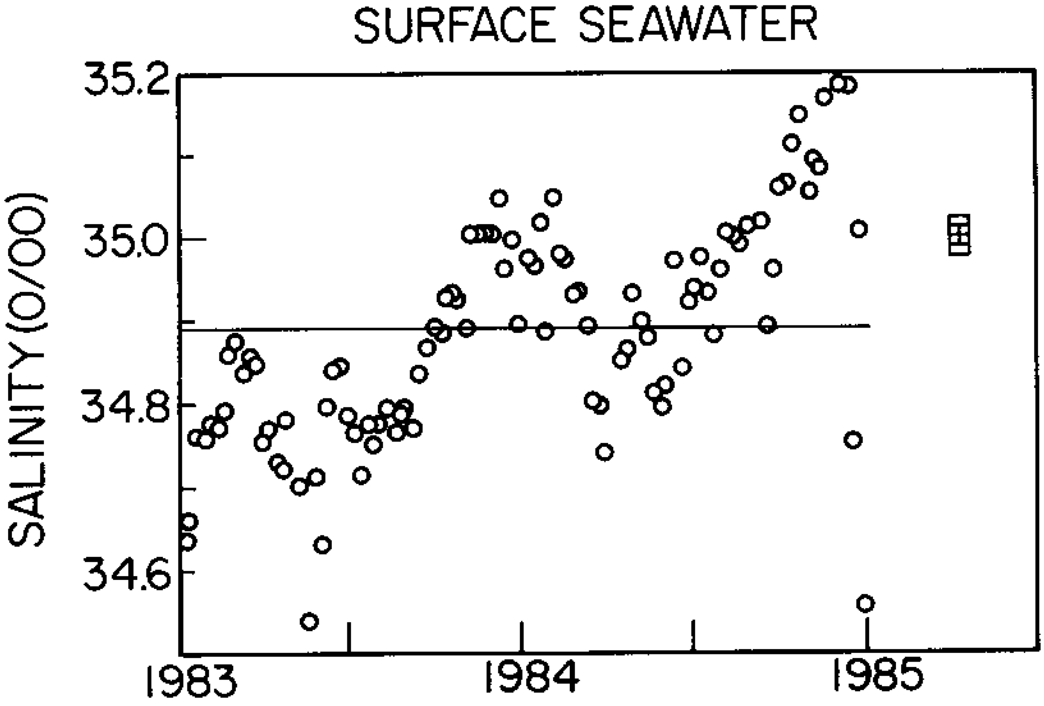
pH at Keahole has been corrected from measurement temperature (~20°C to in situ temperature, and the pH and alkalinity data have been used with the alkalinity data to calculate both total CO_2 and CO_2 partial pressure. Keahole deep water has slightly lower pH and higher P_{CO2} than more offshore water.

There are few data available for oceanic dissolved organic carbon. Williams et al. (1980) report surface values of about 60 μmol/l, and deep water values between 500 and 5000 m ranging between 30 and 48 μmol/l. The surface value they report agrees almost exactly with the Keahole mean (63 μmol/l), while the Keahole deep-water mean (30 μmol/l) coincides with the lower limit of their deep-water range.

Particulate organic carbon in the Keahole water averages about 3 μmol/l in surface water and 0.6 μmol/l in deep water. These values are higher than reported offshore data (Gordon, 1970; Williams et al., 1980) although both the Keahole and offshore data bases for particulate material are modest.

The surface dissolved nutrient data are very similar between Keahole (Figures 4, 5, and 6) and the more offshore sites. Concentrations are low and the only nutrient that differs significantly in concentration between Keahole and offshore water is silicate. The 2-year average surface silicate concentration at Keahole Point is elevated about 1 μmol/l above the offshore silicate concentration of 2 μmol/l (Table 1). We interpret the silicate elevation to represent the effect of groundwater input during periods of high rainfall. Local groundwater averages about 500 μmol/l silicate, so an average of 0.2% groundwater input would be sufficient to raise silicate concentrations by 1 μmol/l while lowering salinity by only 0.07%, or about half the observed standard deviation of surface salinity.

Deep-water nutrient concentrations are also very similar between Keahole and offshore water (Table 2). The plotted deep-water inorganic nutrient concentrations (Figures 4, 5, and 6), especially silicate, show a two-year trend which is not obvious in comparing the tabulated summary statistics



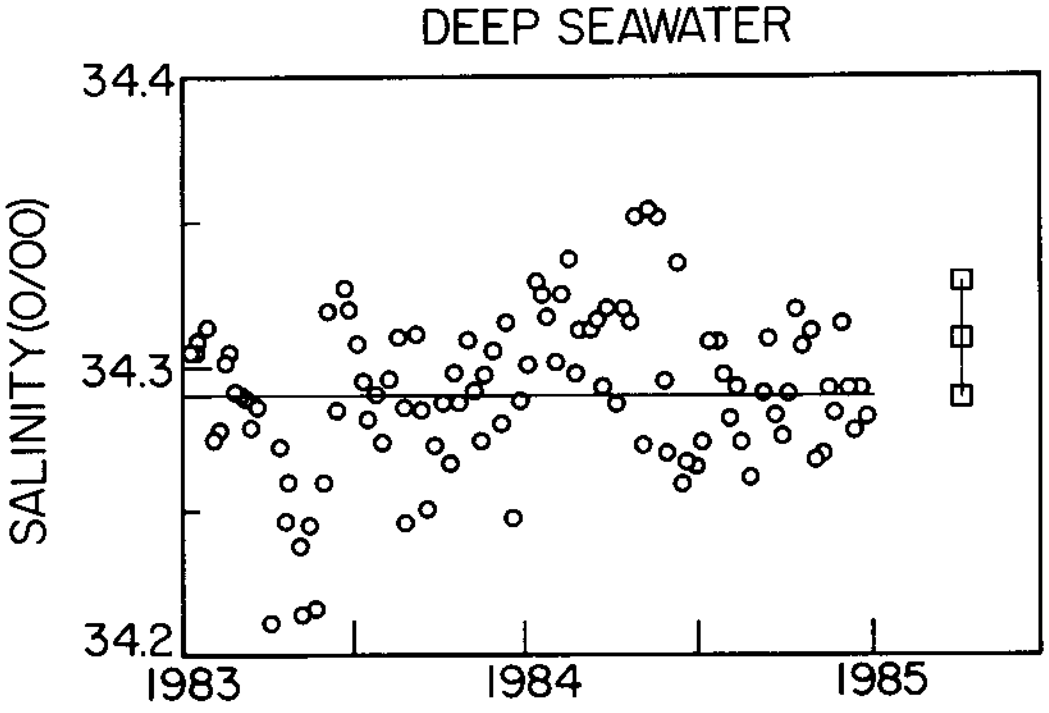


Figure 3. 1983-84 distribution of surface and deep water salinity at Keahole Point. The 2-year means of surface and deep properties are shown as a horizontal line. Also shown (with three boxes connected with a vertical line) are the mean and standard deviations of analyses conducted over a 24-hour period in April 1985.

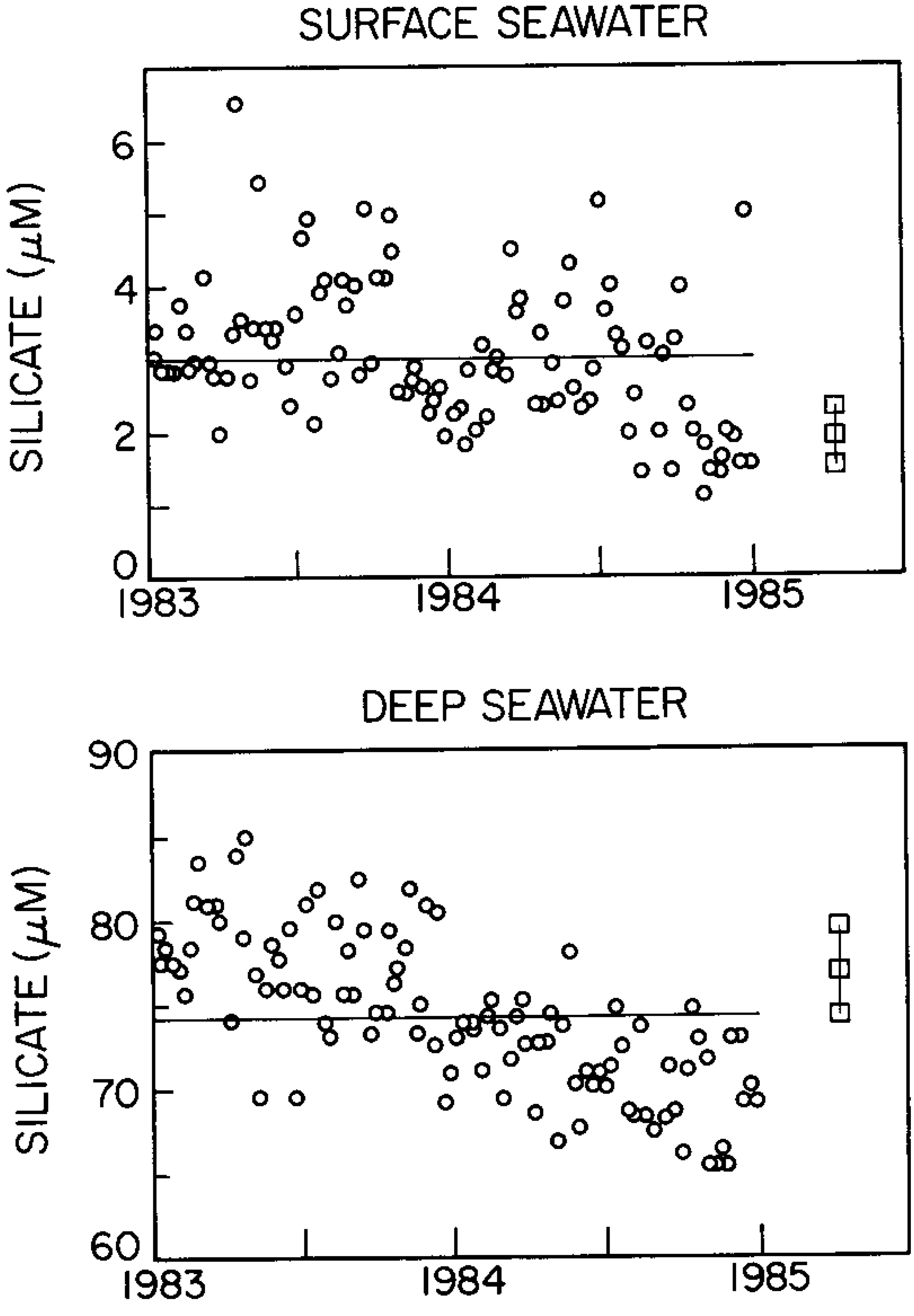


Figure 4. 1983-84 distribution of surface and deep water silicate at Keahole Point. The 2-year means of surface and deep properties are shown as a horizontal line. Also shown (with three boxes connected with a vertical line) are the mean and standard deviations of analyses conducted over a 24-hour period in April 1985.

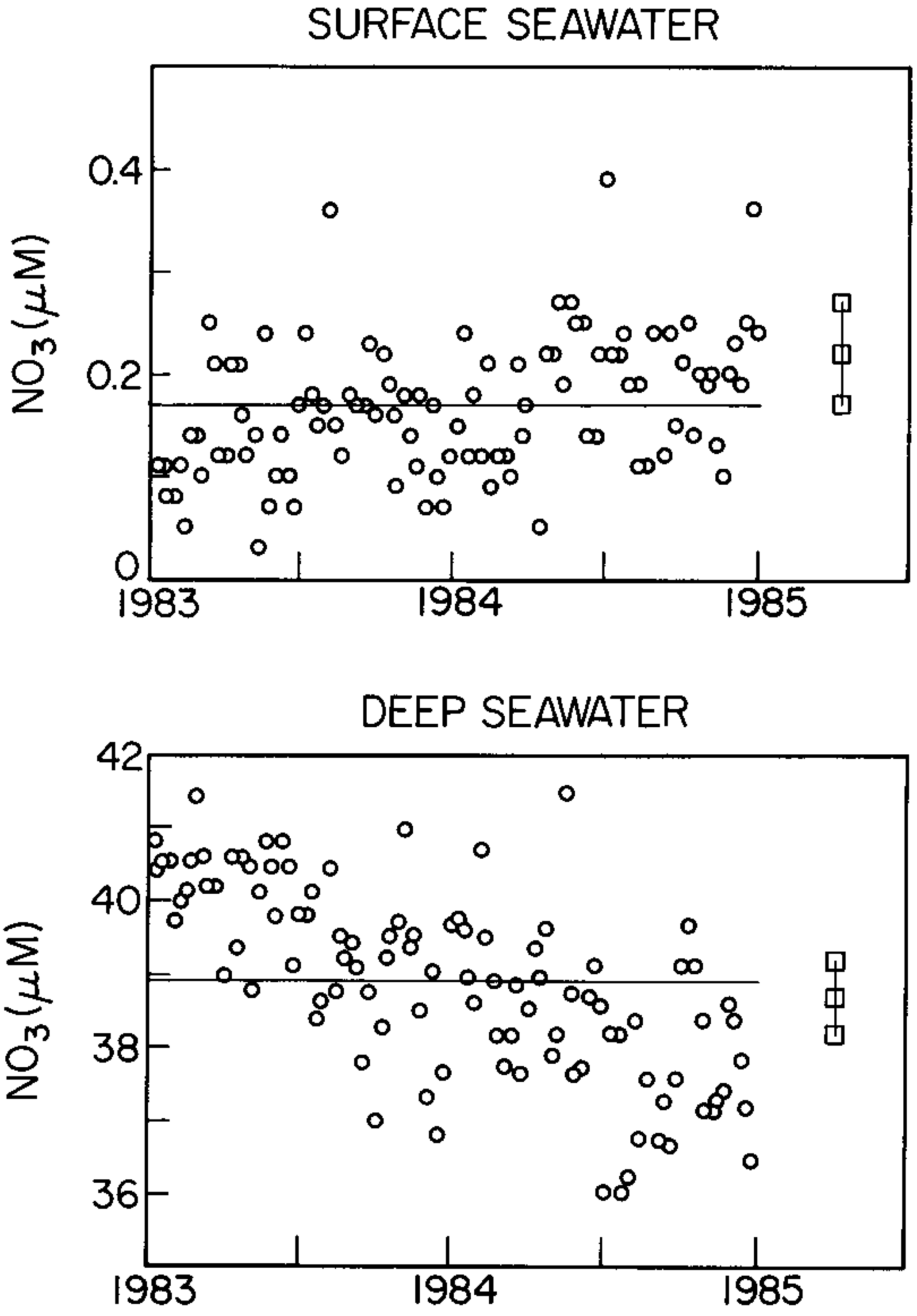
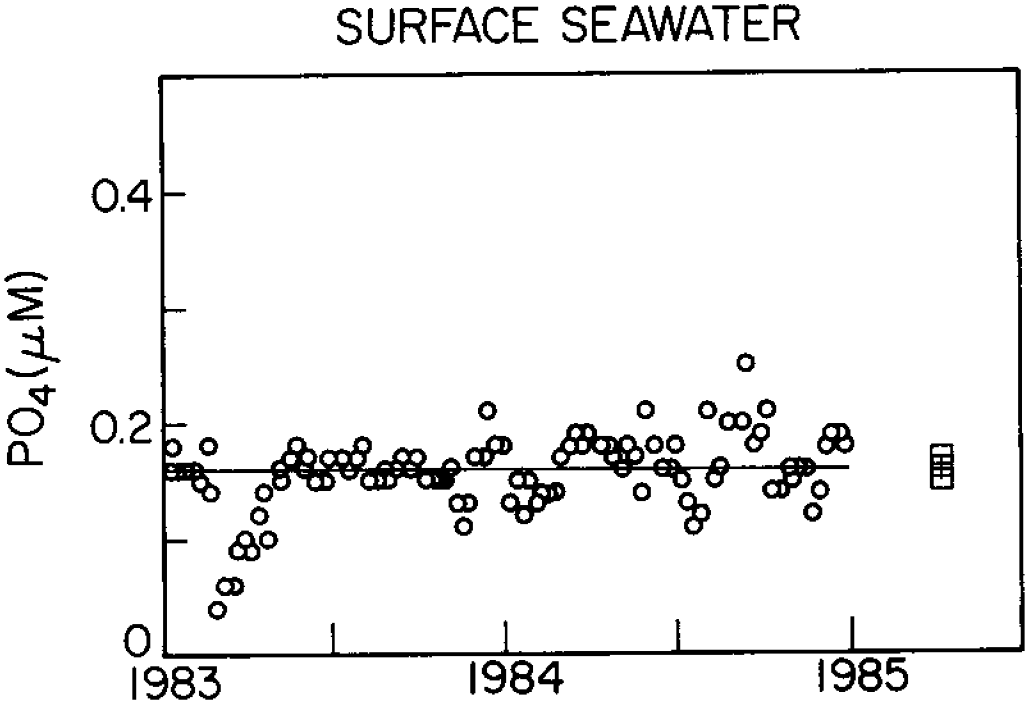


Figure 5. 1983-84 distribution of surface and deep water nitrate at Keahole Point. The 2-year means of surface and deep properties are shown as a horizontal line. Also shown (with three boxes connected with a vertical line) are the mean and standard deviations of analyses conducted over a 24-hour period in April 1985.



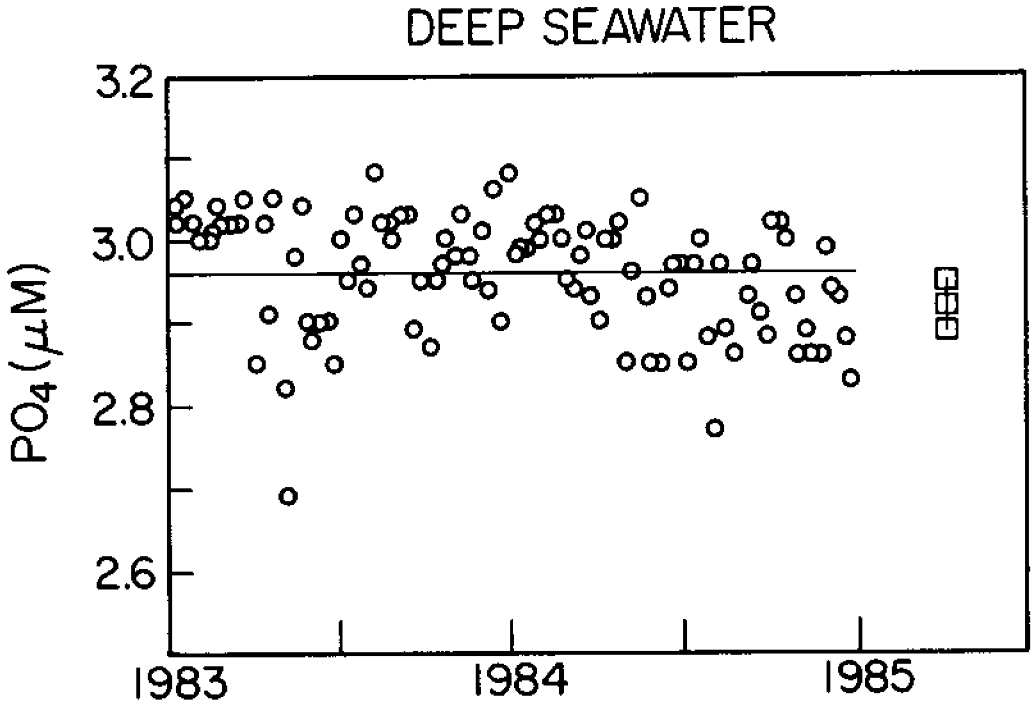


Figure 6. 1983-84 distribution of surface and deep water phosphate at Keahole Point. The 2-year means of surface and deep properties are shown as a horizontal line. Also shown (with three boxes connected with a vertical line) are the mean and standard deviations of analyses conducted over a 24-hour period in April 1985.

for Keahole with those for offshore water. There is a clear decrease of inorganic nutrient concentration with time. No such trend can be detected in the surface concentrations. Table 3 summarizes the regression equations describing the apparent temporal decrease of silicate, nitrate, and phosphate. Silicate concentration decreased by 20% between early 1983 and the end of 1984; nitrate decreased by 11%; and phosphate decreased by 8%. Coefficients of determination (r^2) on these regression equations are relatively low (Table 3). As discussed below, high-frequency oscillations in nutrient concentration account for much of the observed variation in nutrient concentration, hence the low coefficients of determination for the regression equations.

One possible explanation for these long-term decreases might be that biotic activity (perhaps fouling in the seawater pipes) is removing these nutrients. The slightly elevated particulate organic carbon concentrations and P_{CO_2}, relative to deep ocean water, are consistent with fouling and sloughing in the pipe. However, for the nutrient concentration to continue decreasing with time, there would also be a biomass buildup somewhere in the pipes. The required biomass production to achieve the observed nutrient decrease is very large, so we consider an alternative, purely physical explanation: An oscillation in deep water composition associated with waves having periods longer than 2 years could explain the variation. Investigation into the cause of this variation continues and is tending to favor this physical oscillation model (Sansone et al., 1988).

TABLE 3. REGRESSIONS OF DEEP-WATER INORGANIC NUTRIENT CHANGES AS FUNCTIONS OF TIME(IN DAYS) FROM 1 JANUARY 1983 TO 31 DECEMBER 1984

Geometric Mean Regression (μM)			r^2	2-Year Decrease (μM)	% Decrease
Silicate	=	82 - 0.022 x time	0.54	16	20
Nitrate	=	41 - 0.0061 x time	0.48	4.5	11
Phosphate	=	3.1 - 0.0034 x time	0.10	0.25	8

We noted a relatively large unexplained variability in Keahole water composition, possibly related to phenomena acting on a time scale short in comparison to the weekly sampling interval. In order to investigate aspects of this short-term variation, we conducted a 24-hour sampling experiment in April 1985. We hypothesized that the surface water might show diel variation associated with biological activity, and that the deep water composition might vary through vertical water movement in response to internal waves.

Tables 1 and 2 (1985 data) and Figures 7 and 8 summarize results of the 24-hour experiment. During and immediately preceding this experiment, there was no significant local rainfall; therefore pulsed inputs of materials from the island mass (i.e., short-term groundwater flow associated with rainfall) can be dismissed. Three important results emerge from this analysis. First, there is no significant diel signal evidenced in the surface-water composition (Figure 7). Local benthic or

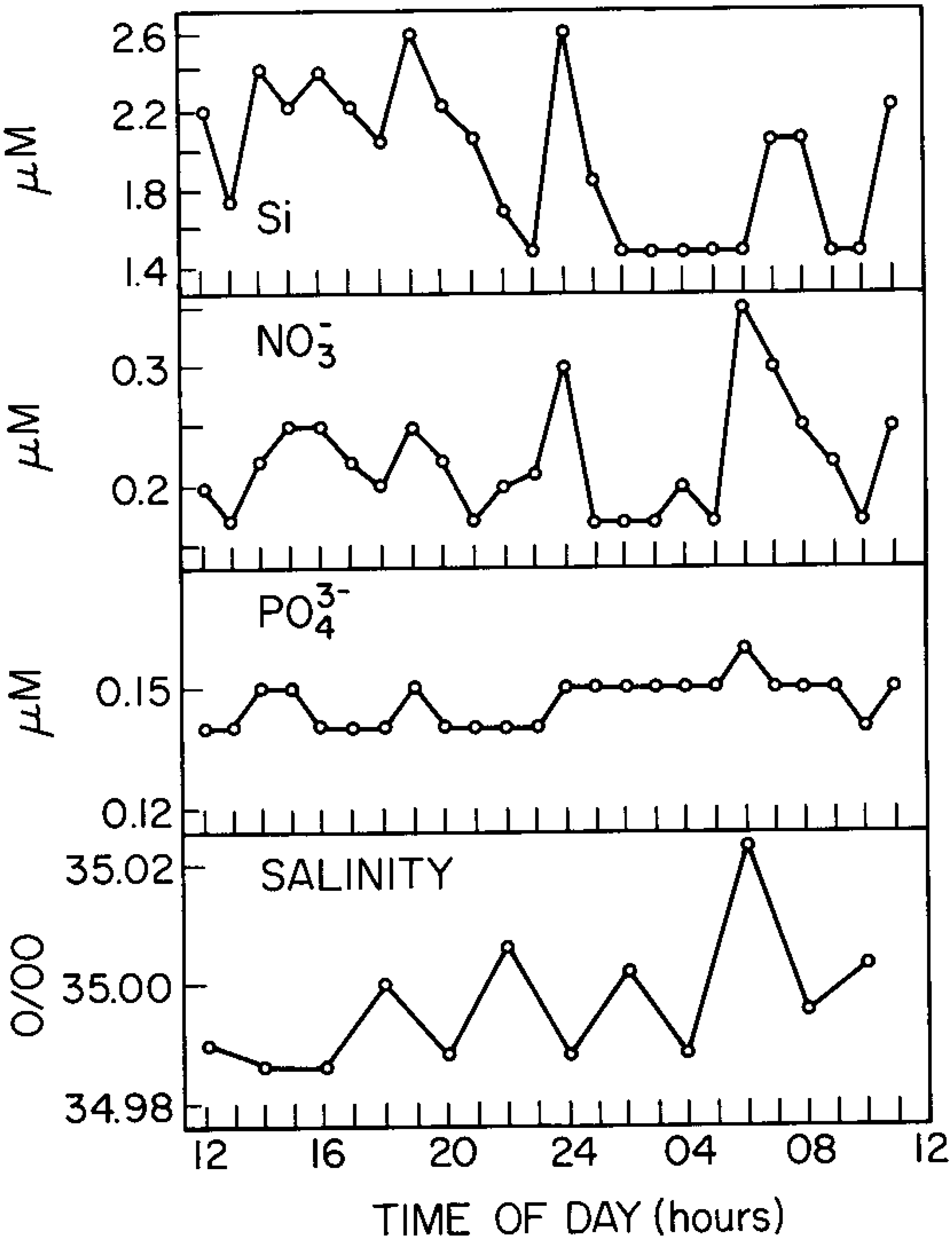


Figure 7. 24-hour distribution of key surface water properties at Keahole Point, 9–10 April 1985

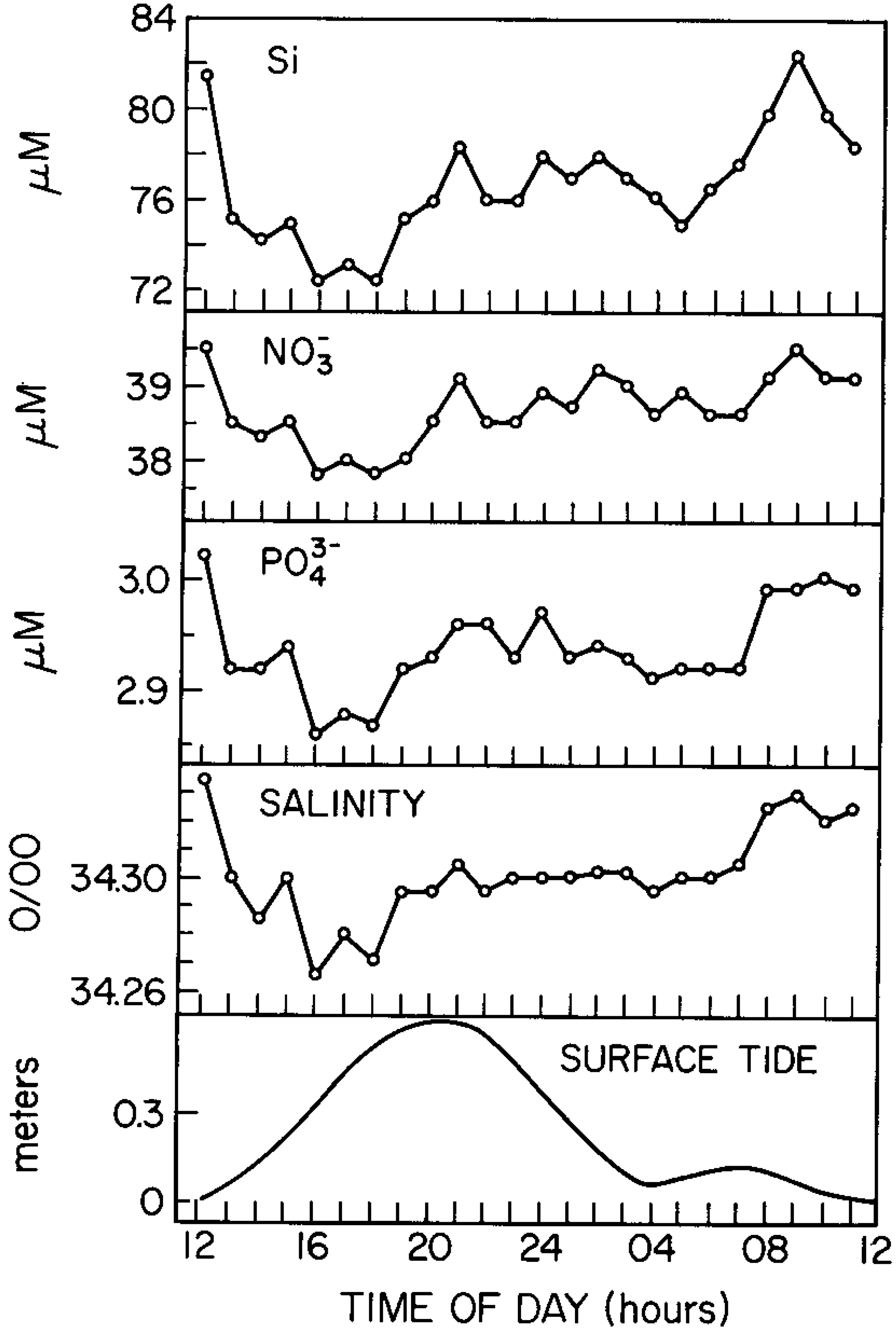


Figure 8. 24-hour distribution of key deep water properties and tabulated tide height at Keahole Point, 9–10 April 1985

nearshore planktonic biological activity is insufficient to alter water composition in any coherent fashion.

Second, the 24-hour standard deviations of most surface-water properties are small compared to the two-year variation (Table 1). The phenomena causing variation in the surface water composition apparently act on a time scale longer than 24 hours.

The third result is a coherent pattern of variation in the deep-water composition (Figure 8). This is in striking contract to the low 24-hour variation of surface-water properties. Although this deep-water variation is not in phase with the shallow-water tidal data, it appears to have a roughly tidal frequency. A longer time series is needed to quantify this conclusion, but the qualitative result appears obvious.

We estimated the trough-to-crest wave height of the apparently tidal-period internal waves at 586 m off West Hawaii by using the variation in nutrient and salinity composition and the linear interpolation of composition gradients at the Hawaii OTEC station (from Table 2). We chose ± 2 standard deviation units (i.e., about 95% of the range of the data) of several compositional properties, divided by the linear estimate of the vertical gradient, as a "wave-height index."

The results are summarized in Table 4. There is a substantial range in the estimated trough-to-crest wave height, presumably associated with analytical, as well as environmental, variation in the observed composition. A second obvious source of uncertainty in such an estimate is the non-linearity of the vertical composition gradients. Nevertheless, the estimated mean wave height, 63 m, appears reasonable.

TABLE 4. CALCULATED 586-m INTERNAL WAVE HEIGHT AT KEAHOLE POINT. CALCULATIONS DESCRIBED IN TEXT.

Variable	± 2 Std. Dev.[1] Over 24 Hours	Vertical Gradient at Hawaii OTEC	Wave Height (m)
Salinity (0/00)	0.08	0.00093	86
Nitrate + Nitrite (μM)	2.0	0.037	54
Phosphate (μM)	0.12	0.0027	44
Silicate (μM)	10.4	0.158	66
Mean ± Std. Dev.			63 ± 18 m

[1] Data from Table 2.

CONCLUSIONS

Water composition sampled by the NELH surface and deep-water intake lines at Keahole Point, Hawaii, approximates offshore ocean surface and intermediate water composition. One major exception to this conclusion is surface-water silicate; on the average, about one third of the surface-water silicate appears to be derived from the adjacent island mass. This input appears to be related to rainfall and local groundwater discharge.

A second surface-water feature which apparently reflects proximity of the Keahole site to the island mass is the slightly elevated temperature. Perhaps some combination of elevated temperature and elevated silicate at least partially account for island-mass effects of elevated nearshore phytoplankton growth.

The deep-water inorganic nutrients show evidence of changing concentration with time. The net changes between the beginning of 1983 and the end of 1984 are relatively small, and are a relatively small part of the total variation observed in the data; nevertheless, the long-term time trends are unmistakable. Either biotic nutrient uptake in the deep-water pipe or long-term oscillations in the water mass from which the water is drawn are the likely explanations for this decrease. We are tending to favor the latter explanation.

Finally, the deep-water composition shows a coherent temporal variation which is apparently related to internal waves. At least over the one 24-hour period which we have examined, the frequency of variability appears to be tidal. We encourage further study of this phenomenon as a simple measure of deep-water tidal oscillation.

The 2 years of data that we have examined and the 24-hour experiment that we have conducted at the NELH facility at Keahole Point provide valuable insight into the composition of water in the North Pacific gyre, and into the composition of water available for various activities undertaken at NELH. More observational and experimental data are needed to verify the conclusions we have derived.

ACKNOWLEDGMENTS

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GROWTH OF NORI (*Porphyra tenera*) IN AN EXPERIMENTAL OCEAN THERMAL ENERGY CONVERSION SYSTEM AT THE NATURAL ENERGY LABORATORY OF HAWAII

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Steven A. Katase

INTRODUCTION

Porphyra species, known as nori in Japan, are among the world's most valuable seaweeds in terms of both total annual crop value and price per unit weight (Kramer, Chin, and Mayo, Inc., 1982; Tseng, 1982). Most nori is sold as dried, paper-like sheets for use in many Japanese dishes; the U.S. market for nori sheets is worth several million dollars and growing (Kramer, Chin, and Mayo, Inc., 1982). *P. tenera*, the traditionally used species (Ueda, 1973), is generally the highest-quality species for sheet production (Noda and Iwata, 1978). *P. tenera* has been cultured by the Japanese for years, and its biology is well known (e.g., Ueda, 1973; Kurogi et al., 1971; Kurogi, 1961). Because of the large market for *P. tenera* and because of its high price, it was chosen as a species for culture in simulated ocean thermal energy conversion (OTEC) effluent water.

The opportunity for OTEC-related nori culture trials first arose in 1979 when the deployment of OTEC-1, a federally sponsored research vessel, was planned off the island of Hawaii. Efforts to secure research space on board OTEC-1 failed. Subsequently, a proposal was submitted to conduct experiments on board the Mini-OTEC barge, another floating platform, during its expected second deployment off Keahole Point. The proposal was accepted by the University of Hawaii Sea Grant College Program and co-funded by the Hawaii Department of Planning and Economic Development. When the redeployment of Mini-OTEC was canceled, a deep-water pipe was installed at the Natural Energy Laboratory of Hawaii (NELH) site at Keahole Point. The nori culture facilities were constructed at this site in early 1982 and experiments ran from mid-1982 until February 1983.

Warm surface seawater and cold deep seawater, similar to those available from the effluents of an OTEC facility, offers the following attractive advantages for nori culture:

1. Low pumping costs for very large volumes of water through shared use between the OTEC and aquaculture facilities.
2. Water temperature range from approximately 8°C to 25°C permits the aquaculture system to achieve optimal temperatures year-round. The optimal water temperature for *P. tenera* is

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about 15°C (Iwasaki, 1961); this temperature could not be achieved economically in an aquaculture system in Hawaii without the use of the cold deep seawater.

3. Higher nutrient concentrations in the deep water (44.0 µg-at/l N and 3.2 µg-at/l P off Hawaii) compared with levels in surface water (0.6 µg-at/lN, 0.2 µg-at/l P).
4. Near-absence of disease-producing, epiphytic, or other contaminating organisms in the deep water.

The potential benefits of using deep seawater for aquaculture were recognized by Othmer and Roels (1973). Subsequently, experiments showed that upwelled water, when mixed with surface water, improved algal growth (Roels et al., 1978; North, 1977).

The experiments performed at NELH were designed primarily to establish the technical feasibility of nori production in simulated OTEC effluents. Therefore, the main questions asked were, "Can *P. tenera* be grown intensively using mixed deep and surface waters in Hawaii?" and "How fast does *P. tenera* grow under these conditions?" Production rate alone, however, is not sufficient to determine the success of a nori culture facility. Quality is a critical determinant of nori price. Nori quality is judged by many factors, including flavor, color, luster, aroma, texture, and degree of contamination. About 100 different degrees of quality are recognized by Japanese nori graders (Woessner, 1983).

MATERIALS AND METHODS

Nori was cultured at NELH using an air-lift suspension method similar to that described in Ryther et al. (1979). The outdoor macroalgae culture facility at NELH consisted of 10 rectangular tanks (3 m long x 1 m wide x 1 m deep), each divided into 3 1-m^3 compartments. Air bubbling from a perforated pipe on the bottom of each tank kept the algae in continuous suspension and circulation. This technique promotes rapid growth of several seaweeds at high culture densities (Ryther et al., 1979; Neish and Knutson, 1979; Bidwell et al., 1985) and uses available sunlight efficiently.

Most experimental systems of this type have been used to culture seaweeds such as *Gracilaria* and *Chondrus* which can, in theory, grow in a vegetative phase essentially indefinitely. *Porphyra*, in contrast, ages noticeably after several weeks, making it a less desirable commercial product. However, raised in batch culture, a 4 to 5-week culture period appears to permit growth to harvestable size without visible quality deterioration.

The leafy thallus phase of the *P. tenera* life cycle is a winter (short-day) phase in Japan (Figure 1). Environmental conditions were therefore altered to foster *P. tenera* growth in Hawaii. Opaque tank covers allowed photoperiod control. In most cases, an 8-hour photoperiod recommended by Iwasaki, (1961) was maintained. The mixture of deep seawater and surface seawater entering each compartment was controlled individually, varying temperature and nutrient conditions simultaneously.

Nori stock material — obtained from Japan as partly dehydrated, frozen fronds on nets — was maintained at -20°C. Nori frozen in this manner remains viable for months and, in Japan, is used to restock culture beds in case of loss (Kurakake, 1969). The nets had been seeded with *P. tenera*, but

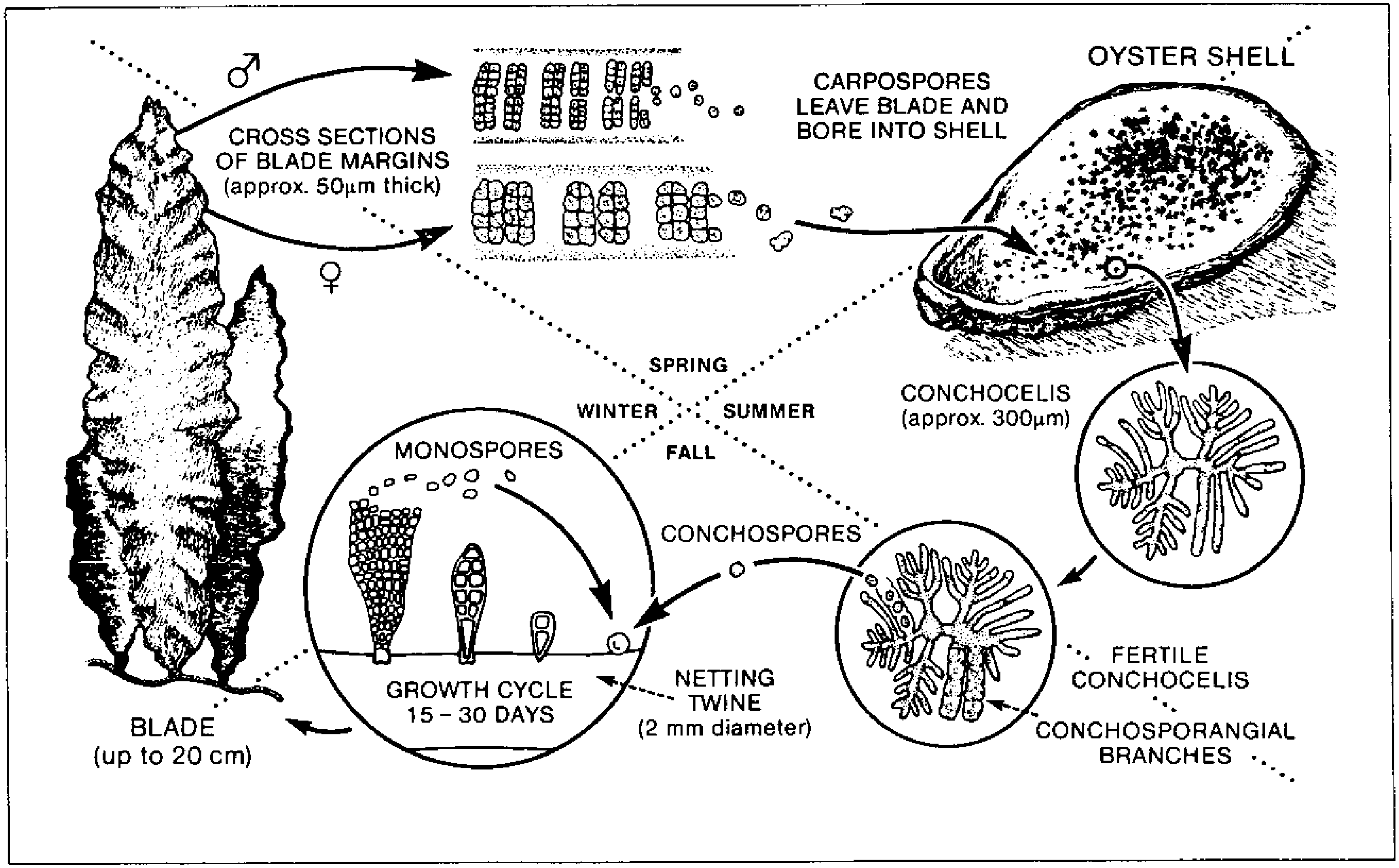

Figure 1. Life history stages of Porphyra *spp. The plant form alternates between the microscopic conchocelis stage which bores into bivalves shells and the thallus stage. (From* Final Programmatic Environmental Impace Statement: Nori Farming and Processing in Washington State. *Reprinted by permission of the author, T. F. Mumford).*

small numbers of thalli of other *Porphyra* species may have been present (O. Imada, Kyowa Hakko Kogyo Co., Tokyo, Japan, 1980: personal communication).

At the beginning of an experiment, a portion of a net was cut into short strands. The strands, with their attached fronds (initially less than 3 cm long) were placed in a tank compartment and "tumble-cultured" at 15°C for approximately 3 days. This procedure allowed the juvenile fronds to rehydrate, begin growth, and become large enough to be retained by the drain screens in the compartments. The nori fronds were then stripped from the net strands, centrifuged briefly to remove excess water, and weighed. For later growth measurements, the nori was collected by draining the contents of each compartment into a mesh bag at the drain outlet. The nori samples were centrifuged to remove excess water and weighed. Small (1 – 4 g wet wt) subsamples were taken from each sample for dry weight determinations and, when desired, for composition analysis before the nori was returned to the tanks.

Incident light was monitored continuously using a Licor quantum sensor and integrator. Influent and effluent pH were measured at noon with a Corning pH meter. Other parameters — including influent and effluent nutrient concentrations, CHN composition of the dried nori samples, and, in one case, metal content of the nori — were measured to the degree that funding allowed. Nutrient and CHN analyses were done by staff of the Hawaii Institute of Marine Biology analytical services facility.

To evaluate the quality of nori produced in the NELH culture system, it was necessary to send samples to Japan for processing. Neither nori processing equipment nor experts in processing techniques and nori grading were available in Hawaii. In February 1983, nori cultured at NELH was taken to Japan by Dr. James Woessner of the Hawaii experimental team. Most of the material was shipped frozen, except for one batch which was fresh-chilled. In Japan, the nori was processed into sheets and then the quality of the product was evaluated by expert graders from Yamamoto Nori and Ohmori Suisan. Both companies specialize in high-quality nori products.

RESULTS AND CONCLUSIONS

Growth trials conducted during the summer of 1982 demonstrated that *P. tenera* can be grown successfully using simulated OTEC effluents in Hawaii. Nori fronds reached harvestable size (30 to 40 cm in length for large individual plants) from the initial size of 3 cm or less in 3 to 5 weeks. These experiments were conducted using low initial culture densities of 10 to 100 g wet wt/m^2. Maximum production was achieved at densities greater than 2 kg wet wt/m^2. Production rates as high as 40 to 60 g dry wt/m^2/day were measured at densities of 2 to 3 kg wet wt/m^2; these yields equal or exceed those attained by other rapidly growing seaweeds in tumble culture (e.g., Ryther et al., 1979). Dry weight production increased rapidly for about the first 3 weeks, after which time it leveled off and then decreased due to shading and perhaps nutrient limitation (Figure 2). Although production per unit area decreased after some period, total biomass continued to increase after more than 40 days (Figure 3).

A later experiment, conducted during September and October 1982, gave a maximum *P. tenera* production rate of 28 g dry wt/m^2/day. During this experiment, nutrient uptake by the nori cultures and nitrogen content of the nori tissue were monitored closely. The cultures showed a strong diel

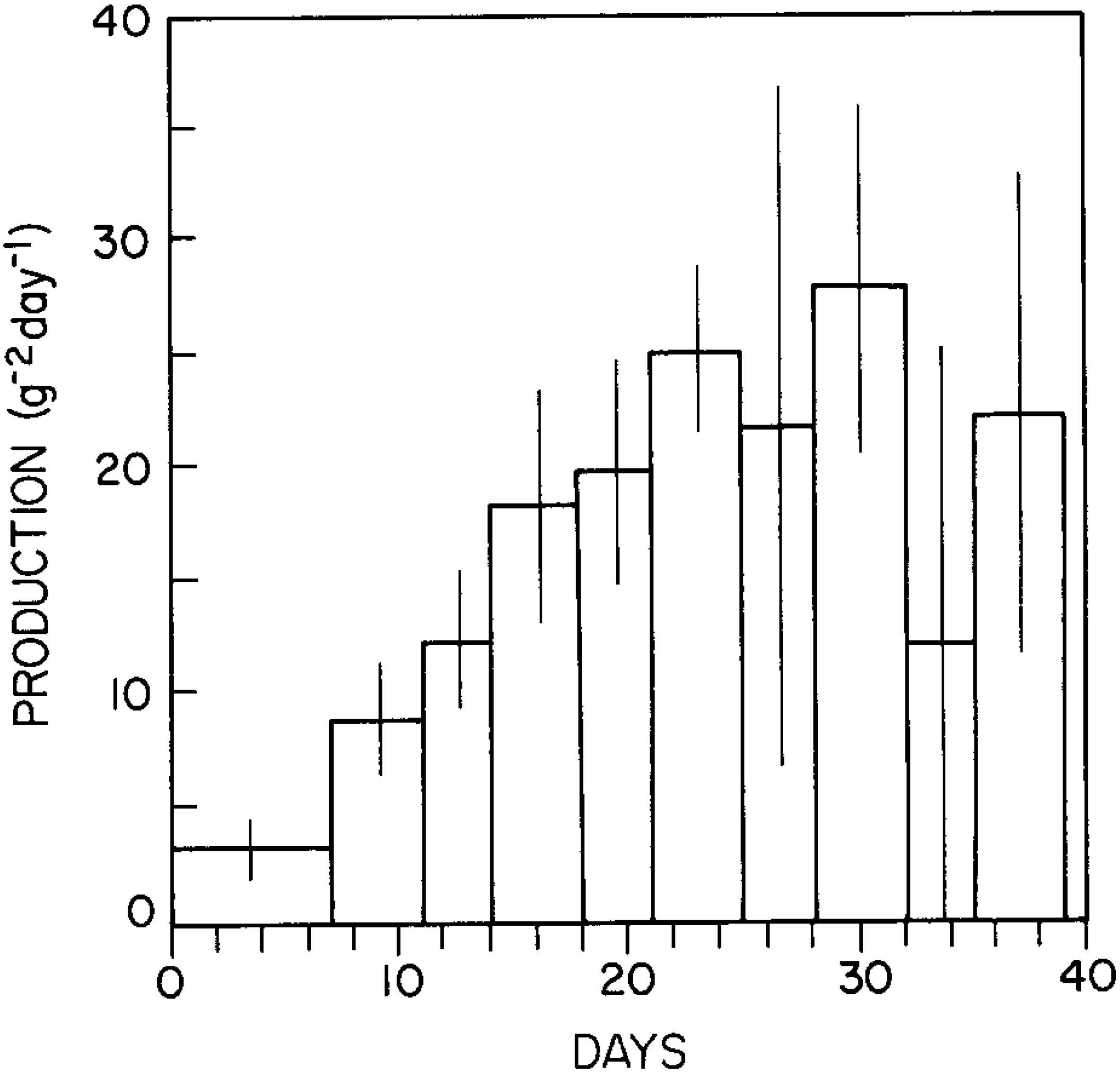

Figure 2. Mean dry weight production between sample periods of Porphyra tenera *cultured at NELH in a mixture of deep and surface waters (mean ± S.D.; n=7). (From Mencher et al., 1983)*

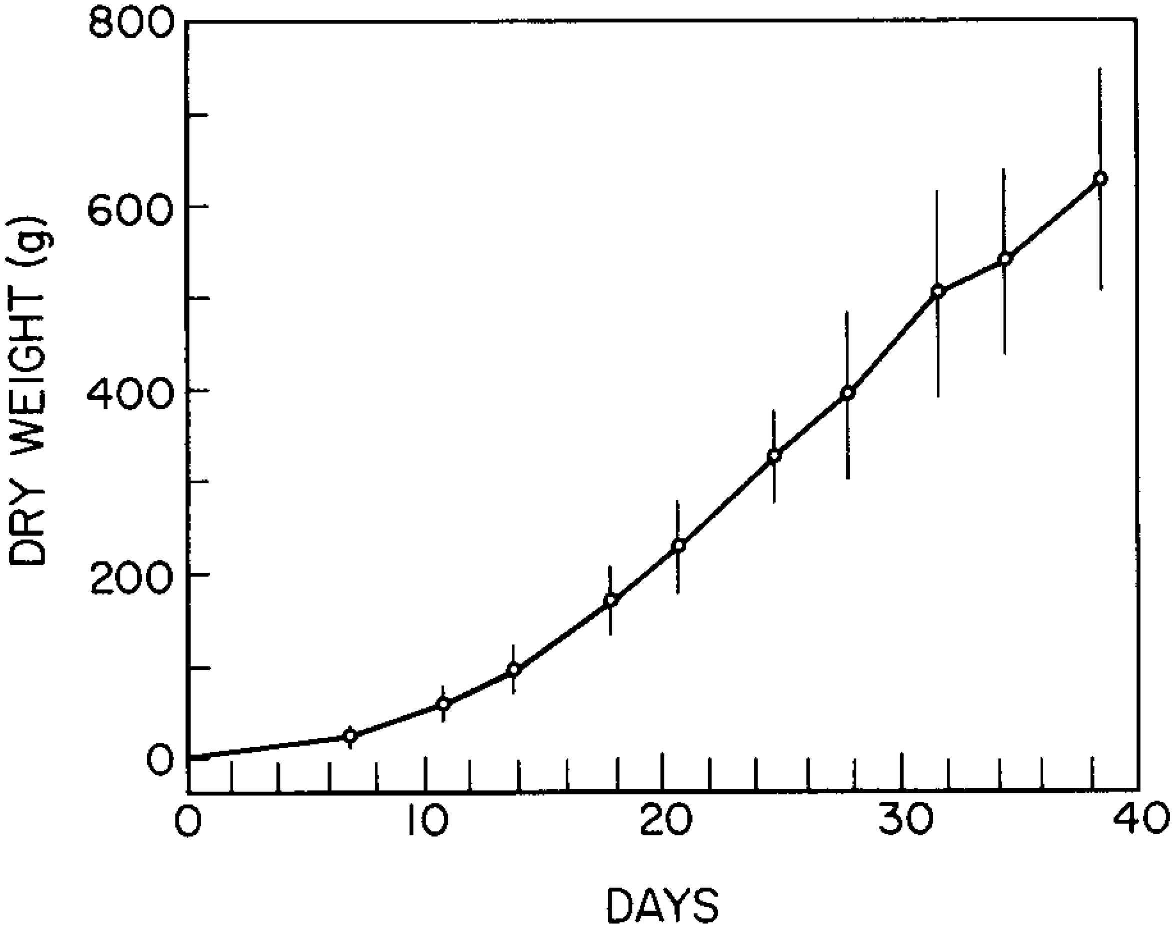

Figure 3. Mean dry weight increase of Porphyra tenera *cultured for 40 days at NELH in a mixture of deep and surface waters (mean ± S.D.; n = 7). Initial dry weight was 4.1 g/m². (From Mencher et al., 1983)*

periodicity of nitrate and phosphate uptake. These nutrients, especially nitrogen, were taken up much more rapidly during the day than at night (Figure 4). This characteristic is not unique to *P. tenera.* Several other seaweeds exhibit a similar reduction in nutrient uptake at night: *Codium fragile* (Hanisak and Harlin, 1978), *Laminaria longicruris* (Harlin and Craigie, 1978), and *Hypnea musciformis* (Haines and Wheeler, 1978). Under the conditions of this experiment, the nori removed up to 57% of the nitrate/nitrite and 27% of the phosphate from the water as it passed through the compartments. Knowledge of the nutrient uptake capabilities of the nori cultures will help in predicting the potential productivity of an OTEC-supplied nori culture system.

Nitrogen content as a percentage of dry tissue weight increased from 6.9 ± 0.2% to 7.7 ± 0.5% during the first 3 weeks of the experiment, and then declined abruptly to 6.5 ± 0.3%. It remained nearly constant after the third week of culture. Since high nitrogen content is correlated with high quality of nori (Noda, 1971), this result suggests that the OTEC-cultured nori may have been higher in quality during the third and fourth weeks of culture than it was thereafter. The drop in nitrogen content may have been caused by lower nutrient availability in the dense cultures, or it may have been caused by an aging effect. In the former case, it may be desirable to increase the water and nutrient exchange rates or to supplement them with additional nutrients; whereas in the latter case, earlier harvesting of the cultured nori might yield a higher-quality product.

Disease (e.g., *Pythium*) causes crop losses in Japanese nori culture grounds (Nihon Suisan Gakkai, 1973). There was no evidence of such disease or of epiphytes in the cultured nori at NELH. During one experiment, two compartments showed minor contamination with *Ulva* sp., a green alga; proper sanitation will eliminate this contamination. Freedom from disease, epiphytes, and contamination will result in the production of more uniform better quality nori sheets.

Asexual reproduction (monospore settling and growth) occurred regularly in the tanks as it does during net culture in Japan (Yoshida, 1972; Kurogi, 1961). Monospore production might provide an alternative or a supplement to the more traditional conchocelis phase cultivation as a source of seedstock for a culture operation.

Nori cultured at NELH in a mixture of surface and deep waters had a significantly different metal content profile compared with nori cultured in surface waters in Korea (Pak et al., 1977). Zinc, chromium, and cadmium concentrations in NELH nori were significantly greater ($p < .05$) than in nori cultured in Korea (Table 1). These differences could be a reflection of the greater concentrations of those elements in the NELH deep water. Fast et al. (see paper in this publication) also discuss this situation for salmon reared in NELH deep water. Whatever the case, the concentrations of heavy metals in nori cultured at NELH were within safe limits for human consumption.

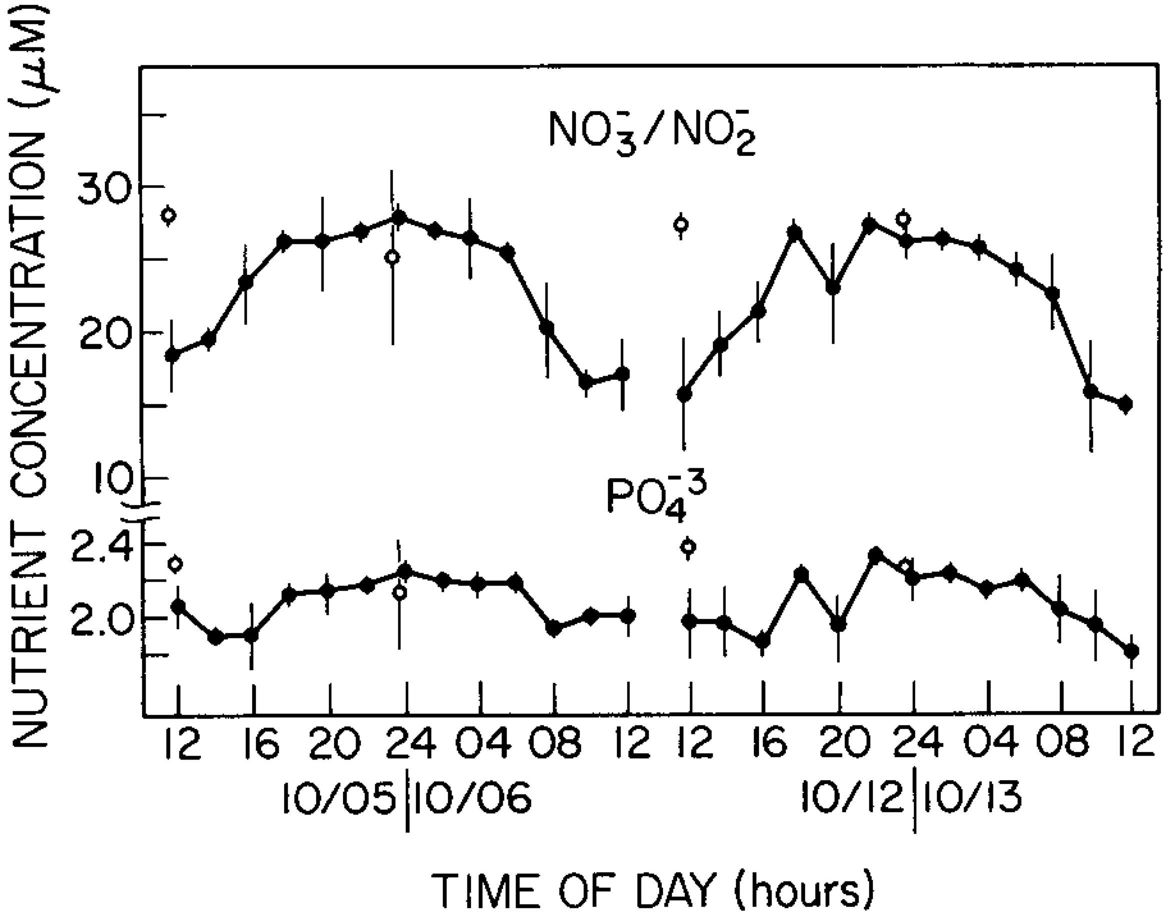

Figure 4. Mean influent water (open circles) and effluent water (solid circles) nutrient concentrations at NELH during the two 24-hour sampling periods of Porphyra tenera *(mean ± S.D., 3 compartments). Upper curves show nitrate/nitrite concentration; lower curves show phosphate concentration. The large variability of influent concentrations at 2400 hours on 10/5 is a sampling artifact caused by incomplete mixing of deep and surface waters in the sample. (From Mencher et al., 1983)*

TABLE 1. METAL CONTENTS OF *P. TENERA* GROWN IN MIXED DEEP AND SURFACE WATERS AT NELH COMPARED WITH THOSE GROWN IN SURFACE WATERS IN KOREA (FROM MENCHER ET AL., 1983)

Metal Concentrations (µg/g dry wt)	NELH[a] (Mean ± S.D.)	Korea[b] (Mean ± S.D.)
Fe	293 ± 29	243 ± 80
Zn	64.3 ± 5.4	32.8 ± 19.0
Cu	13.5 ± 3.4	24.8 ± 13.8
Ni	<0.2	—
Pb	6.8 ± 3.4[c]	2.3 ± 1.9
Cr	5.8 ± 0.9	1.8 ± 1.2
Cd	8.9 ± 1.5	1.1 ± 0.5

[a] Data from this study; 3 samples with 2 replicate subsamples

[b] Data from Pak et al. (1977); 4 samples

[c] Pb levels for one sample were an order of magnitude less than those of two others.

PROCESSING TRIALS IN JAPAN

The transport and processing of NELH-produced nori in Japan are detailed in Woessner (1983) and are summarized here.

Nori used for the processing trials in Japan was cultured in January and February 1983. About 20 kg fresh weight of nori were processed. After arrival in Japan, the frozen material was thawed in cold (5°C to 10°C) seawater. The thawed nori was judged to be too red, without aroma, too flat in taste, and without cohesiveness (stickiness), relative to good-quality Japanese nori. The NELH nori also contained wrinkled fronds, which are not normally encountered in Japanese nori culture.

The nori was mixed with fresh water, chopped, and made into sheets with a Nichimo Wonman processing machine. The Japanese nori-grading experts judged the processed OTEC-cultured nori to be too red, low in luster, and too flat in taste, but clean and not too hard. Without natural cohesiveness, the sheets had to be made thick in order to prevent holes, resulting in a rough, "fluffy" product. Overall, the nori was judged to be of very low quality relative to Japanese-cultured nori. Nevertheless, the Japanese considered the NELH nori to be a good first-try effort and suggested ways in which the quality could be improved.

One reason for the low quality of the processed nori appeared to be cell damage during freezing. Apparently the nori had been frozen with too much water before being taken to Japan. In addition, the nori cells had not been exposed to significant variations in environmental conditions as they would be in Japanese culture beds. This nonexposure decreased the resistance of the cells to the stresses of freezing, processing, and drying. In principle, an OTEC-nori culture system should be flexible enough to allow intentional variation of environmental parameters such as temperature and perhaps light intensity as well as periodic drying during the early growth stages of the nori to improve quality.

The Japanese experts noted that seedstock quality can strongly affect the quality of the final product. The seedstock used for the NELH experiments was held in a frozen state for several months — longer than is considered desirable in Japan. Partial cell damage to the seedstock could have caused the wrinkled nori fronds observed in the NELH culture system. On-site production of seedstock and, ultimately, selection of nori strains better adapted to tank culture conditions should prevent the problems associated with poor-quality seedstock.

In addition to varying environmental conditions to promote cell strength, changing the overall culture conditions from those used in the baseline studies at NELH is a possible means of improving product quality. For example, lower light intensities — which can be achieved either by shading or by an increase in culture density — might result in the production of a darker, less red-colored nori than that exposed to full Hawaiian sunlight. However, because of time and funding limitations, it was not possible to examine a wide range of environmental factors in relation to the quality of OTEC-cultured nori.

Finally, the quality of OTEC-cultured nori could also be improved if it did not have to be transported long distances to be processed. On-site processing is ideal, but this was not possible during our relatively small-scale experiments.

ONGOING RESEARCH

Additional research and development work has been conducted to determine the feasibility of producing superior-quality nori on a commercial scale. One of us, Steven A. Katase, conducted pilot-scale research on nori aquaculture from March 1986 to March 1987 with assistance from Takaokaya Company Limited of Tokyo, Japan, and a Phase I grant from the U.S. Department of Agriculture's Small Business Innovative Research program.

Innovative aquaculture techniques with potential commercial applications were developed to culture another species of nori, *Porphyra yezoensis*. The nori was cultured in land-based tanks using the cold deep seawater and warm surface seawater available at NELH. Two 25-m^3 (23.7 m^2 surface area) circular growout tanks were constructed and modified to provide conditions for rapid growth. Up to 211 g fresh wt/m^2/day were produced in the tanks during a 9-day period, or 45 kg per tank. The average water flow was 57 l/min cold seawater and 38 l/min warm seawater, with an average water temperature of 18°C. Initial stocking density was 200 g/m^2 of cut nori fronds from a commercial nursery operation at NELH (Figure 5).

Nori experts from Japan graded the nori grown in these experiments as high quality, with good dark color, luster, texture, and taste. Mr. Kabashima, president of Kabashima Fisheries, and Mr. Takaoka and Mr. Ito, president and vice-president of Takaokaya, stated that the quality of the nori grown during the 1986–87 experiments was a tenfold improvement over that produced during the 1982–83 experiments. The large improvement in quality was attributed to (1) use of a high-quality

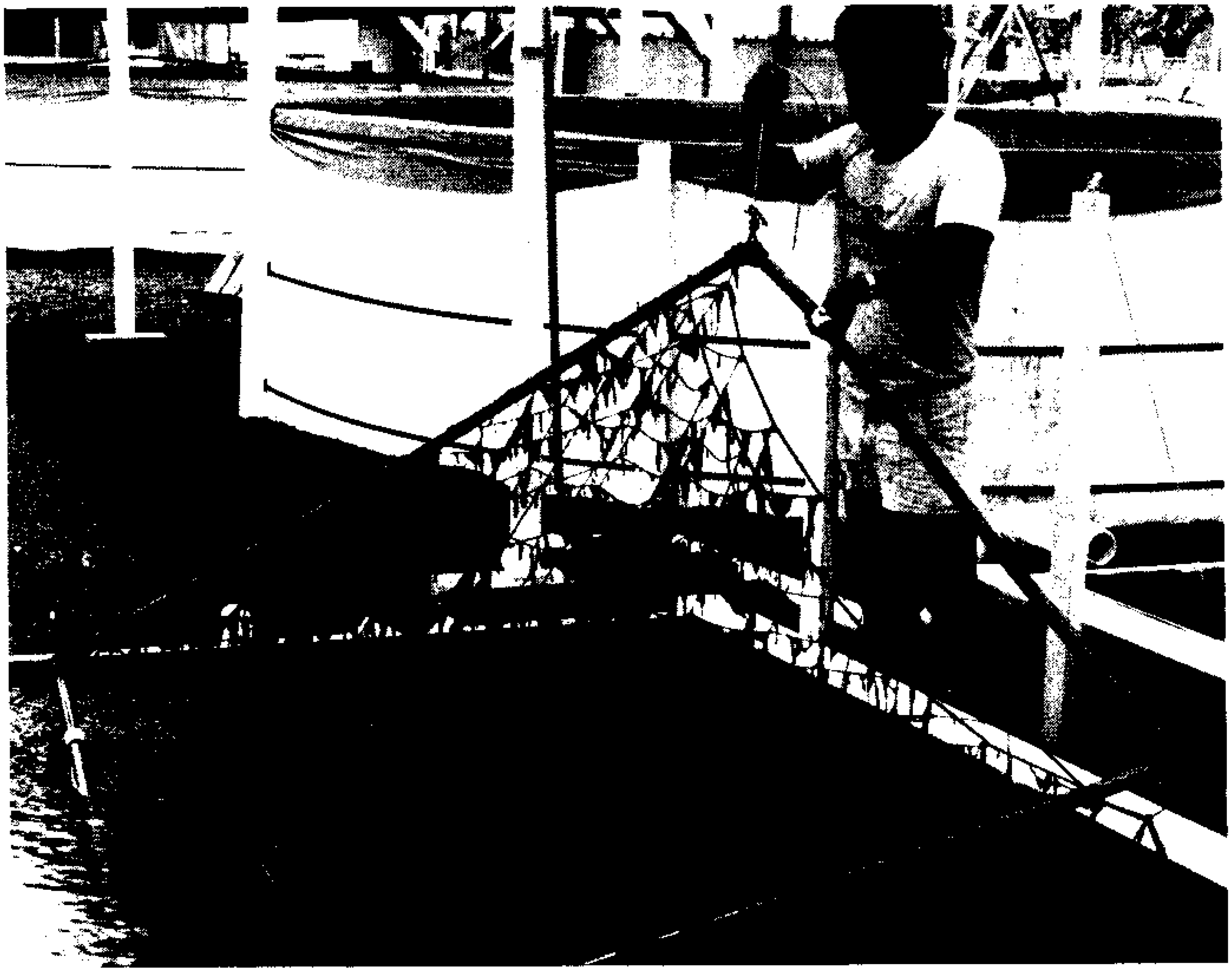

Figure 5. Nori (Porphyra yezoensis) *seed on nets sent from Japan under culture by Aquaculture Concepts at NELH during 1986. After initial growth on the nets, the seed is stripped into larger culture tanks for tumble culture using compressed air.*

strain of *P. yezoensis* developed in Japan, (2) production of juvenile nori fronds in Hawaii rather than using frozen material, (3) use of shade cloth to decrease the high light levels found in Hawaii, (4) reduction of growout time, and (5) time of day the nori was harvested.

Additional experiments remain to be conducted on the nursery system in order that larger volumes of juvenile nori fronds can be produced on a consistent basis. Further research is also required to develop a site-specific strain of nori with superior-quality traits which will not become sexually reproductive during a 14-day growout period.

An 8-acre site at NELH has been reserved for potential Phase II nori research and Phase III commercialization. Private funds have been secured for the development of the new site and a Phase II proposal has been submitted to the Small Business Innovative Research program requesting funds for research operations. Ground preparation of the site will take place in September 1987.

CONCLUSIONS

The experiments conducted at NELH during 1982–83 demonstrated that nori can be grown at high production rates in an intensive tank culture system using simulated OTEC effluents. The nori produced at NELH was initially of low quality relative to Japanese-cultured nori, but the flexibility of an OTEC-related aquaculture system may permit substantial quality improvements. If future studies are conducted at NELH, they should include the following:

- Examination of the effects of short-term and long-term variations of environmental factors on the growth and quality of tank-cultured nori
- Development of seedstock production methods specifically suited for a high-density, unattached growout system
- On-site processing by personnel experienced in the production of high-quality nori sheets
- Based on the above, an economic analysis of nori production at NELH, or a similar site, using mixed deep and surface waters

ACKNOWLEDGMENTS

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ABALONE CULTURE AT THE NATURAL ENERGY LABORATORY OF HAWAII

David K. Barclay
Arlo W. Fast

INTRODUCTION AND BACKGROUND

Hawaiian Abalone Farms, a commercial enterprise, began testing the feasibility of culturing abalone in cold deep seawater in 1982 at the Natural Energy Laboratory of Hawaii (NELH), which is located at Keahole Point on the island of Hawaii. The technology for larval culture and growout had been developed over a 10-year period in California by its parent company, Monterey Abalone Farms, at a cost of $5 million (Whitten, 1984). NELH was chosen because of the accessibility to clean cold seawater with low bacterial levels. The results of the 2-year feasibility test at NELH were successful. A long-term lease was signed in 1984 for 21 acres of land adjacent to NELH and construction began on a commercial demonstration module for the culture of the red abalone *Haliotis rufescens* (Figure 1).

Research has been conducted on the abalone since 1882 when Matsubara initiated studies on its biology. Artificial fertilization of the larvae, the key step toward controlled culture of the animal, was accomplished by Saburo Murayama in 1935. In the late 1950s, attempts by the Hawaii Department of Land and Natural Resources to seed the Mexican green abalone *Haliotis fulgens* on the northeast coast of the island of Oahu were unsuccessful (M. Fujimoto, 1986: personal communication). Since these early pioneering efforts, abalone culture has become a promising business opportunity with facilities for growout in California, Japan, and France and most recently in Hawaii.

The development of controlled production facilities for abalone is largely a result of the depletion of wild stocks. The catch fishery for abalone in the United States, for example, is currently 15% of what it was 20 years ago. A similar situation exists in other countries that once had substantial natural abalone stocks. Concurrent with the declining supply has been an increase in the demand and a subsequent increase in price paid for abalone. Today, fresh abalone can cost as much as $30 per pound. According to G. S. Lockwood of Hawaiian Abalone Farms (1987: personal communication), the annual worldwide abalone consumption probably exceeds $250 million.

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*Figure 1. Broodstock red abalone (*Haliotis rufescens*) at Hawaiian Abalone Farms, Keahole Point, Hawaii*

ABALONE BIOLOGY AND CULTURING TECHNIQUES

At maturity, a 5 to 7-year-old female abalone spawns approximately 7 million eggs. The amount of time from fertilization to hatching is temperature dependent, eggs hatch into free-swimming trochophore larvae between 10 to 72 hours at a temperature range between 10°C and 15°C (Figure 2). In 12 to 24 hours, the trochophore larvae become veliger larvae which are characterized by a velum. The velum has hundreds of hair-like cilia which provide propulsion through the water. The veliger larvae remain free swimming for 4 to 6 days. Toward the end of this period, the veliger develops a rudimentary foot, which is used to attach the larva to a substrate. At the time of settling, the free-swimming veliger becomes a snail-like animal, 250 microns in size. From the time of hatching to attachment on a substrate, the larvae subsists on their yolk reserves.

Once the veliger attaches itself to a substrate, it begins feeding on microorganisms such as bacteria, yeast, and protozoa which are innoculated in the larval rearing tanks. The 60-day period from the time of settlement to the development of the radula is perhaps the most difficult one for the culturist. During this period the abalone are very delicate. Nursery systems must be maintained to avoid perturbations with regard to temperature and water quality. Culture temperatures are maintained between 10°C and 15°C. The radula is a rasp-like organ used to remove from the substrate.

Once the radula is fully developed, the abalone are capable of scraping the substrate and ingesting benthic diatoms and other algae. In 40 to 90 days, respiratory pores develop as a notch in the shell. Culturists refer to the beginning of the juvenile stage of development as the "notch stage." During this stage the abalone are maintained in nursery tanks over which the culturist has total control of light, temperature, and water quality. At 6 months, juvenile abalone begin feeding on larger diatoms and giant kelp *(Macrocystis)*. At this point in their development, abalone are ready for stocking in land-based culture systems or for release to enhance the natural fishery.

Two types of culture growout systems are used for commercial abalone production: (1) ocean deployment systems and (2) land-based systems. Both systems have distinct advantages and disadvantages. Ocean deployment systems commonly use cages suspended from oil platforms and has the advantages of lower capital costs, no water pumping costs, and freedom from the problems associated with nearshore pollution. The disadvantages of this system are difficulty of accessibility, potential for storm damage, need for predator control, and transport costs. Land-based systems, consisting of tanks or raceways, have the advantages of unlimited accessibility and greater long-term control of the abalone's environment (Figures 3 and 4). Its disadvantages include greater capital and operating costs. A design of any growout system should be configured to reduce labor and maintenance costs while allowing intensive culture.

Using either system, it takes 3.5 to 5 years for an abalone to reach 100 to 125 mm (3.9 to 4.9 inches) in length. Commercial growers in California produce abalone ranging in size from 50 to 100 mm (2 to 4 inches) for Asian markets (Conte, 1981). It takes about 2 years to produce a 50 to 100-mm abalone with intensive culture systems (Figure 5).

The strategy for marketing abalone by California culturists is aimed primarily at in-state white tablecloth restaurants. In addition, growers market seed abalone to other growers. In 1982, 78,650

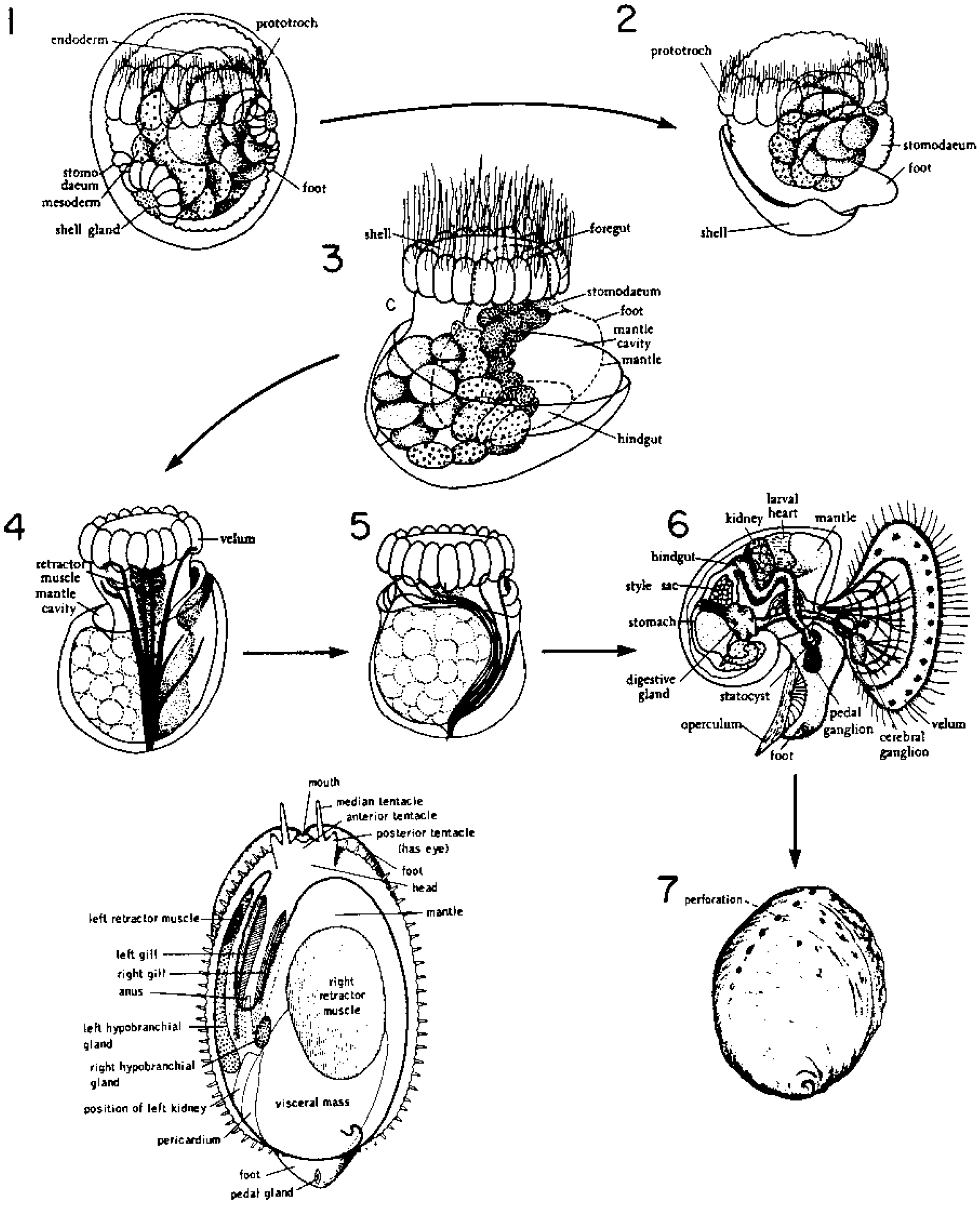

Figure 2. Stages in the development of Haliotis tuberculata*: (1) the young trochophore just before hatching, (2 and 3) the foot and the shell gland begin to form, (4 and 5) retractor muscles form and larva undergoes torsion, (6) side view of veliger stage, and (7) juvenile abalone. Bottom left, dorsal view of adult* Haliotis *sp. (Taken from Meglitsch, 1972, and Barnes, 1974)*

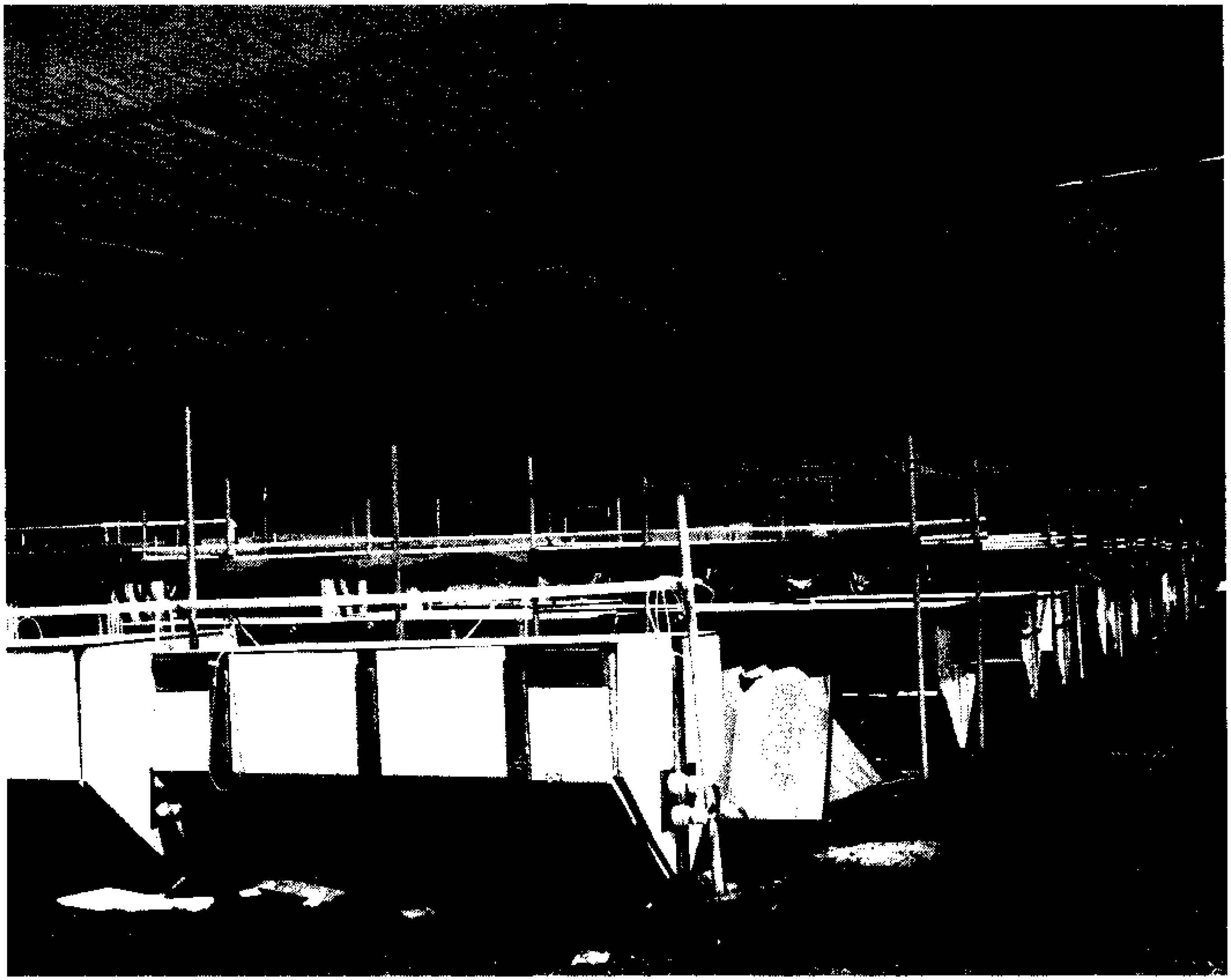

Figure 3. Specially designed growout tanks used by Hawaiian Abalone Farms. The tanks are insulated and made of fiberglass and are covered overhead by shade cloth.

Figure 4. Abalone condominium-like habitat used in growout tanks

Figure 5. Small, market-sized red abalone at Hawaiian Abalone Farms.

0.5-inch seed marketed was worth $77,580. Two to three-inch abalone sold wholesale for an average price $15.60 a pound (West Coast Aquaculture Foundation, 1984).

HAWAIIAN ABALONE FARMS

The abalone culture system used by Hawaiian Abalone Farms is unique for two reasons: (1) the system uses cold deep seawater, as opposed to near-surface seawater commonly used in temperate climates and (2) the primary food for growout is the giant kelp *Macrocystis*, which is cultured on land in two 30-m (105-ft) diameter tanks (Figure 6). Abalone farms along the west coast of the United States also use kelp, but theirs is harvested from offshore beds on a regular basis and transported by boat to the shore-based abalone growout facilities.

Hawaiian Abalone Farms is using between 6 and 7 acres of their 21 acres of leased land, but only about 1 acre is in actual abalone production (Lockwood, 1987: personal communication). Plans are to eventually produce 2 million abalone per year at the 21-acre site (Lockwood, 1987: personal communication). Imminent expansion includes the completion of a 4-acre pond for kelp production and the installation of a new 2,500-gpm coldwater pipeline. In addition, Hawaiian Abalone Farms is seeking to lease more land at the Hawaiian Ocean Science Technology Park which is now under development next to NELH.

Hawaiian Abalone Farms markets its product in several forms. It is currently selling the 2 to 3-inch abalone to the gourmet, or white tablecloth, market and has plans to market larger abalone for use as *sashimi* It also plans to sell its canned and frozen food products to the Chinese market (Lockwood, 1987: personal communication).

ACKNOWLEDGMENTS

We gratefully acknowledge the help of Kelen Dunford and George Lockwood for their help in preparing this paper.

*Figure 6. Giant kelp (*Macrocystis*) frond grown by Hawaiian Abalone Farms at Keahole Point to feed to larger abalone. The kelp are grown in 30-m diameter tanks shown in the background.*

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AMERICAN LOBSTER (*Homarus americanus*) AQUACULTURE DEMONSTRATION PROJECT AT THE NATURAL ENERGY LABORATORY OF HAWAII

P. W. Chapman
R. J. Guerra
M. Thays

INTRODUCTION

From September 1982 to September 1983, Sanders Associates, Inc. of Merrimack, New Hampshire, was involved in an aquaculture demonstration project at the Natural Energy Laboratory of Hawaii (NELH), which is located at Keahole Point, Hawaii. The species of study was the American lobster *Homarus americanus* (Figure 1).

By mid-1982, Sanders Associates had completed a 5-year culture research effort and a 2-year developmental program with the American lobster in Kittery, Maine, and in Nashua, New Hampshire, respectively. In addition, Sanders Associates' personnel and equipment were used to conduct a concurrent 15-month site validation and technology demonstration at Amfac's International Shellfish Enterprises Facility in Moss Landing, California. The 7-year experimental and pilot programs resulted in the development of a licensable technology package for the culture of the American lobster. This effort included the review of more than 2,600 technical documents, spanning 121 years. The resultant license package includes unique and proprietary systems and hardware designs, proprietary husbandry and business management technology data, four patents issued with one patent pending, and more than 250 special operating procedures.

Site selection analysis conducted by Sanders Associates during 1982 indicated that there are a limited number global locations where ambient conditions might be appropriate for commercial culture of the American lobster. The analysis showed that Hawaii is the only U.S. location with potential because it has year-roundseawater temperature, which requires little or no modification for culturing the American lobster.

Flow-through culture systems could be used, eliminating the need for much equipment. Simple, flow-through culture systems greatly reduce equipment costs, building size, and energy costs. Additionally, flow-through operations should allow higher operating temperatures with minimal water quality problems, potentially yielding higher growth rates.

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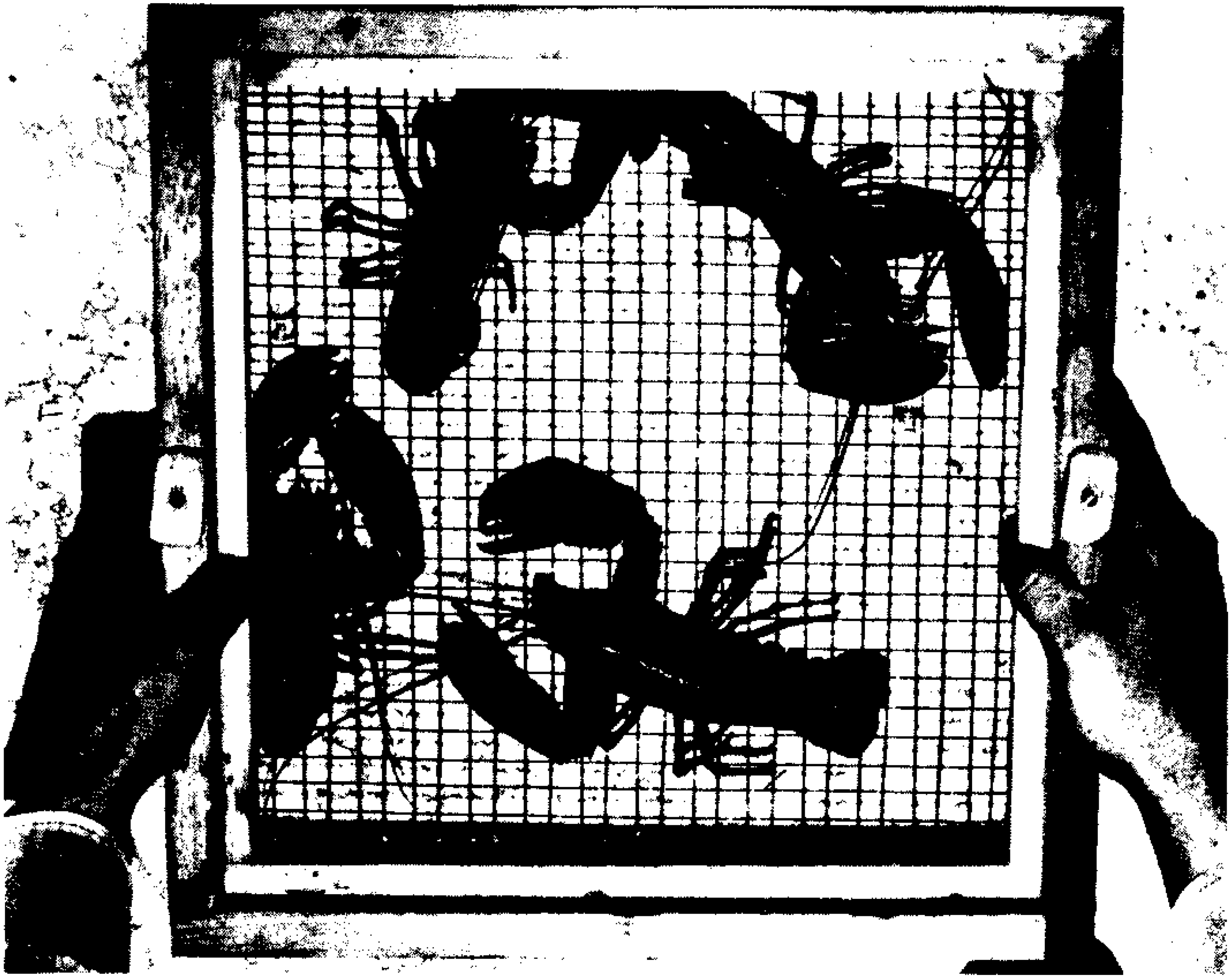

Figure 1. The American lobster Homarus americanus cultured in captivity. (Photo courtesy of California Sea Grant College Program)

PROJECT SITE VALIDATION

During 1982, Sanders Associates entered into a cost-sharing agreement with the state Department of Planning and Economic Development for a site verification and demonstration of the American lobster culture system at NELH. The site verification, which should precede any commercial venture, was conducted to determine: (1) growth and survival relationships for all stages and seasons under ambient conditions; (2) cost and logistics factors for locally produced diets which use indigenous fisheries by-products; and (3) a refined site-specific business plan.

The primary requirements for the successful culture of any species are (1) an appropriate which duplicates or enhances the animal's natural habitat; and (2) a nutritious food, which is accepted by the animal, has properties suitable for use in a culture system and supports acceptable growth and survival rates. These keystones must be economically compatible with a business model. Included in the environmental consideration is the elimination or control of unwanted biofouling organisms, which may inhibit the growth of a cultured species or seriously affect system operation and maintenance.

PROJECT GOALS

Sanders Associates' goals for the demonstration project were:

1. To assess the suitability of ambient seawater at NELH for the culture of American lobster
2. To determine optimal operating conditions for a Hawaii-based flow-through culture system for the American lobster
3. To modify and evaluate the existing lobster diet recipe for a least-cost Hawaii-based formulation
4. To determine specific growth and survival rates, costs, and market factors for the Hawaiian location
5. To revise the initial Hawaii pro-forma financial analysis to reflect site verification findings
6. To seek investors for a Hawaii-based lobster culture venture under license to Sanders Associates

MATERIALS AND PROCEDURES

By September 1982, we located all the necessary culture equipment to NELH. The demonstration equipment included a 20 ft x 50 ft inflatable building (Figures 2 and 3), a broodstock holding system, a larval hatching and rearing system, a postlarval rearing station, 24 MOD II growout tanks, and a 72-basket MOD III growout demonstrator (Figure 4). Figure 5 shows the orientation of the lobster project relative to other OTEC aquaculture projects.

Sanders Associates' aquaculture team, assisted by NELH personnel, installed the building, equipment, and associated internal plumbing. Since the inflatable shelter was originally designed for hydroponics, it had to be modified for our aquaculture application. These modifications included installation of a 92% agricultural sunscreen over the shelter to reduce heat build-up and system

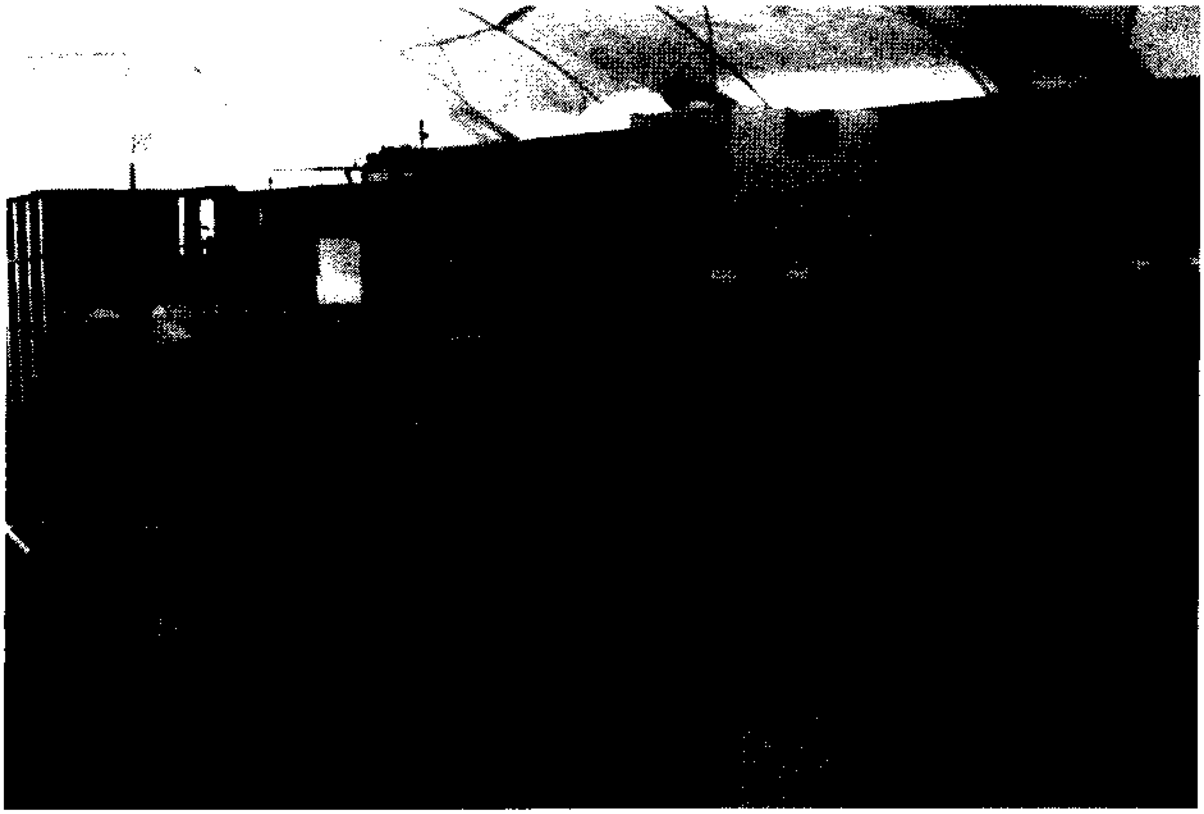

Figure 2. The inflatable 20 ft x 50 ft building to the left housed the lobster aquaculture demonstration project from September 1982 through September 1983. The tanks in the foreground contain seaweed under cultivation, and the storage tank in the background is associated with an abalone demonstration project.

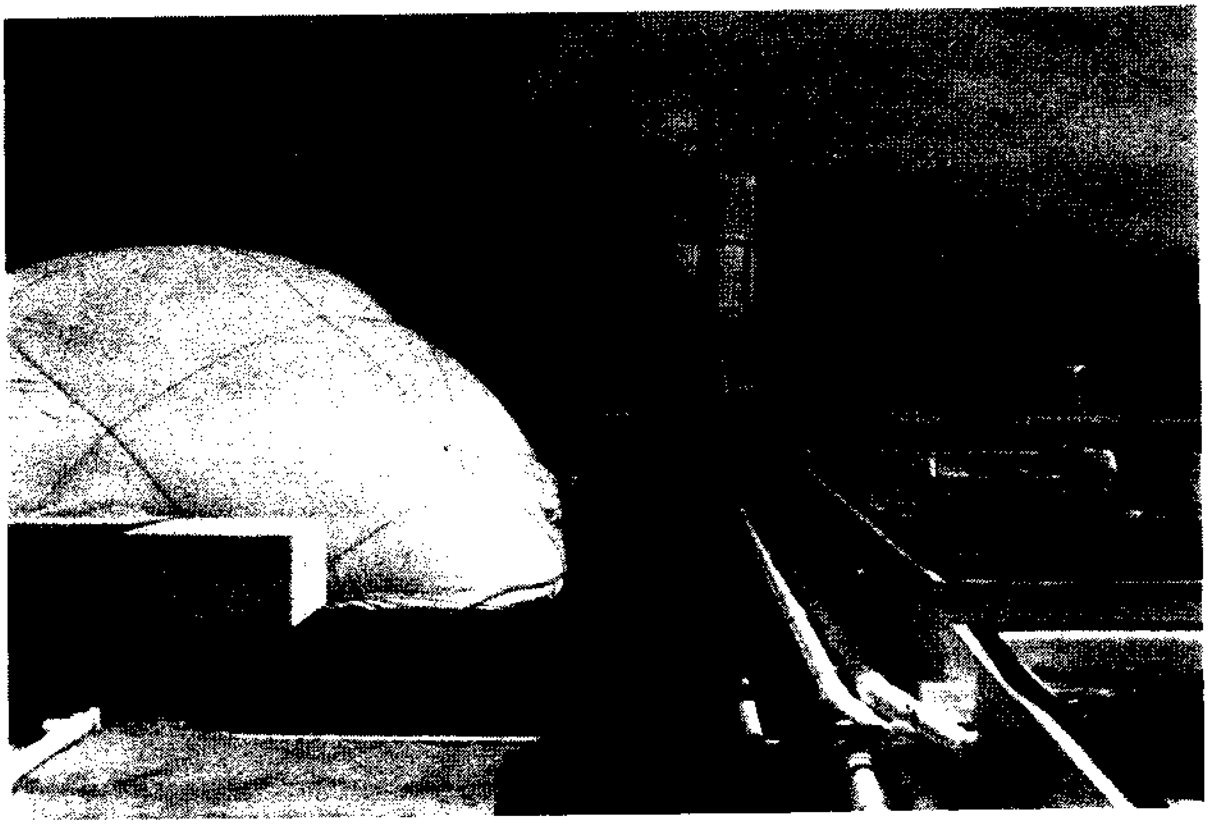

Figure 3. Inside the inflatable building are the larval system with sump pump and filter (immediate foreground), the hatching car (the square box on top of the larval system), the postlarval system (aquarium-like structure behind the larval system), and the growout system tanks (left background).

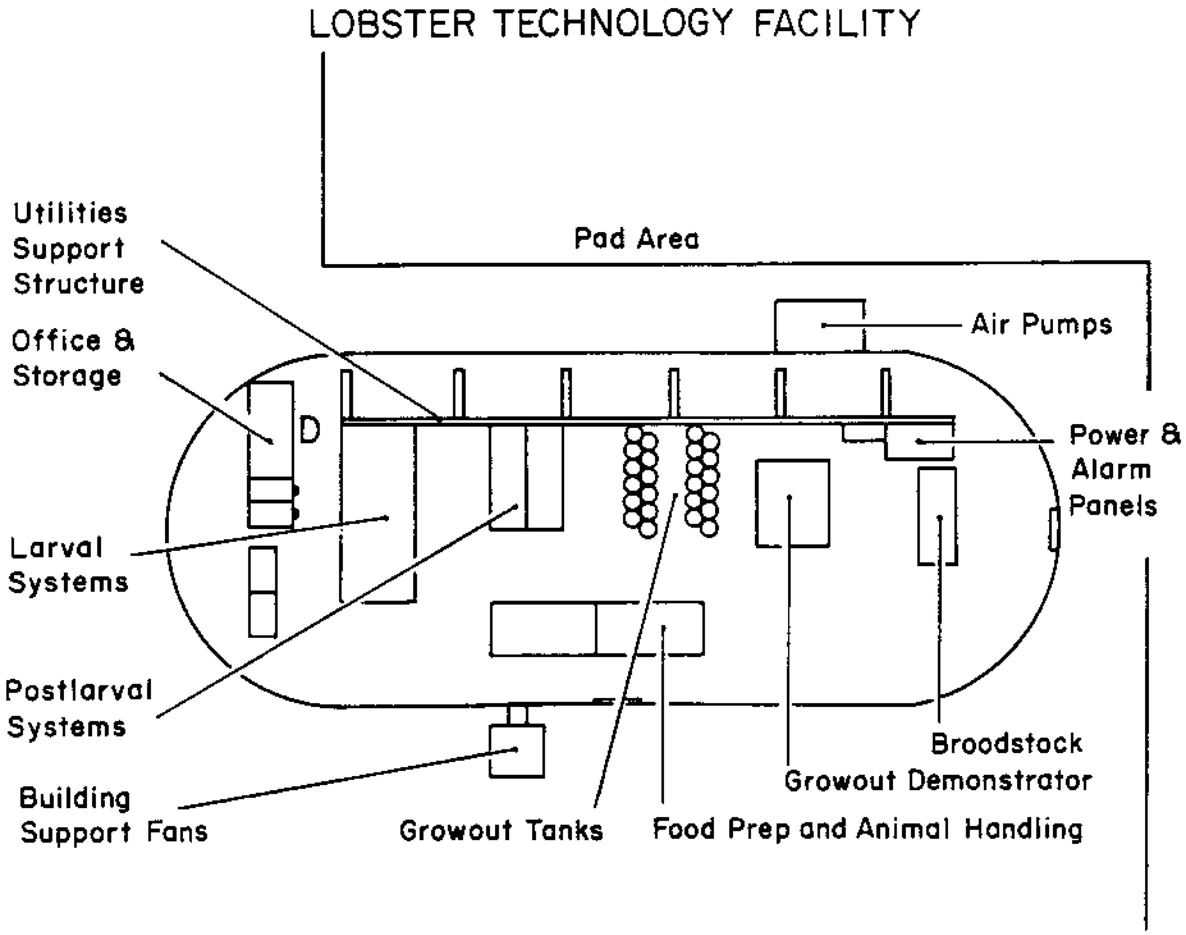

Figure 4. Layout of lobster culture equipment inside the 20 ft x 50 ft inflatable building used for site verification at the Natural Energy Laboratory of Hawaii

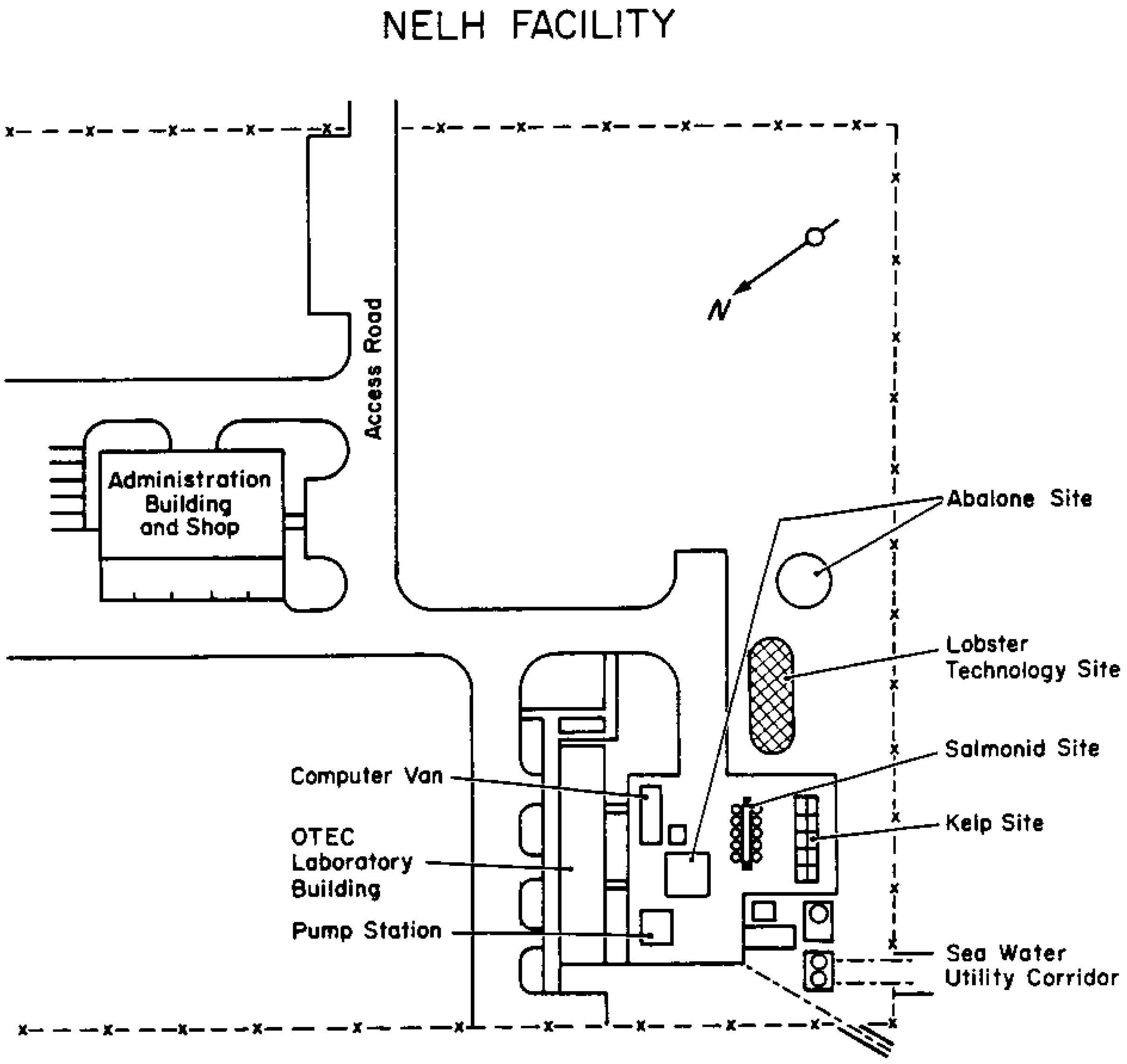

Figure 5. OTEC aquaculture site layout at the Natural Energy Laboratory of Hawaii during 1982–83

biofouling and installation of a quieter blower. Because of the permeability of the crushed lava and coral building pad, special precautions were required to maintain building inflation air pressure.

After installation of the shelter and other culture equipment, 1,500 postlarval, 2,000 juvenile, and 6 adult lobsters were shipped from Sanders Associates' Moss Landing site; 10 "berried" females were shipped from the U.S. East Coast. The lobster culture stock shipped to NELH comprised the full spectrum of animal sizes and growth stages. The lobster population at NELH fluctuated between 2,000 and 6,000 animals during the 12-month test period.

The first Hawaii hatch of over 16,000 larvae occurred in January 1983, and the next four hatches occurred in overlapping intervals from April 1 to May 1, 1983, and again from May 21 to June 10, 1983. These hatches resulted in of animals beyond available facility capacity. The postlarval system was filled to capacity from these hatches when the animals reached the appropriate size. Surplus lobster were shipped to the mainland in accordance with the covenants of the Hawaii import permit. Animals from the later hatches remained in the culture system at NELH until the project was terminated and provided valuable growth and survival data.

Lobster survival, growth, feed conversion, and other pertinent data were collected throughout the test period. Water quality was monitored daily. These data were compared with data collected at previous research sites operated by Sanders Associates.

CONCLUSIONS AND RECOMMENDATIONS

Water Conditions

Ambient surface seawater temperatures in Hawaii are above the optimal level for lobster culture and are especially lethal during the summer months. A viable American lobster production operation in Hawaii would require either pumping from a cool saltwater well or a continuous mixing of deep and surface waters to provide a workable operating temperature. The following list summarizes culture considerations.

1. The optimum temperature was 20°C ± 1°C.
2. Minimum water flow rates for acceptable water quality are substantially lower for a flow-through system in Hawaii than those normally required for closed, recirculating systems in colder climates.
3. NELH water has negligible concentrations of chemicals toxic to American lobster (i.e., NH_3, PO_4, NO_2).
4. NELH surface water contained many species of biofouling organisms and had relatively low bacteria counts and was rich in nutrients.
5. The mixing of deep and surface waters encouraged blooms of both bacteria and biofouling organisms under full sunlight. This can be controlled satisfactorily with shade cloth or some other opaque material.
6. Surface water at NELH had a high dissolved oxygen content. The cold deep water (8°C to 12°C) contained inadequate dissolved oxygen and required intensive aeration. Mixing surface and deep waters provided a satisfactory solution.

Half of the initial culture tests at NELH was conducted using ambient surface waters; the other half was controlled at 20°C ± 1°C by blending OTEC deep and surface waters. This test scheme was used because we found high mortality rates at temperatures greater than 22°C. Losses occurred at the higher temperatures because of excessive metabolic rate among the lobster and because of biofouling. The biofouling was corrected by covering the growout system with an opaque shroud to reduce the light level. Biofouling can also be effectively controlled by using well water or a mixture of surface and deep waters resulting in lower than ambient temperatures and lower nutrient concentrations. High water temperature, rather than biofouling constituted the major stress factor. Subsequently, the operating temperatures in all growout systems were reduced to 20°C, except for a "control" which was kept at ambient temperature to confirm our initial findings.

Culture Trials

Animals were successfully mated at the NELH test site. However, the test period ended before egg extrusion and hatching could occur.

The ambient photoperiod at NELH promoted rapid egg development, even with broodstock held at lowered temperatures. This could be beneficial and easily accommodated. Survival in the postlarval system was good using mixed surface and deep waters at 20°C.

At reduced operating temperatures (20°C ± 1°C), the MOD III growout demonstrator gave high survival rate and was suitable equipment for growout. It is easy to maintain and allows for reduced animal handling, as well as reduced environmental stress and injury to animals.

Although animal mortalities with the Hawaii diets at 20°C temperature were acceptable, the growth rates were not. Growth was less than required for a viable commercial venture. In addition, the cost of locally available ingredients was too high.

Waste Solids and Water Disposal

A commercial production site in Hawaii with high water usage may require costly water treatment or injection wells for effective wastewater disposal. Tests conducted at NELH, however, showed that tilapia readily thrive on system detritus and uneaten lobster food. This may be a cost-effective alternative means of reducing water treatment costs, while providing another cash crop.

Achievability, Marketing, and Venture Development

From a technical standpoint, American lobster culture could be accomplished in Hawaii. The required system modifications and operating mode changes, however, appear to be far more costly than initially anticipated. The apparent advantages of the year-round higher ambient water temperature may not compensate for these other constraints.

The relatively small local market for American lobster would consume only a portion of the production necessary to justify a commercial lobster venture in Hawaii. The Hawaii market is currently being serviced adequately from U.S. East Coast sources at competitive retail prices. Most of the lobsters produced in Hawaii would have to be exported, but it is questionable whether this could be done at a profit.

The culture of American lobster could benefit by being combined with the culture of other species in a synergistic way. This would spread the risk, provide earlier cash flow and the stability of a multiproduct businessresulting in a venture economically which is viable. Tilapia is a logical candidate species, as are oysters and some seaweeds. Each species would be held in a separate system operated at its own best condition, but each would use by-products from the other operations. Administrative and marketing costs would be shared.

Based on our findings, we do not recommend the single species culture of the American lobster in Hawaii at this time.

SEAWATER ENTRY EVALUATION OF COHO SALMON REARED AT THE NATURAL ENERGY LABORATORY OF HAWAII

Lisa Helms
E. Gordon Grau
Arlo W. Fast

INTRODUCTION

Coho salmon *(Oncorhynchus kisutch)* are temperate and sub-arctic zone fish which require water temperatures less than 17°C and preferably below 13°C. Under laboratory conditions, their optimal temperature is about 12.2°C (Klontz et al., 1979).

Coho salmon, like all other salmonids, require freshwater during their initial development. The time at which coho salmon are physiologically adapted to enter seawater varies greatly, depending on locale and/or strain. The physiological process which prepares coho salmon for seawater entry is called smoltification. Normal seawater entry may occur as early as age 6 months or as late as several years of age (Childerhose and Trim, 1979). However, if fish are prevented from entering the ocean, they undergo a process called desmoltification and lose their ability to tolerate seawater.

Coho salmon are the most easily cultured of the Pacific salmon species. Their captive culture includes larviculture, nursery rearing, and growout to marketable size in hatcheries, raceways, tanks, and floating net pens. Coho salmon are widely cultured in many cold saltwater areas of the Pacific Northwest (North America), Japan, and Scandinavia.

Because of their cold temperature requirements and ease of culture, coho salmon was considered a likely candidate for culture in association with ocean thermal energy conversion (OTEC) power plants. To assess this potential, an evaluation of several aspects of salmon performance under simulated OTEC culture conditions was required. This paper focuses on only one aspect of salmon performance — smoltification.

Primary concerns were whether coho salmon would smoltify within 6 to 7 months and whether smoltification would occur under tropical photoperiods such as those found in Hawaii. Almost certainly, a commercial OTEC salmon operation in the tropics would require that the smolts be produced locally since their importation from conventional salmon-rearing areas would be prohibi-

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tively costly. Local production, to be cost effective, should minimize the egg to smolt development time since salmon requires cold freshwater during this period. Minimizing time to smoltification should have a major impact on the economics of salmon culture at OTEC sites.

A more thorough description of this work is presented in Grau, Fast, Nishioka, and Bern (1985a) and in Grau, Fast, Nishioka, Bern, Barclay, and Katase (1985b).

SMOLTIFICATION BACKGROUND

The process of smoltification includes several physiological, morphological, and behavioral changes which in nature lead to the salmon's successful entry into the marine habitat. Although several physiological changes are integral to this transformation (Dickhoff et al.,1982; Folmar and Dickhoff, 1980, 1981; cf. Clarke, 1982; Zaugg, 1982), no one change adequately predicts optimal hatchery release times (Figure 1).

One major difficulty is asynchrony of physiological indicators among different populations and species of salmon (Clarke, 1982). The timing of events associated with the parr-smolt transformation among coho salmon from different latitudes provides an excellent illustration. In coho salmon, thyroxine (T_4), a thyroid hormone, peaks during the period of the transformation. Several recent studies suggest that this T_4 peak occurs earliest in California populations, followed by populations in Washington, and lastly those in British Columbia (W. C. Clarke, E. G. Grau, R. S. Nishioka, and H. A. Bern, unpublished data; Grau et al., 1981). Differences among populations in the timing of such physiological change make it difficult to characterize the temporal relations among potential indicators of smoltification based upon reports in the literature.

MATERIALS AND METHODS

The temporal relationship between two frequently used indicators of smoltification — elevated thyroid hormone levels and performance in the seawater challenge (SWC) test — was examined (cf. Clarke and Blackburn, 1977; Folmar and Dickhoff, 1981; Dickhoff et al., 1982). This temporal relationship was examined for coho salmon held at two different temperatures and under two different photoperiods in tanks at the Natural Energy Laboratory of Hawaii (NELH) at Keahole Point on the island of Hawaii.

Egg Source and Rearing Systems

Eyed coho salmon eggs from the Iron Gate Hatchery on the Klamath River, Yreka, California, were air shipped to NELH by the California Department of Fish & Game in January 1983. The eggs were hatched in a recirculation-type incubator in water chilled to 9.5°C. After hatching, the fry were transferred to four 1.52-m diameter x 1.52-m high circular tanks in which they were held for the duration of the study. A mixture of new (690 l/h) and recirculated freshwater was chilled by heat exchange with OTEC seawater to either 11°C or 17°C using a tubular titanium heat exchanger. This water was supplied to each tank at the rate of 18,400 l/h. The fish were fed a commercial salmon diet (Rangen, Buhl, ID) 4 to 8 times a day at the rate of 3% of body weight per day. The hatching and

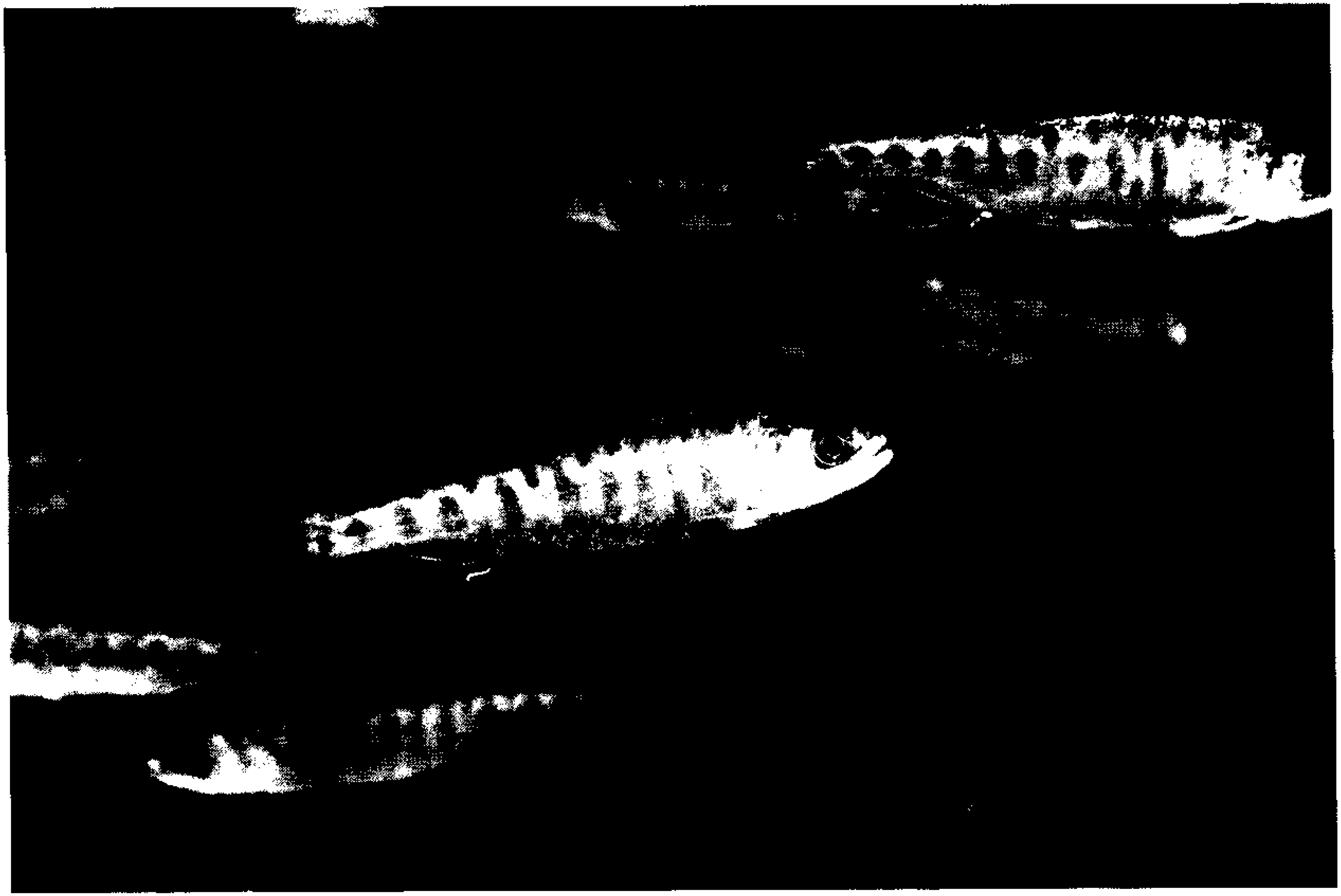

Figure 1. Pre-smolt. Note parr marks along fish's sides. Photo courtesy of California Sea Grant College Program.

rearing systems are described in more detail in the paper on growth of coho and chinook salmon by Barclay, Fast, and Katase in this publication.

Experimental Design

After transfer to the four circular tanks, the fish were exposed to a factorial treatment combination of two temperatures and two photoperiods. The temperatures were 11°C and 17°C; the photoperiods, ambient Hawaii and California (latitude 40°N).

Sampling commenced in early April 1983 when the fish were 4 months old and continued into May 1984. Blood samples were collected weekly for thyroid hormone and osmolality determinations (N = 5 to 21; generally 10 to 16). For the SWC studies, 2 groups of fish (N = 6 to 12) were transferred every 2 weeks from each holding tank to identical rectangular tanks — one containing freshwater and the other seawater. The water temperature in these tanks and the photoperiod regime under which the fish were held were identical to those of the holding tank from which each group of fish had been taken (i.e., 11°C or 17°C; ambient Hawaii or California photoperiod). Blood from 6 to 8 fish which were sacrificed from each tank was collected at the time of transfer and at 8, 24, and 48 hours following transfer.

RESULTS

Peak seawater entry performance, defined as the smallest elevation in blood osmolality (mOsm/kg) after seawater transfer, occurred in middle (17°C) or late (11°C) July (Figure 2). Fish held at 11°C performed better in the SWC tests throughout the study than fish held at 17°C. Although after September only the 11°C fish remained in the study, there was a brief period in October when their performance improved slightly. The improvement, however, was not as great as that observed in July. During March of the following year, performance was nearly equal to that of the previous July.

Consistent with other reports (Conte et al., 1966; Dickhoff et al., 1982), the ability of salmon to accommodate acute seawater stress, possibly representing preadaptation in freshwater fish for seawater entry, is activated only during restricted times.

Convincing and reproducible evidence suggests that coho salmon survival in seawater net pens is strongly correlated with the elevation of thyroid hormones during smoltification (Folmar and Dickhoff, 1981; Dickhoff et al., 1982). Recent evidence also suggests that the correlation between the completion of the thyroid hormone surge and seawater survival is a result of improved seawater osmoregulatory performance.

Our studies were aimed, in part, at determining the temporal relationship between changes in thyroid hormone levels and performance in the SWC tests, replicated under four sets of conditions. On the basis of the SWC test results, there appear to be two, or possibly three, periods favorable for juvenile coho salmon raised at 11°C to enter seawater. The two most obvious of these periods of optimal seawater adaptability occurred in June–July 1983 (6 to 7-month-old fish) and February–April 1984 (14 to 16-month-old fish) (Figure 2). Both of these period were preceded by

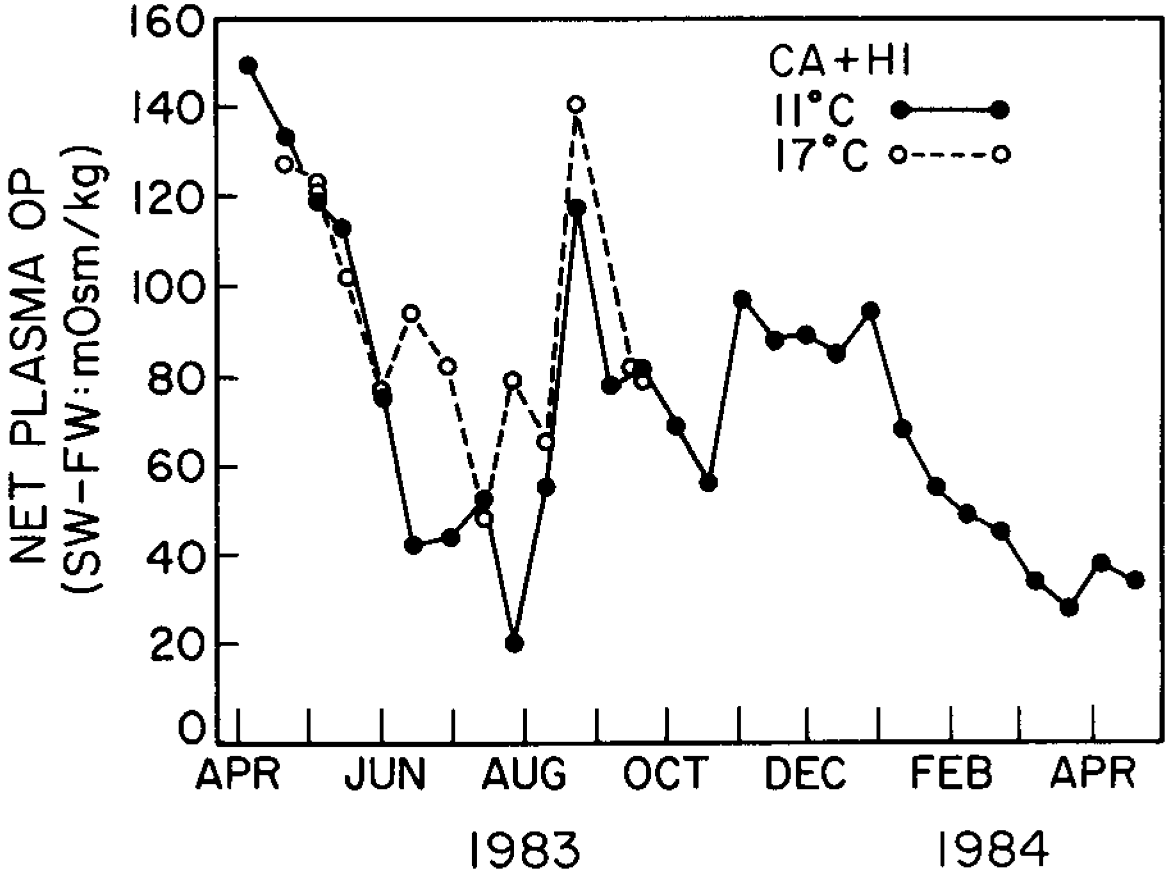

Figure 2. Variations in the net elevation of plasma osmolality (OP) in seawater over that in freshwater 2 hours after the coho salmon had been transferred from their holding tanks. (CA + HI) refers to the combining of values measured in fish maintained under California and Hawaii photoperiod regimes at the Natural Energy Laboratory of Hawaii, Keahole Point, Hawaii. (Copied with permission from Grau et al., 1985b)

elevated thyroid hormone levels. A third period of enhanced osmoregulatory ability, as indicated by SWC test results, occurred in October 1983 when T_4 levels were low.

Our studies at NELH confirm the findings of Dickhoff et al. (1982) in which accelerated underyearling fish showed peaks of both T_3 and T_4 during May–July when the fish were 5 to 7months old (Figures 3 and 4). In our study at both temperatures (11°C and 17°C), the thyroid hormone surge was completed before the peak of SWC performance.

The patterns of thyroid hormone changes and performance of SWC were strikingly similar between fish held at the two temperatures and were virtually identical between fish held under the California or ambient Hawaii photoperiod (Figures 3 and 4). Unfortunately, owing to operational problems which resulted in the massive death of fish held at the higher temperature, the 17°C portion of the experiment was terminated in September 1983.

Previous studies have shown that during smoltification in yearling coho salmon, there is a strong correlation between peak plasma T_4 levels and the new moon phase of the lunar cycle (Grau et al., 1981, 1982). Although the sampling pattern of the studies conducted at NELH was not frequent enough to test for coincidences with lunar phase, the study did provide both expected and new findings. The two T_4 peaks that occurred in yearling fish in February and March occurred in the samples taken closest to the new moon in both photoperiod regimes as expected (Figure 3). The peak occurring in December, however, coincided with the full moon. Recent studies suggest that such occurrences may be more common than previously thought (R. S. Nishioka and H. A. Bern, unpublished data).

The timing of the changes in the thyroid hormones occurring in the underyearling fish during May and June is not easily explained. Neither of the two T_4 peaks occurred at the new or full moons. Rather, they fell astride a peak in T_3 which was seen in samples collected after the June new moon. Although this observation is interesting, it is by itself not very enlightening. Taken together with evidence provided by Dickhoff et al. (1982), this suggests that the lunar-phased T_3 peak may offer a reliable cue for hatchery release times. In light of the finding of Dickhoff and coworkers that the survival of accelerated underyearling coho salmon in seawater net pens is correlated with the completion of the period of the T_3 peak (not the T_4 surge), this matter warrants further investigation.

CONCLUSIONS

Our study clearly demonstrated that coho salmon underyearlings reared in freshwater in the range of 11°C to 17°C under ambient photoperiods can be successfully transferred to seawater at age 6 to 7 months for growout. This is important in tropical areas such as Hawaii where cold freshwater (<17°C) is limited and growout of smolts is costly. In more temperate areas, smoltification normally takes 9 to 10 months longer than we observed. Timing of seawater entry with physiological condition of the fish, however, is of paramount importance. The transfer of 6 to 7-month-old smolts to seawater will improve the economics of salmon culture at OTEC plants.

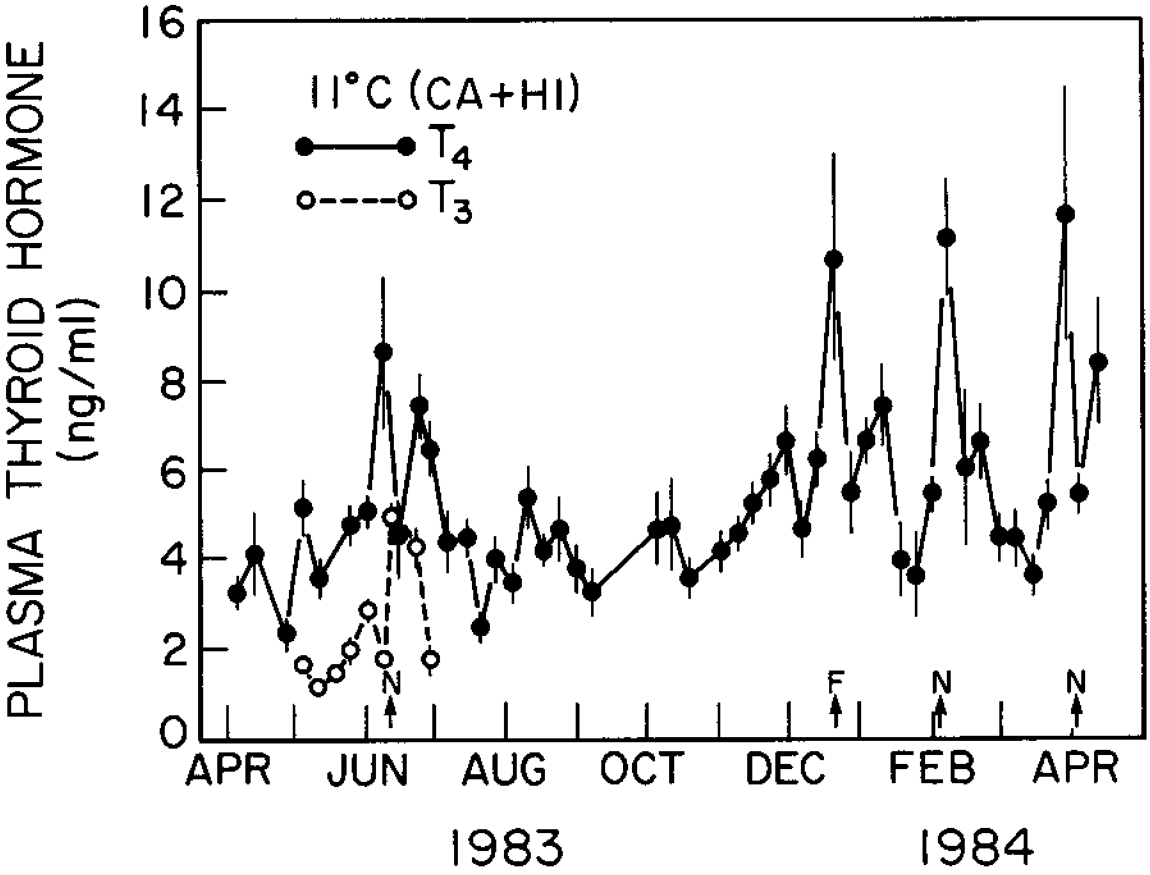

Figure 3. Variations ($x \pm$ S.E.) in plasma thyroid hormones (T_3 and T_4) in coho salmon held at 11°C. (CA + HI) refers to the combining of values from fish maintained under California and Hawaii photoperiod regimes at the Natural Energy Laboratory of Hawaii, Keahole Point, Hawaii. (Copied with

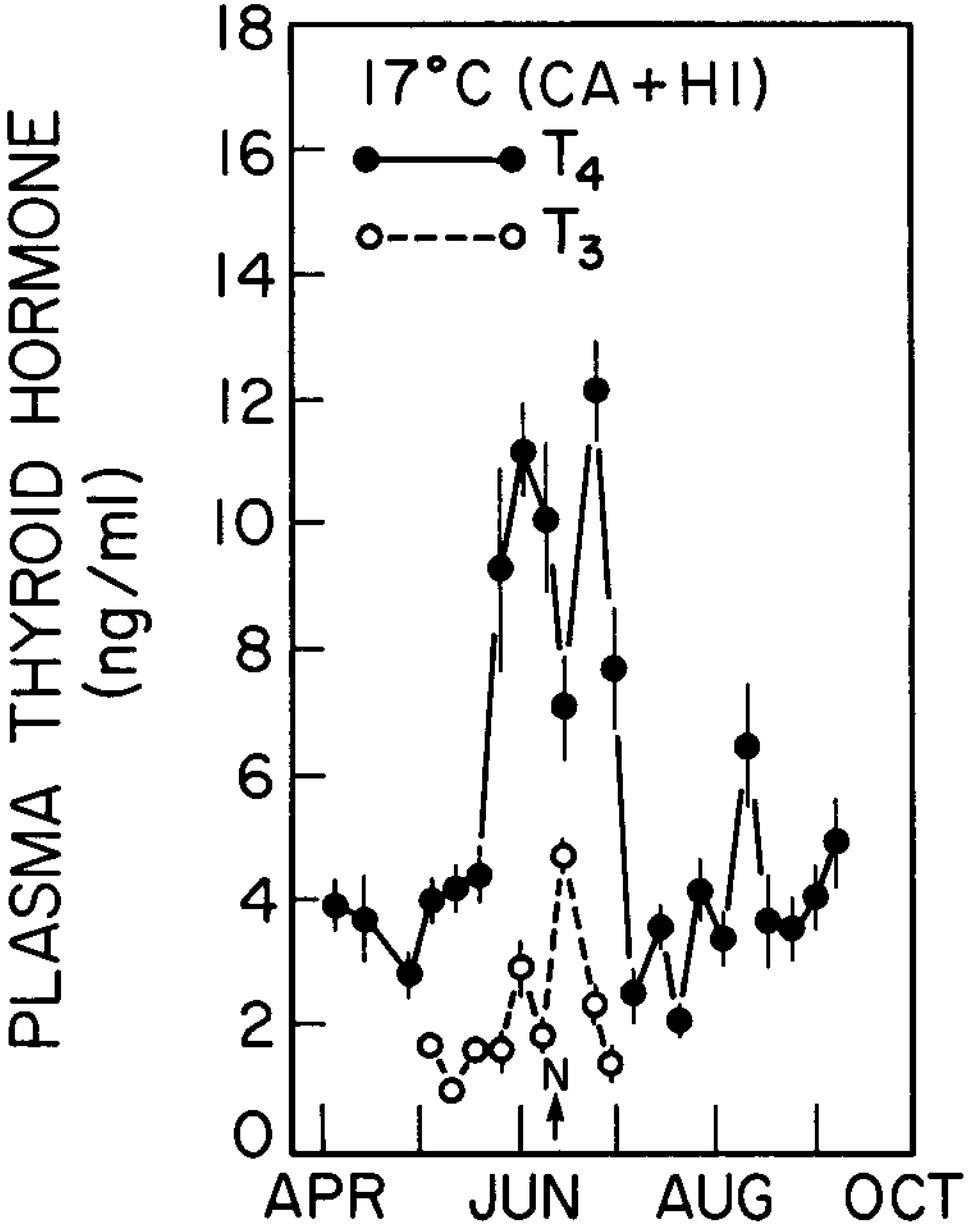

Figure 4. Variations (x ± S.E.) in plasma thyroid hormones (T_3 and T_4) in coho salmon held at 17°C. (CA + HI) refers to the combining of values from fish maintained under California and Hawaii photoperiod regimes at the Natural Energy Laboratory of Hawaii, Keahole Point, Hawaii. (Copied with permission from Grau et al., 1985b)

ACKNOWLEDGMENTS

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GROWTH OF COHO AND CHINOOK SALMON IN AN EXPERIMENTAL OTEC SYSTEM

David K. Barclay
Arlo W. Fast
Steven A. Katase

INTRODUCTION AND BACKGROUND

One of the major research goals of our aquaculture efforts at the Natural Energy Laboratory of Hawaii (NELH) during 1982–84 was to assess the culturability of salmonid fishes under simulated ocean thermal energy conversion (OTEC) conditions. This assessment included many facets, all of which impact the final determinations of whether salmonid culture is technically and economically feasible. This paper focuses on coho and chinook salmon growth, survival, and feed conversion in both freshwater and seawater.

Some of the first salmonid experiments attempted at NELH were growouts of coho salmon (*Oncorhynchus kisutch*). The coho salmon tests were started during March 1982, with fish reared at the Hawaii Institute of Marine Biology (HIMB) on Coconut Island, Oahu. These fish were reared in recirculating freshwater using a large, water refrigeration system, biofilters, heat exchangers, and a growout tank with a total water volume of 10,000 liters (2,600 gal). They were flown from HIMB to the Natural Energy Laboratory of Hawaii and introduced directly into cold seawater from the OTEC deepwater pipe. They had high mortalities owing to the handling and shipping stresses and to osmoregulation problems which we now know are related to physiological conditions and proper timing of seawater entry (Grau et al., 1985).

Our subsequent growout experiments, which we present here, were conducted from March 1983 through October 1984. Tests were conducted with both coho salmon and chinook salmon (*O. tshawytscha*). The coho salmon were involved in the smoltification tests reported by Grau et al. (1985), but the chinook salmon were not. The heavy metal content of both coho and chinook salmon used in the growout tests was evaluated by Fast, D'Itri, Barclay, Katase, and Madenjian (see paper in this publication).

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MATERIALS AND METHODS

Eyed eggs were air shipped to NELH from the California Department of Fish & Game's Iron Gate Hatchery, which is located near Redding, California. Coho and chinook salmon eggs hatched at NELH during January 1983 were used to produce fish for the seawater growouts experiments during 1984. Coho salmon eggs hatched at NELH during January 1984 were used to produce fish for the freshwater growouts experiments during 1984. All eggs were incubated in a standard, Heath-Techna, fiberglass egg incubator, using recirculated, chilled water as described by Katase et al. Incubation techniques for salmonids eggs are identical for trout eggs.

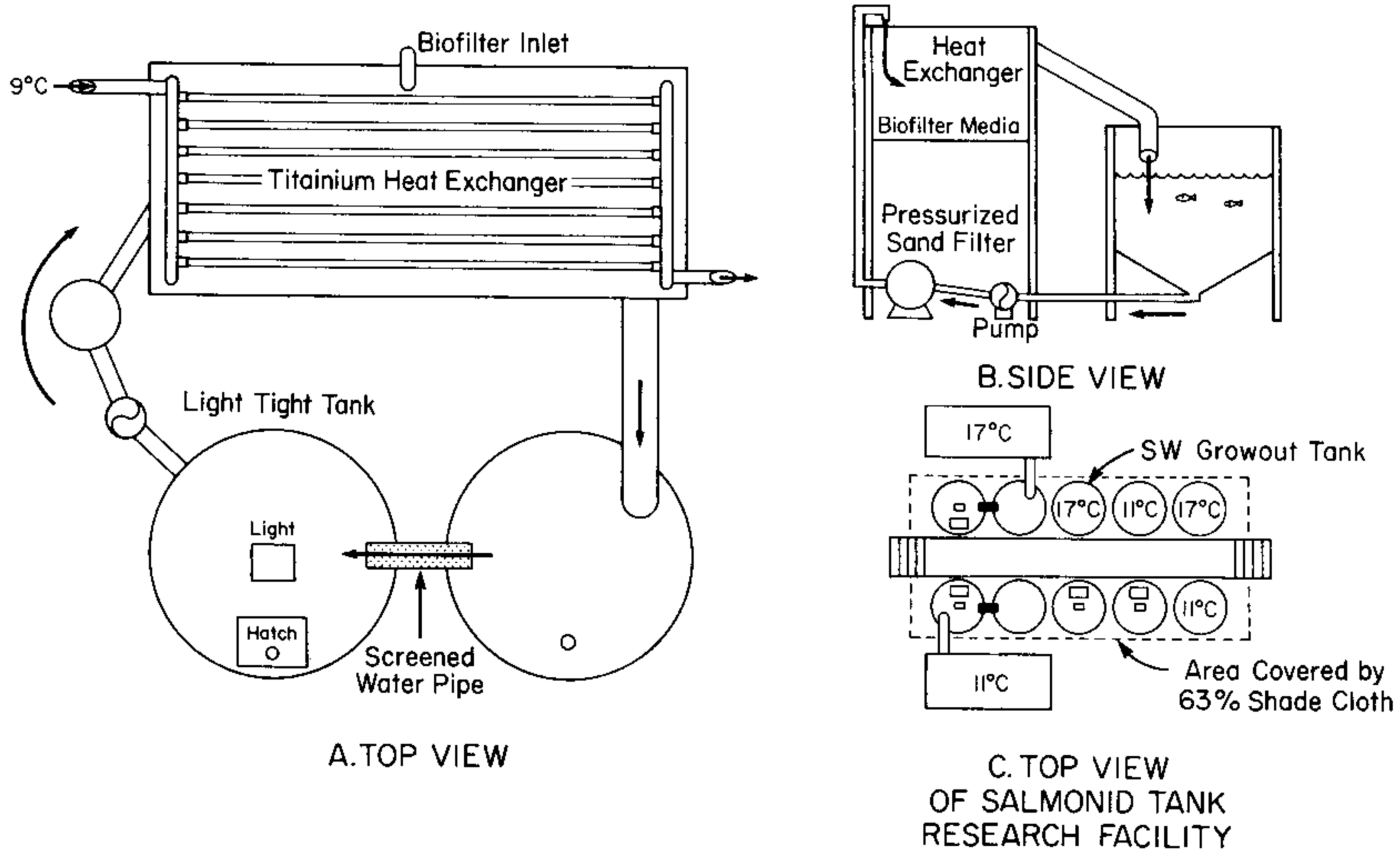
When the fry had almost completely absorbed their yolk-sac, they were moved from the incubator into two freshwater recirculating systems. Each system consisted of two interconnected, 1.2-m diameter fiberglass tanks; a 2,000-liter rectangular biofilter; a pressurized filtration system consisting of a 3/4-HP water pump and fiberglass sand filter; and a heat exchange system in the biofilter (Figure 1). Each tank, with a volume of 2,000 liters, was foam-insulated and had a cone bottom. Biofilter media consisted of 5.0 cm x 7.5 cm polyethylene coke rings which filled the entire biofilter. The pressurized filtration system was used to pump water from the cone-bottomed growout tank through the sand filter into the biofilter. Water then flowed by gravity from the biofilter back to the growout tank.

The heat exchange was constructed using 2.5 cm diameter x 3 m long, thin-walled titanium tubing and was used to chill the freshwater. By controlling the flow of deep OTEC water having a temperature of 9°C through the titanium tubing, the freshwater temperature in the culture system was regulated. One freshwater recirculation system was maintained at 11°C, the other at 17°C. In the case of the latter system, a solenoid valve was integrated with a thermostat and a relay to maintain the temperature within a range of ± 0.05°C. The temperature in the 11°C recirculation system was maintained with a constant flow of cold seawater through the heat exchanger. Air diffusers were installed in the biofilter and the growout tanks of both systems. Air was supplied by a 3-HP EG&G Rotron blower. The freshwater recirculation systems were siphoned daily to remove feces and uneaten feed. Biofouling was a problem in the recirculation tanks that were exposed to sunlight. Screens in these tanks had to be cleaned frequently to maintain adequate water flow rates.

The total water volume recirculated with each freshwater system was 150 l/min. This included a continuous inflow of 680 l/h of new freshwater.

Photoperiod was controlled in one tank of each system with a light tight lid and a 150-watt flood lamp attached to a timer. The other tank of each system was covered with netting but was otherwise open to ambient light conditions.

The seawater growout tanks were identical to the fiberglass cone-bottomed tanks used with the freshwater recirculation systems. The test area, including the 10 fiberglass tanks, was covered with a 63% shade cloth suspended by a wooden frame (Figures 1 and 2). This prevented the fish from getting sunburnt, helped maintain temperatures in recirculation systems, and reduced biofouling in all open tanks. The seawater growout tanks were supplied with inlets of both warm surface seawater and cold deep seawater to allow for temperature regulation in the tanks by mixing of the two source waters.



A.TOP VIEW

B.SIDE VIEW

C.TOP VIEW
OF SALMONID TANK
RESEARCH FACILITY

Figure 1. Freshwater recirculation system used to rear coho and chinook salmon from sac-fry to smolts at NELH, Keahole Point, Hawaii. (A) Top view of one of the recirculating systems showing the two circular growout tanks, biofilter, and titanium heat exchanger in the biofilter. (B) Side view of one of the recirculating systems showing the circular, cone-bottomed growout tank, water pump, pressurized sand filter, and biofilter. (C) Top view of salmonid tank research facility showing the 10 test tanks: 4 are used for freshwater recirculation, another 4 for seawater flow-through growout, and 2 for photoperiod-induced maturation and reproduction.

Figure 2. Experimental OTEC aquaculture facilities at NELH. The round fiberglass tanks on the lower left, covered overhead with shade cloth, were used for salmon and trout experiments. The rectangular tanks to the right of the fish tanks were used for nori tumble culture. The surface and deep seawater pipes on the left lead from the ocean between the lighthouse and the top of the fish tanks to the header tanks on the upper right.

One of the prominent chemical characteristics of deep OTEC water was a low dissolved oxygen content, averaging 1.5 mg/l ± 0.5 mg/l (Mencher et al., 1983). Because of this condition, both warm seawater and cold seawater flowed through a packed column before entering the growout tanks. The packed columns were constructed of 15-cm diameter PVC pipe, 100 cm long, with a 90° elbow at the base (Figure 3). These were similar to those described in Owsley (1981). Each column was filled with 2.5-cm diameter coke rings and was suspended over the top of the tank such that the water flowed out of the elbow in a counter-clockwise direction into the tank. This created a circular current to which the fish could orient. The packed columns also facilitated a thorough mixing of the warm and cold water.

An outer double standpipe was used in the seawater growout tanks. The outer standpipe was constructed of 15-cm diameter PVC pipe. The bottom was fitted with an adjustable leg which could be used to make a small gap (about 2.5 cm) between it and the bottom of the tank. Effluent water would then flow from the bottom of the tank between the outer and the inner standpipes during discharge. The design was effective in removing feces and uneaten feed continually in the flow-through treatments. Nylon netting with 6-mm mesh was placed over all tanks, except the photoperiod control tanks, to prevent the fish from jumping out and potential predators from catching the fish.

Swim-up-fry were initially fed a semi-moist starter ration sold by Bioproducts Inc. For the remainder of the growout period, a commercially produced salmon feed manufactured by Ranger Inc. was used. Generally, fry were fed the semi-moist feed for a period of 2 weeks after which time they were switched to dry #2 crumble. Feed size was increased until the fish were able to eat a 3/16-inch pellet. Swim-up-fry were fed 6% of their weight per day. This amount was gradually decreased to approximately 3% per day growout. In the final months of growout, a pellet containing canthaxanthin was used. It has been shown that canthaxanthin adds a red color, considered to be desirable for consumer acceptance, to the flesh of cultured salmonids.

Demand feeders such as those described in Statler (1982) were used in the seawater growout tanks (Figure 3). The feeder consists of a cone-bottomed container and a steel rod. The container is positioned above the tank. A steel rod, which acts as a lever, extends down through a hole at the bottom of the feed container and into the tank. When the lever is moved, a small portion of feed drops into the tank. The fish quickly learn to tap the lever and thereby feed themselves on demand.

Coho salmon hatched during January 1983 were released into seawater tanks of the same temperature as their respective freshwater tanks on June 24, July 29, and August 24, 1983. The fish were released on different dates in order to assess their seawater readiness and subsequent survival as a part of the concurrent smoltification assessments (Grau et al. 1985). Chinook salmon were released into seawater tanks on August 3, 1983. Both coho and chinook salmon were held in seawater tanks until the start of the growout experiments in January 1984.

For the chinook salmon seawater growout experiments, 429 fish were stocked in each of two tanks. For the coho salmon seawater treatments, 235 fish were stocked in each of two tanks. Flow rates for different stocking densities were based on the equation developed by Westers (1970):

$$\text{lb/gpm} = \frac{\text{lb/cu ft}}{R} \times 8$$

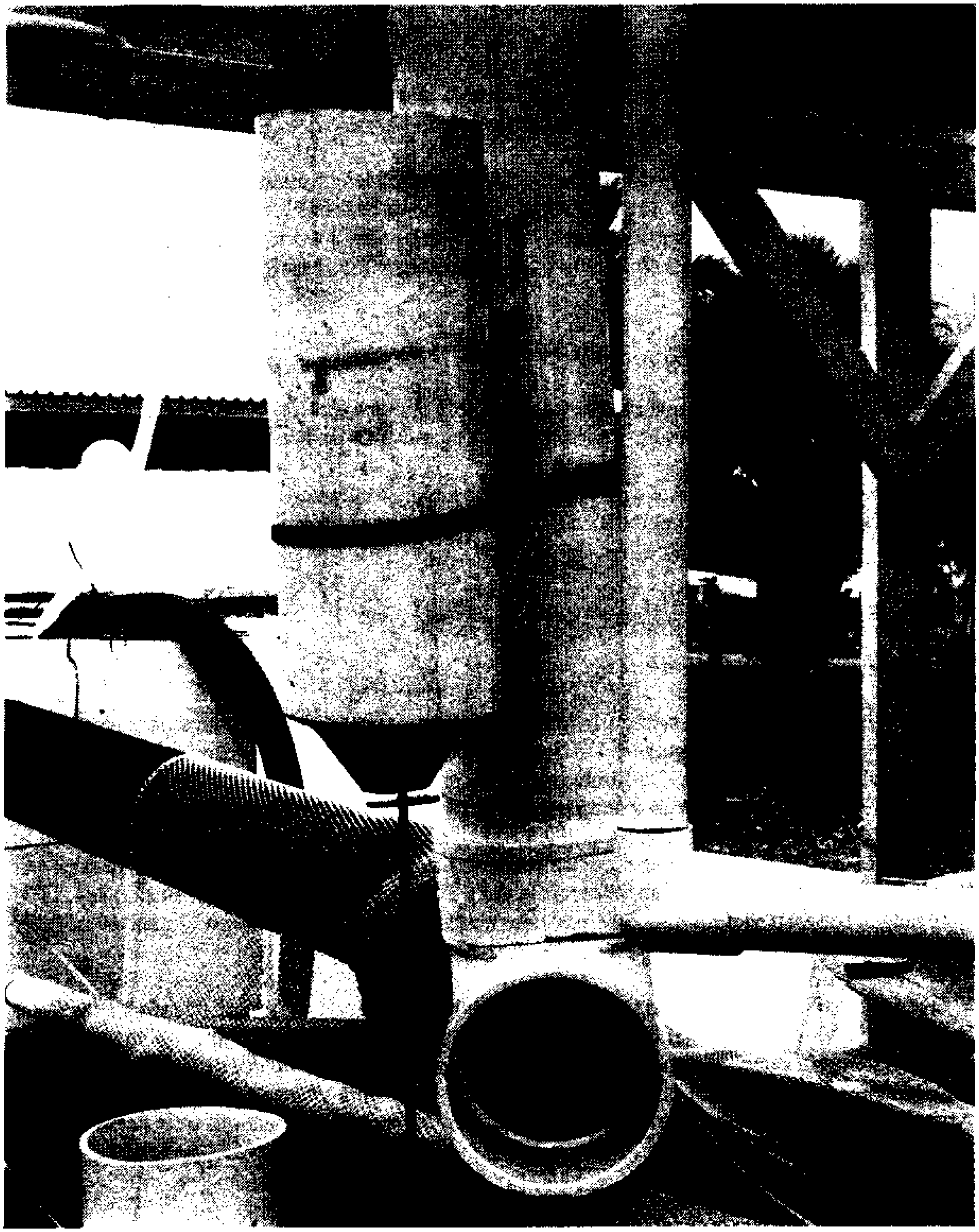


Figure 3. Demand feeder and packed column used in the salmon growout experiments at NELH. The feeder is attached to the packed column with a black plastic band. The packed column (not in operation) blended the warm and cold seawaters and increased the dissolved oxygen content to near 100% saturation.

where R represents the number of exchanges per hour and the constant 8 represents a conversion factor equating gallons per minute to cubic feet per hour.

Fish in the seawater systems were measured for weight and length every 2 months. This sampling interval was modified in certain instances when we felt that the health of the fish would be jeopardized by sampling. Fish in the freshwater systems were measured every 2 weeks for weight only. MS-222, an anesthetic, at a dosage of 50 mg/1, was used on the larger seawater fish before weighing.

OVERALL EXPERIMENTAL DESIGN

In freshwater, a 2x2 factorial design was used for coho salmon. The factors were temperature (11°C and 17°C) and photoperiod (California at 40°N and ambient Hawaii at 20°N).

In seawater, a 2x2 factorial design was used. The factors were temperature (11°C and 17°C) and fish species (coho salmon and chinook salmon). Photoperiod was ambient Hawaii.

RESULTS

Coho Salmon Growout in Freshwater

The growth rate of coho salmon reared at 17°C was significantly greater than that at 11°C, regardless of photoperiod (Figures 4 and 5). During mid-June 1984, coho salmon reared at 11°C averaged about 11 g on either California or Hawaii photoperiods. At the same time, coho salmon reared at 17°C averaged about 25 g and 20 g, respectively, on California and Hawaii photoperiods.

By late August 1984, coho salmon had increased substantially in size, although fish reared at 17°C were significantly larger than those reared at 11°C (Figures 4 and 5). By August 22, 1984, 11°C coho ranged between 39 g and 42 g, whereas those reared at 17°C ranged between 57 g and 69 g (Table 1).

At 17°C, coho salmon grown under the California photoperiod were significantly larger for at least part of the growout period from May 1 through August 22, 1983. The same holds true, but to a lesser extent, for coho salmon reared at 11°C. It is not clear whether these differences are due to actual photoperiod differences or the fact that the California photoperiod tanks had covers. Associated with the covers are reduced light intensities and reduced distractions from personnel and other movements near the tanks.

Survival for all fish was excellent (greater than 95%) for all treatments.

Coho salmon feed conversion ratios (FCR) for all freshwater treatments were excellent. Fish reared at 17°C had a mean FCR of 1.14:1 (dry food fed:live weight gain of fish) for the study period. Fish reared at 11°C had an FCR of 1.5:1.

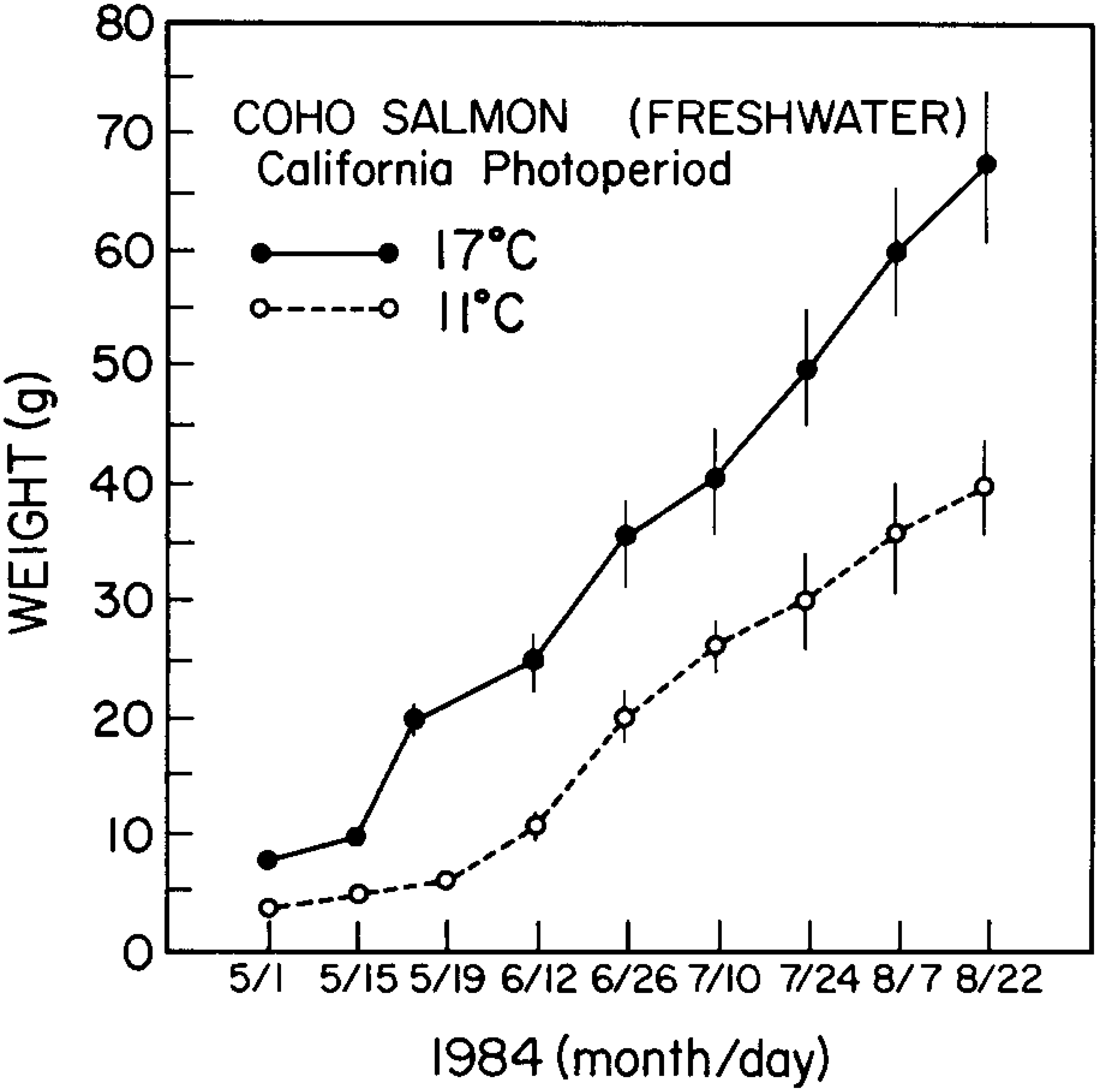


Figure 4. Growth rates of coho salmon reared at NELH in freshwater and under California photoperiod at 11°C and 17°C. The mean size and 95% confidence interval are shown for each sampling.

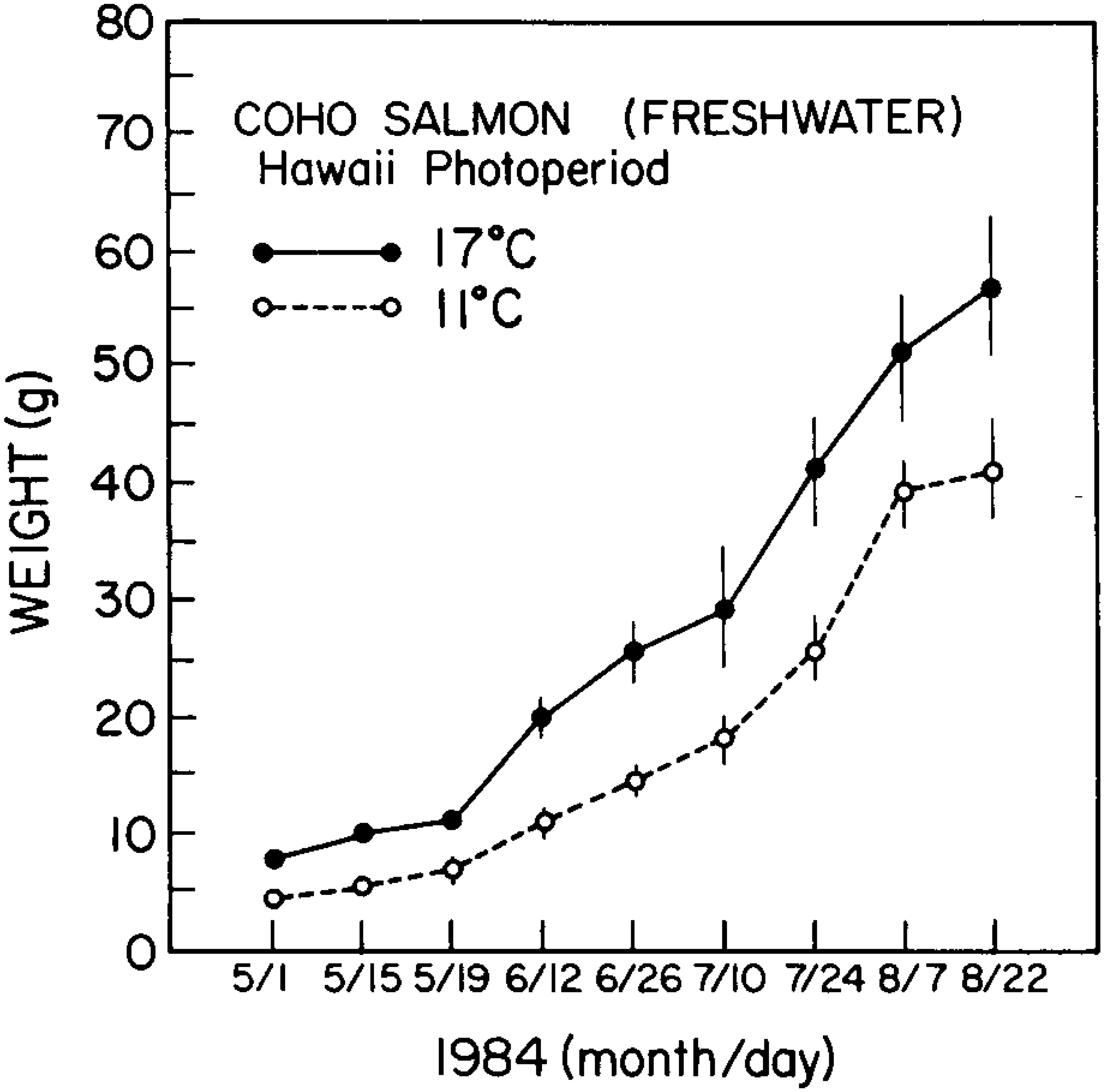


Figure 5. Growth rates of coho salmon reared at NELH in freshwater and under ambient Hawaiian photoperiod at 11°C and 17°C. The mean size and 95% confidence interval are shown for each sampling.

TABLE 1. MEAN WEIGHT, NUMBER MEASURED, AND STANDARD DEVIATION ON AUGUST 22, 1984, OF COHO SALMON REARED IN FRESHWATER AT NELH. THE SALMON WERE HATCHED IN JANUARY 1984 AND REARED AT TWO TEMPERATURES AND UNDER TWO PHOTOPERIODS.

	California Photoperiod		Hawaii Photoperiod	
	11°C	17°C	11°C	17°C
Mean Weight (g)	39.4	69.2	41.7	57.4
Number Measured	54	54	54	47
Standard Deviation	14.1	22.1	13.1	21.9

Coho and Chinook Salmon Growout in Seawater

Between February and December 1984, coho salmon mean weight increased from 110 g to more than 300 g (Figure 6, Table 2). There was no significant difference in mean weight between coho salmon reared at 11°C and 17°C during any of the growout periods. The average length of these fish was 303 mm in December 1984.

Between February and December 1984, chinook salmon mean weight increased from 90 g to more than 300 g (Figure 7, Table 2). As with coho salmon, there was no significant difference in mean weight between chinook salmon reared at 11°C and 17°C during any of the growout periods.

Not only were there no significant differences between average weight of fish reared at either temperature for either species, but there were also no significant differences between species. The variability in body weight was, however, much greater for coho salmon, especially after August 1984 (Figures 6 and 7).

The variability in size is reflected in the weight distributions of coho and chinook salmon during December 1984. Coho salmon weights ranged from 171 g to 920 g and their lengths ranged from 225 to 434 mm (Table 2). Chinook salmon weights were less variable, but they still had a large range from 152 g to 670 g (Table 2). Their lengths ranged from 215 mm to 357 mm. The final weight distribution for chinook salmon had 65% of the fish in the 250 g to 400 g range, compared with only 45% of the coho salmon for this same size range at 17°C.

Known mortalities, ranging from 22% to 65%, were high for all treatments (Table 3). Known mortalities, defined as those fish found dead in the tanks and removed daily, were greater for coho salmon than for chinook salmon and much greater for fish reared at 17°C for either species than at 11°C. Unaccounted fish defined as those missing from the tank, were especially large for chinook salmon (27%) at both temperature treatments. The most likely explanation for these losses is theft. Because of the unaccounted fish losses, we were unable to determine FCR for seawater growout.

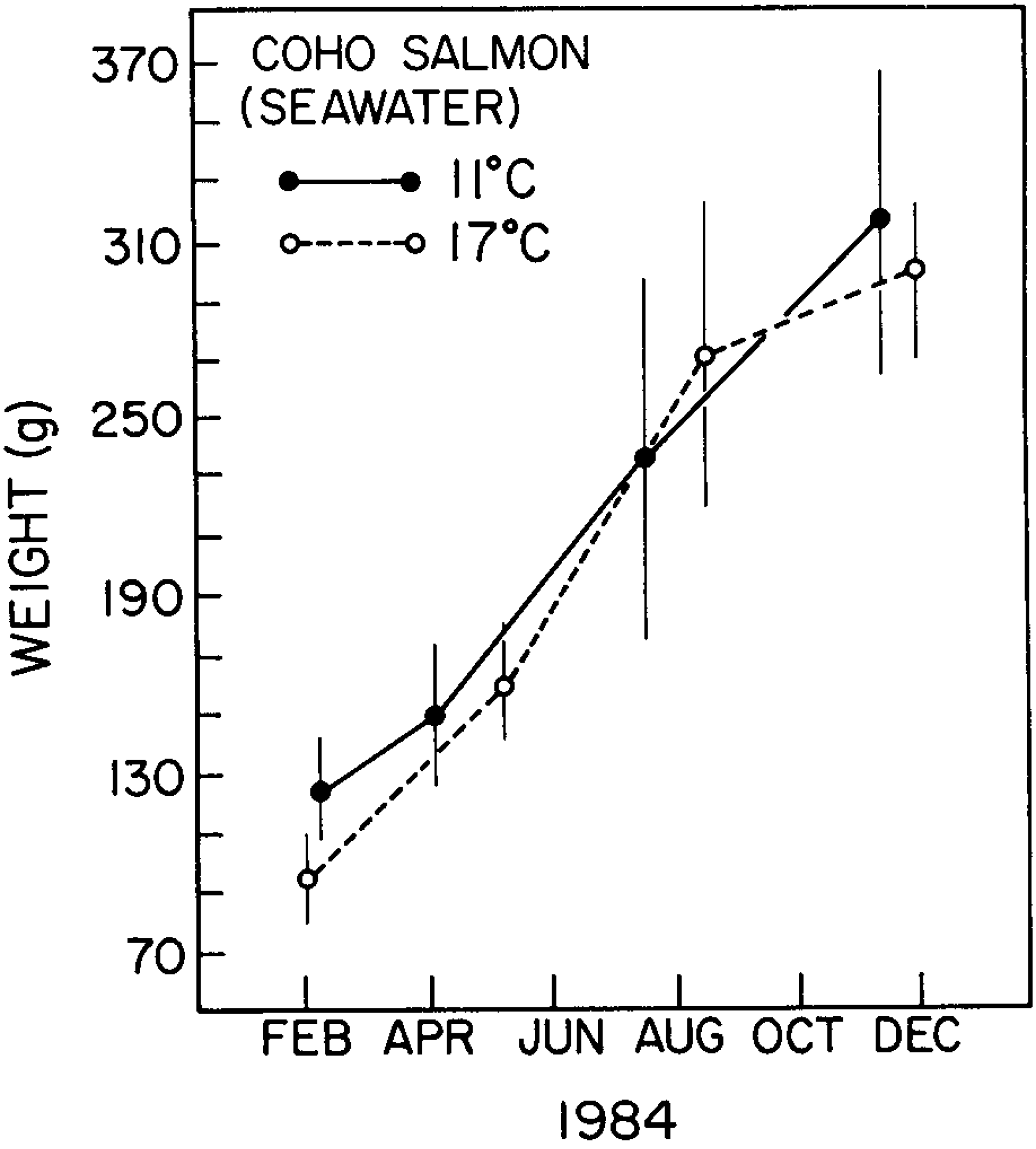


Figure 6. Growth rates of coho salmon reared at NELH in seawater and under ambient Hawaii photoperiod at 11°C and 17°C. The mean size and 95% confidence interval are shown for each sampling.

TABLE 2. MEANS, STANDARD DEVIATIONS, RANGES OF LENGTH AND WEIGHTS, AND CONDITION FACTORS OF COHO AND CHINOOK SALMON REARED AT 11°C AND 17°C. THESE ARE THE FINAL MEASUREMENT AT TERMINATION OF SEAWATER GROWOUT IN DECEMBER 1984.

	Length (mm)	Weight (g)	Condition Factor
COHO SALMON			
11°C (n = 30)			
Mean	303.9	353.3	1.230
Standard Deviation	42.8	151.5	0.261
Minimum	225.0	191	0.686
Maximum	434.0	920	2.405
17°C (n = 30)			
Mean	303.2	342.6	1.173
Standard Deviation	32.2	139.4	0.131
Minimum	256.0	171.0	0.870
Maximum	378.0	707.0	1.355
CHINOOK SALMON			
11°C (n=30)			
Mean	282.9	302.2	1.308
Standard Deviation	21.4	79.7	0.144
Minimum	245.0	175.0	1.007
Maximum	325.0	495.0	1.763
17°C(n = 30)			
Mean	284.6	336.5	1.460
Standard Deviation	29.8	111.0	0.522
Minimum	215.0	152.0	1.082
Maximum	357.0	670.0	4.105

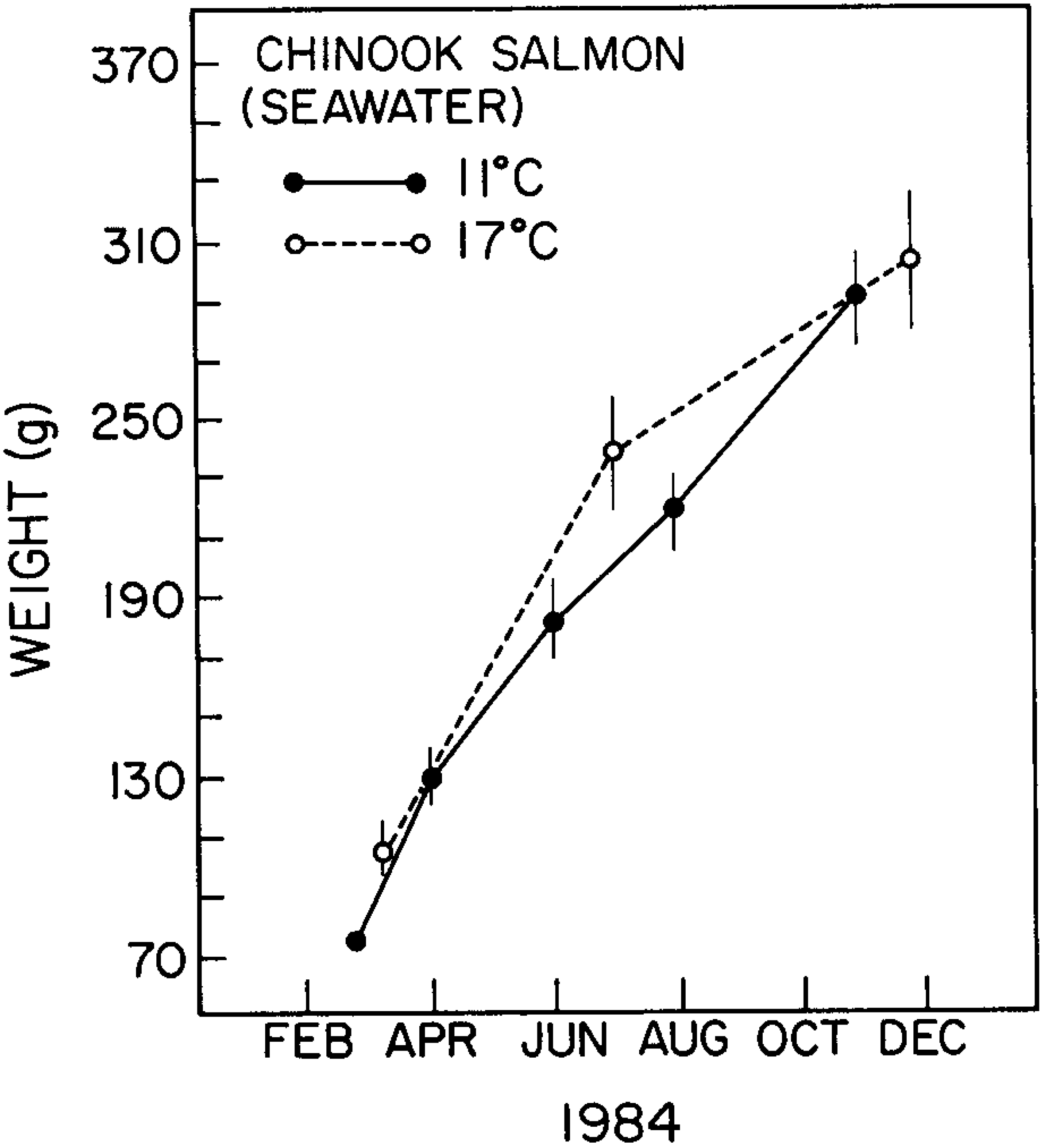


Figure 7. Growth rates of chinook salmon reared at NELH in seawater and under ambient Hawaii photoperiod at 11°C and 17°C. The mean size and 95% confidence interval are shown for each sampling.

TABLE 3. TALLIES DURING DECEMBER 1984 FOR COHO AND CHINOOK SALMON REARED IN SEAWATER AT NELH. THE NUMBERS OF FISH STOCKED, HARVESTED, FOUND DEAD, AND UNACCOUNTED FOR ARE SHOWN.

Treatment	No. Stocked	No. Harvested	Known Mortality	Unaccounted
CHINOOK SALMON				
11°C	429	219	94 (22%)	116
17°C	429	101	212 (49%)	116
COHO SALMON				
11°C	235	116	77 (33%)	42
17°C	235	70	154 (65%)	11

DISCUSSION

The growth of coho salmon in freshwater at NELH was substantially greater than the growth of fish spawned and reared concurrently at the Iron Gate Hatchery. By June 1984, the mean weight of our coho salmon ranged from 8 g to 25 g, depending on temperature and photoperiod treatments (Figures 4 and 5). At the same time, the mean weight of coho salmon at the Iron Gate Hatchery was less than 4 g (Figure 8). By August, the difference was even greater: coho salmon at NELH ranged in size from 25 g to 60 g; the average size at the Iron Gate Hatchery was less than 10 g.

Water temperature differences undoubtedly account for the large differences in freshwater growth between coho salmon at NELH and those at Iron Gate Hatchery, as well as between fish held at different temperatures at NELH. Size of NELH coho salmon at 11°C and 17°C were always significantly different regardless of photoperiod (Figures 4 and 5). As discussed earlier, although coho salmon reared under California photoperiod at NELH tended to grow faster, this interpretation is confounded by the effects of placing a cover on the California photoperiod tanks. Water temperatures at the Iron Gate Hatchery were lower than at NELH. The average temperatures at Iron Gate were 9°C for the period from March through June and 14°C for July and August (Figure 8).

Clarke and Shelbourn (1980) evaluated the effects of five temperatures (8°C, 11°C, 14°C, 17°C, and 18°C) on the growth of Pacific Northwest coho salmon in freshwater over a 5-month period. The initial average weight of the fish was 0.4 g., whereas average weights after 5 months were 8.5 g, 20.6 g, 33.0 g, 39.7 g, and 22.2 g, respectively. Growth at 18°C was significantly less than at 11°C, 14°C, or 17°C, which indicates that 18°C is approaching the thermal maximum for coho salmon, and that accelerated growth temperatures should be 17°C or less. We had excellent coho salmon survival rates at 17°C at NELH.

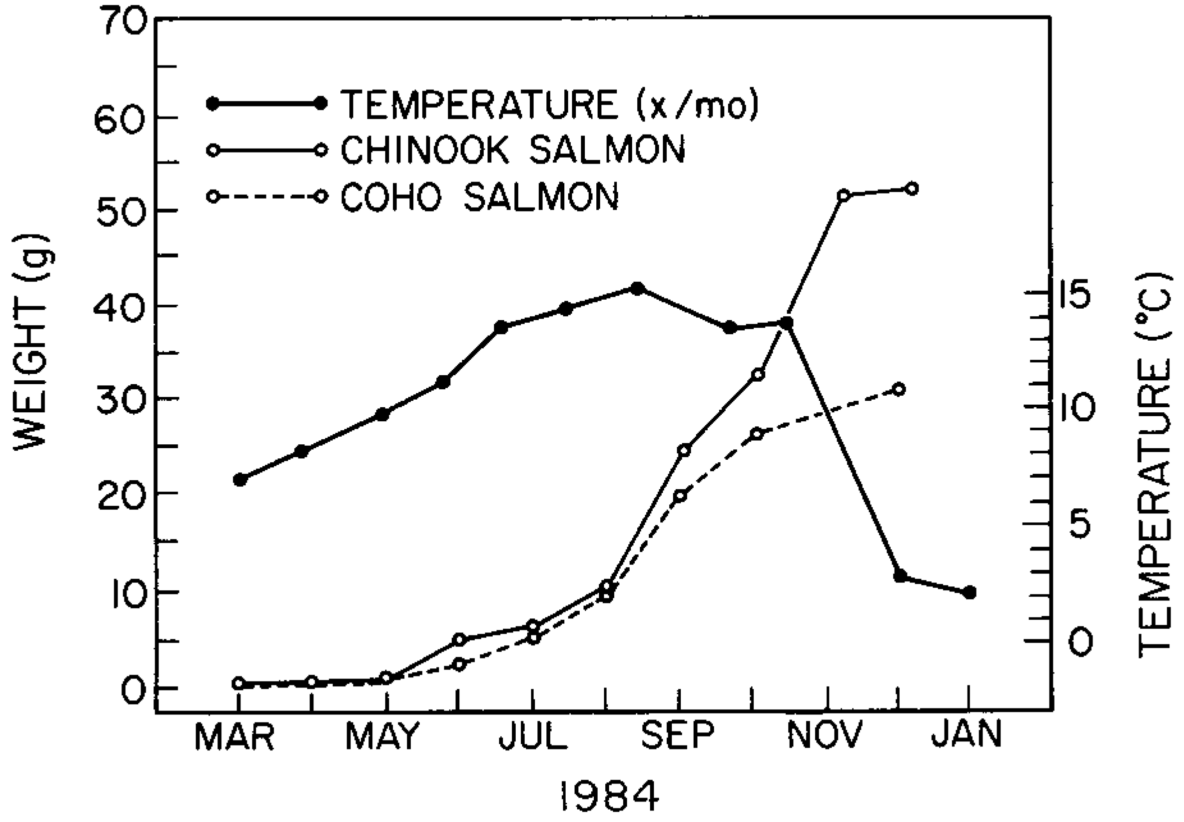


Figure 8. The average size of coho and chinook salmon at the California Department of Fish & Game's Iron Gate Hatchery (40° N) during 1983–84. Water temperature is also shown (C. A. Hiser, Iron Gate Salmon and Steelhead Hatchery Copco Star Route, Hornbrook, California, unpublished data, 1987).

Brannan et al. (1976) and Mahnken and Waknitz (1979) also clearly demonstrated that coho salmon growth and smoltification in freshwater can be accelerated greatly by increased up to temperatures 17° C to 18°C. Coho salmon reared at ambient mean temperatures of less than 10°C took 12 to 13 months to reach smolt size of 15 g to 20 g, whereas those reared at 12°C to 15°C reached this size and smolted during May and June at 0-age. We also confirmed that fish reared at constant temperatures of 11°C and 17°C at NELH would smoltify during 0-age and were ready for seawater entry (Grau et al., 1985). Although NELH coho salmon reared at 11°C were much smaller than those reared at 17°C, both groups performed about equally well upon saltwater entry.

CONCLUSIONS AND RECOMMENDATIONS

The conclusion from our work at NELH on coho salmon smoltification and from the work by others on this subject, then, is that we can safely accelerate the growth of underyearling fish and that we can effectively transfer them to seawater within 6 to 7 months of hatching. This finding is important for OTEC-related culture of salmonids since in most cases the freshwater phase of growout is the most costly and troublesome. Seawater entry within 6 to 7 months of hatching can improve the economics of salmon growout in OTEC culture systems.

The growth of coho salmon in freshwater is greatly affected by temperature, but the growth of both coho and chinook salmon in seawater at NELH was not significantly different at 11°C or 17°C (Figures 6 and 7). We were surprised by this finding, although Mahnken and Waknitz (1979) found that specific growth of coho was influenced much more by size than by temperature over a range from 7°C to 14°C. We had nevertheless expected to see growth differences related to temperature. What we found instead was substantial differences in survival rates at 11°C and 17°C. Average known mortality for both coho and chinook salmon was 28% at 11°C and 57% at 17°C (Table 2). Coho salmon had greater known mortalities at both temperatures than did chinook salmon.

Elevated temperatures, especially above 11°C, can cause serious disease problems in both coho and chinook salmon (Fryer and Pilcher, 1974; Mahnken, 1975; Mahnken and Waknitz, 1979). The most common, temperature-related pathogens are *Vibrio* and furunculosis (*Aeromonas salmonicidia*). We had expected less disease problems at elevated temperatures at NELH because of the low microbial population densities in both surface and deep waters. Serious disease problems occurred, however, especially with *Vibrio* (James Brock, 1984: personal communications).

Compounding the disease problems caused by elevated temperatures were stress factors. We believe that the small tank size at NELH, the frequent movements of people around the tanks, and our handling of the fish — all contributed to stress, which clearly can be a major cause of disease development. Stress should be minimized in any OTEC growout facility.

Stress can be minimized by using large tanks or raceways and by using covered tanks. Our covered tanks at NELH had no biofouling by macrophytic algae. Tanks exposed to the filtered sunlight had significant algal growth on the sides of the tank and the inlet and outlet screens. The fish in the photoperiod tanks had much less visual contact with people and objects outside the tank. These may be important considerations in the design of an OTEC salmon facility.

Regardless of the cause, salmon mortalities of greater than 20% in seawater growout are unacceptable for commercialization. We believe that mortality can be reduced to less than 20%, but further experiments must be made to confirm this.

The growth rates of coho and chinook salmon at NELH were less than expected. Pen growout of coho salmon in Puget Sound, Washington, showed that these fish can grow from 15 g to 340 g within 6 to 8 months at water temperatures between 7°C and 14°C (Mahnken, 1975; Mahnken and Waknitz, 1979). With excess rations, coho salmon typically grow to 325 g within 11 months. Our fish at NELH grew from about 100 g to 300 g in 11 months (Figures 6 and 7). The slower growth of our coho and chinook salmon, together with their high mortalities, indicates that their seawater growth rates were below optimum owing to the stress factors discussed above. We believe that once stress is reduced, growth will increase and exceed that found in normal temperate and cold climates.

This discussion would not be complete without some mention of special problems associated with OTEC culture of salmonids. Interruptions with the cold seawater supply resulted in fish mortality both directly and indirectly. We found through experience that the temperature rise in our seawater growout tanks was 1°C/h with waterflow interruption. Assuming backup aeration was utilized, a tank of salmon held at 15°C could survive with little or no stress and mortality for several hours. During extended periods of coldwater interruption, either part or all of the fish would die. Fish that did survive were prone to disease, primarily *Vibrio*. Fortunately, the pump failures that occurred during the seawater growouts here were short in duration. We did have an outbreak of *Vibrio* in the 17°C seawater treatment which we believe was caused by an interruption of cold seawater at the start of the experiment. We also found that the handling of the fish and resultant scale loss was a primary cause of disease throughout our work with salmonids at NELH. In addition to the use of antibiotics, we found that lowering the temperature in the infected tank helped control the disease. Temperature regulation at an OTEC salmon farm is a major benefit with regard to both growth and disease control.

In summary, our research at NELH clearly demonstrated that salmon culture at OTEC power plants is technically feasible. There are several culture items that need improvement. We are confident that these can be improved to provide equal or better performance of the fish relative to salmonids cultured elsewhere.

ACKNOWLEDGMENTS

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INDUCED MATURATION, OVULATION, AND SPAWNING OF RAINBOW TROUT, *Salmo gairdneri*, IN AN OTEC SEAWATER SYSTEM

Steven A. Katase
Arlo W. Fast
David K. Barclay

INTRODUCTION

Most ocean thermal energy conversion (OTEC) power plants will be or are located in tropical areas in order to achieve the greatest temperature differences between surface and deep waters. Coldwater fishes, such as trout and salmon, do not normally live in tropical areas. The main exceptions are trout which have been stocked as exotics in high mountain streams of some tropical countries. These exceptions may not have much relevance for the culture of coldwater salmonids at OTEC plants. This leaves us with the problem of sourcing salmonid eggs or smolts for growout at OTEC plants.

The problem of sourcing salmonid eggs for an OTEC-associated culture system has two likely solutions. First, eggs may be shipped to the OTEC site where they can be hatched and the fish reared to smolt size in freshwater before transfer to seawater for growout. Present sources of eggs are from wild or confined stocks in places where the salmonids naturally occur, such as the Pacific Northwest coast of America. Eggs from such sources are usually available in quantities at a reasonable price and can be easily air shipped to almost any place in the world. One potential problem with this type of egg sourcing is the importation of disease, which could contaminate the OTEC culture facility and cause economic losses. As for the second likely solution, eggs may be produced on-site from broodstock fish reared and matured in seawater. This solution would most likely avoid the disease problem, although the cost of egg production might be greater since it would mean maintaining fish through a closed life cycle.

The primary motivation for our study was the consideration of using an OTEC site for an egg production facility which could supply high-quality, disease-free salmonid eggs. Because of the low pathogen level in the OTEC deep water, it may be possible to maintain disease-free broodstocks and to produce disease-free eggs. This can not be done with marine stocks of salmonids although it is possible for freshwater strains where the hatchery is located on a disease-free water source, such as a spring or well. A deep-water OTEC pipeline is the marine equivalent of a freshwater spring or well.

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However, the possibility of establishing such an egg production facility at an OTEC site is contingent on several factors. Among these factors are being able to mature, spawn, and produce viable eggs in seawater.

Another advantage of establishing an OTEC egg production facility is that through temperature and photoperiod manipulations, salmonid stocks could be made to spawn during any month of the year. Although photoperiod is routinely used at commercial trout egg production facilities, such facilities are not able to easily manipulate temperature. An OTEC facility can conviently do both.

We knew of no one who had reared, matured, and spawned salmonids in seawater under natural or similated OTEC conditions. The questions were whether this could be done technically and whether such a process would make economic sense. We address only the first question in our present study.

Photoperiod and temperature ques are principal factors affecting salmonid reproductive cycles. These two ques have been manipulated to induce or retard the maturation and ovulation process in a variety of salmonid species. Since then, many other researchers have worked on this aspect of reproductive control, including Bromage et al. (1984), Henderson (1982), Kunesh et al. (1974), Carlson (1971), and Nomura (1962). Most of their work was done with positive results in freshwater. At the same time, there has been little work on induced salmonid maturation and ovulation in brackishwater or seawater, and there are no publications on photoperiod-induced maturation in seawater.

The literature on salmonid maturation in brackishwater and seawater indicates that these conditions normally result in low survival of the broodstock and poor viability of the eggs. Wertheimer (1984a) found low broodstock survival and reduced gamete viability of chum salmon (*Oncorhynchus gorbuscka*) and pink salmon (*O. keta*) held in brackishwater (28–32 ppt), compared with broodstock held in freshwater. Allee (1981) observed lower broodstock survival and unacceptable egg viability in coho salmon (*O. kisutch*) which were matured in seawater at Oregon Aquafoods. Broodstock survival during seawater maturation was from 60% to 65%, and egg viability ranged from 0% to 100% with a 53% mean. Kems (1981) reported significant prespawning mortalities in pink salmon during seawater maturation. Mortality increased as maturation progressed. McAuley (1981) also had 77% mortality of coho salmon broodstock held in seawater, with only a 45% survival rate to the eye-up stage of the 700,000 eggs taken. Hickey (1981) spawned coho salmon matured in seawater with only 21% of the eggs surviving to hatch, ranging from 3.5% to 99%. Clarke (1981) found similar results with coho salmon matured in seawater with fertilization rate averaging 50%, ranging from 8% to 91%.

As part of our experiments, we evaluated the prospects of rearing fish, particularly coldwater fish such as salmon, in association with OTEC power plants. These power plants generate electricity by taking advantage of the temperature differences between surface ocean waters (25°C or higher) and deep ocean waters (4°C). Avery (1978), Hartline (1980), Craven (1981), and Daniel (see paper in this publication) describe in detail how these plants operate. In an effort to evaluate the technical feasibility of egg production at an OTEC power plant, we conducted experiments on the maturation ovulation, and spawning of rainbow trout (*Salmo gairdneri*) in seawater at the Natural Energy

Laboratory of Hawaii (NELH). At this site, we used 9°C cold seawater pumped from the 600 m depth which simulated water discharged from an operating OTEC power plant.

In addition to simply inducing reproduction, we evaluated the feasibility of inducing two spawns during one year rather than one spawn as is characteristic of rainbow trout. With species such as rainbow trout or Atlantic salmon (*S. salar*), which can spawn more than once during their lifetime, inducing more than one spawn per year could substantially increase egg production as well as provide eggs on a more uniform basis throughout the year. Both benefits could reduce egg production costs and enhance the economics of fish culture at OTEC plants.

MATERIALS AND METHODS

Broodstock rainbow trout for the induced maturation experiments were reared in Hawaii from eggs imported from Buhl, Idaho. The eggs were imported during August 1981 and reared in a freshwater spring in Hilo by Akeolea Aquatics. During December 1982, the 500 to 700 g fish were transported to NELH and acclimated to seawater (35 ppt and 10°C). The fish were kept in circular fiberglass tanks with a 1.2-m diameter, 2,000-liter volume, and 30° cone bottom. The tanks had a flow-through of about four exchanges per hour and were self-cleaning.

The chemical characteristics of this water is described by Mencher et al. (1983) and Smith and Walsh (see paper in this publication). This water has a dissolved oxygen concentration of 1.5 mg/l, which is lethal to these fish. Consequently, the deep water was run through a packed column such as those described by Owsley (1981) before being used in the fish tank.

Two of the tanks (7 and 8) described above were made opaque and fitted with timer controlled lights (150 watts). The photoperiod cycle in tank 7 simulated two calendar years condensed into one 12-month period (Figure 1). The amplitude and range of the photoperiod simulated that at Buhl, Idaho (42° N). It ranged from a maximum of 15.25 hours of light on July 21, 1983, to a minimum of 9.0 hours on October 1, 1983. The photoperiod was then held constant at 9.0 hours of light until spawning occurred and then gradually increased to 15.25 hours of light by February 1, 1984. Hours of light were again decreased to 9.0 hours by March 1, 1984, and held constant until a second spawn was obtained.

The photoperiod in tank 8 was similar to that in tank 7, except that maximum and minimum hours of light were exaggerated and light was not held constant until July 1984 (Figure 2). Starting in June 1983, hours of light were increased to 18 hours on September 1, 1983, and then gradually decrease to 3 hours in February 1984. Later in February 1984, the hours of light were abruptly increased to 18 hours, with a gradual decrease to 3 hours by July 1, 1984.

Twenty-five broodstock-sized fish were placed in each tank (Figure 3). The fish were fed Rangen salmon diet at 3% body weight. A standard growout formulation was used during the first spawning cycle; a formulation containing canthaxatin was used during the second cycle.

As the expected spawning dates approached, the fish were visually inspected once a week for ripeness with minimum handling. Thereafter, the fish were anesthetized with MS-222 and manually

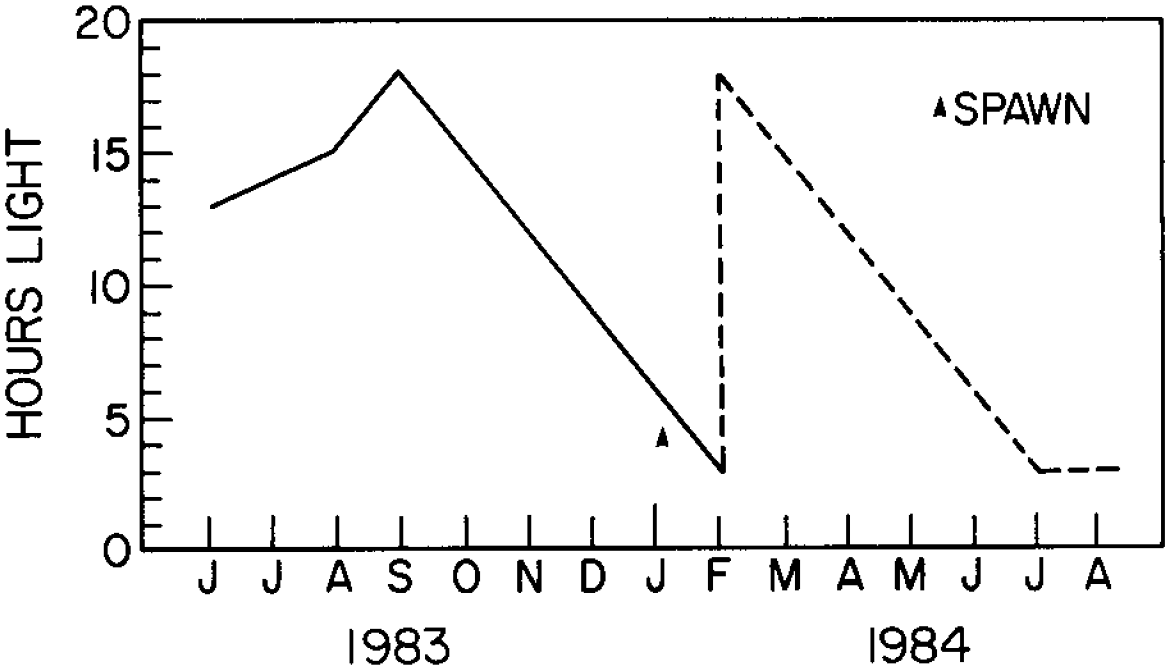

Figure 1. Photoperiod regime and times of spawning for broodstock rainbow trout held in tank 7. The hours of light per day are shown as the solid/dashed curve; the spawning times are indicated by arrows.

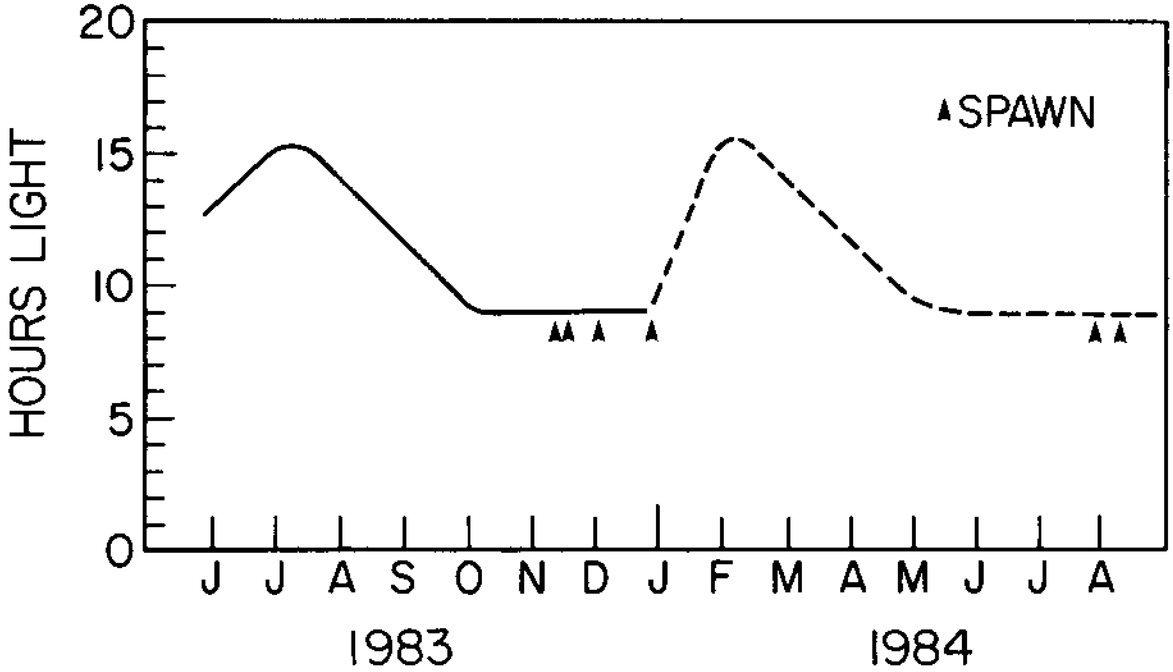

Figure 2. Photoperiod regime and times of spawning for broodstock rainbow trout held in tank 8. The hours of light per day are shown as the solid/dashed curve; the spawning time is indicated by an arrow.

Figure 3. A female broodstock rainbow trout reared in seawater and successfully matured and spawned at NELH. The fish is held by the senior author.

checked for ripeness once a week. The spawning procedures were used in an air-conditioned van to reduce heat shock. Fertilized eggs were incubated in a recirculation system which consisted of a 1,800-liter reservoir, a Heath-Techna incubator, a Frigid refrigeration unit, and a header tank. The header tank delivered water to the incubator. The water then flowed by gravity back into the reservoir where the refrigeration unit was placed. The water was pumped from the reservoir, which was insulated with 2.5-cm polystyrene foam, by a 12-volt submersible bilge pump to the hatching trays. The pump was operated off a battery with an automatic 115-volt charger, so that if the 115-volt current were interrupted, the pump would continue running for about 20 hours.

RESULTS

Tank 7

The fish reared on the less accentuated photoperiod spawned from November 17, 1983, through January 2, 1984 (Figure 1, Table 1). On the first spawn two ripe females and three ripe males produced 3,000 yellowish colored eggs. These eggs were not incubated since the incubator was not in operation at that time. On November 21, 1983, 12 fish were ripe: 8 males and 4 females. Two of the females had spawned on the earlier date. One previous spawner produced only 400 eggs (Table 1, tray 6), of which 99% survived. The eggs from the other previous spawner and one of the virgin spawners were combined in tray 5; however, the eggs from the previous spawner were not viable. This accounts for the low survival rate of 50%. The eggs from the other virgin spawner were put in tray 4; 94% survived.

On December 6, 1983, there were seven ripe females and five ripe males. The eggs in tray 1 (Table 1) came from a virgin spawner and a fish that spawned on November 21. The eggs from the two fish were noticeably different, with most of the egg mortalities coming from the previous spawner. The eggs in tray 2 were from a virgin spawner, whereas the eggs in tray 3 were from two fish, one of which had spawned on November 21. Once again, most of the egg mortalities in tray 3 came from the previous spawner.

On January 2, 1984, two females and seven males were ripe. The females had both spawned before. The eggs this time were over-ripe, and, of the 1,100 taken, none survived.

Following the first set of spawns in tank 7, the photoperiod was cycled again, and the fish were checked for ripeness starting in June 1984 (Figure 1). On July 29, 1984, two females and several ripe males were found. The females produced 4,350 and 3,493 eggs, respectively (Table 1). The eggs were a dark orange-red color and were released under little pressure. The male used to fertilize the eggs in tray 5 produced coagulated milt, which could account for the low survival rate of these eggs (32%). On August 13, 1984, four females and two males were ripe. Two of the females produced 3,916 and 4,253 reddish colored eggs each, with respective survival rates of 94% and 81%. The eggs from the other two females totaled only 1,500. The eggs were combined in tray 4; only 60% survived.

TABLE 1. INDUCED SPAWNS OF RAINBOW TROUT IN 1983 AND 1984 WITH PERCENT SURVIVAL

Date	Tray	No. Eggs	Mortality	% Eyed
Tank 7				
11/17/83	–	3,000	N/A*	N/A*
11/21/83	4	2,000	112	94
	5	2,200	1,107	50
	6	400	1	99
12/06/83	1	3,426	979	71
	2	2,973	21	99
	3	1,905	170	91
01/02/84	5	1,100	1,100	0
07/29/84	4	4,350	940	78
	5	3,493	2,381	32
08/13/84	2	3,916	217	94
	3	3,253	790	81
	4	1,500	607	60
08/19/84	5	2,788	173	94
	6	3,857	724	81
Tank 8				
01/09/84	6	1,800	721	40

*Eggs not incubated since incubator was not available

On both spawning occasions, the fish in tank 7 became ripe after the photoperiod had reached the minimum hours of light and was being held constant (Figure 1). The time from photoperiod maxima to first spawn was 4.5 months in the first case and 5.5 months in the second case. The fish took longer to ripen after the photoperiod was held constant during the second spawning period.

Tank 8

On January 9, 1984, ripe females were first detected in tank 8 (Figure 2). At that time, 3 ripe females and 15 ripe males were found. Two other females were nearly ripe. The ripe females produced only 1,800 eggs. These did not flow easily, and the survival rate was only 40% (Table 1). The fish were not checked again during this spawning period, but we believe that they would have produced more viable eggs within 7 to 10 days. They were not checked because the egg incubators were fully committed to another study at that time, and, as a result, we had no place to incubate whatever eggs may have been produced by these fish.

GENERAL FINDINGS

Before and between anticipated spawning periods, few broodstock mortalities occurred. During and following spawning, however, substantial mortalities occurred owing to the aggressive behavior of the males. The males, which comprised 65% of our population, developed classical salmonid secondary sex characteristics such as hooked jaws, arched back, and changed body form. Associated with these changes were activities which involved increased chasing, biting, and ramming. These activities caused open wounds, osmoregulatory problems, infections, and death. In all, we had a 50% broodstock mortality rate during these tests.

Males were always found ripe, even between spawning periods, whereas females were ripe only during specific times. Between spawning periods, the females reabsorbed their developed eggs.

CONCLUSIONS AND RECOMMENDATIONS

It is clearly possible to mature and spawn rainbow trout twice a year in a seawater system using photoperiod control. Although we observed an average 75% viability of eggs, this may be increased to more than 90%. The lower survival rate in our case was due to our inexperience with spawning these fish. Most often we took the eggs at non-optimum times. Eggs taken too soon or too late gave reduced survival. Repeated spawning of the same fish during a given spawning period also produced lower survival rates during the subsequent spawns.

Survival of eggs produced from fish matured in seawater could be improved by using techniques detecting the stage of ripeness based on the external morphology of the fish. Additionally, cannulation to determine egg quality, followed by hormone injections, could improve stripping success and egg viability and synchronize the spawning. Synchronized spawning would greatly simplify cohort rearing.

The fish in tank 7, which were raised on a less abrupt photoperiod cycle, gave far better spawning success. We feel that this success was only partly due to the photoperiod form. During the first spawning period (January 1984), we believe that we would have observed good spawning results in tank 8 had we been more diligent in following maturation and in stripping the eggs as they matured. Since we were not, most of the fish in tank 8 were forced to reabsorb their eggs during the second photoperiod cycle. By contrast, the fish in tank 7 had all spawned, some more than once. Consequently, we believe that the lack of rematuration success in tank 8 during the second spawning period was due mostly to our handling of the broodstock and not necessarily to the photoperiod differences between the two tanks. Unfortunately, we were not able to fully assess the relative effects of the two different photoperiods of maturation and spawning.

A 2:1 male to female ratio is undesirable owing to the aggressive actions of the males. Perhaps the ratio should be reversed. We are also uncertain what would be an optimum density (#/m^2) for broodfish. We believe that density, tank configuration, lighting, tank color, and other factors could all affect aggressive behavior and, thus, the survival of the broodstock.

Inclusion of canthaxantin in the diet changed the egg color from yellow to orange-red, and it may have improved egg viability. In any event, both the Rangen growout and maturation diets were adequate for broodstock maturation.

Broodstock maturation and spawning of rainbow trout at operating OTEC plants are clearly possible technically. However, the availability of eggs and their cost from outside sources will determine whether it is more economically viable to produce eggs at an OTEC plant or to import the eggs. We have not determined the cost to produce eggs at the plant since this involves many unknowns, including the number of eggs needed and the specifics of the OTEC plant. The economics of rearing fish or any other aquaculture product at OTEC plants is very site specific. Such analyses are beyond the scope of this study.

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HEAVY METAL CONTENT OF COHO AND CHINOOK SALMON REARED IN SIMULATED OTEC WATERS

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Steven A. Katase
Charles P. Madenjian

INTRODUCTION

Our work at the Natural Energy Laboratory of Hawaii (NELH) and the work of others at St. Croix, Virgin Islands (see "Introduction" to this publication), demonstrated that a variety of plants and animals can be cultured in deep seawater pumped to the surface. Deep water is known to differ chemically from surface water in a number of ways (see paper by Smith and Walsh in this publication). These differences, especially with respect to heavy metals, were of concern to us. We were concerned that, even though the fish reared in deep upwelled water would grow satisfactorily, they would accumulate metals or other substances from the water and, thus, be unfit for human consumption.

There are several reasons to suspect increased concentrations of different metal concentrations in fish reared in waters pumped from the ocean depths. First, deep waters are known to have substantially different concentrations of certain elements than surface waters. In particular, concentrations of cadmium, zinc, nickel, phosphorus, and nitrogen are much higher in water at the 800 m depth than in water at the surface. Lead concentrations, on the other hand, are much greater in surface waters (Figure 1). Lead concentrations are 5 to 15 times greater at the surface than below the 3,000-m depth, apparently due to anthropogenic processes, especially the burning of leaded gasoline (Schaule and Patterson, 1981; Stukas and Wong, 1981). Zinc and cadmium concentrations show just the opposite gradient. Zinc concentrations in deep water are more than 8 nmol/kg, compared with less than 0.1 nmol/kg at the surface (Bruland and Franks, 1983). Deep-water and surface-water cadmium concentrations are more than 1.0 nmol/kg and less than 0.1 nmol/kg, respectively (Bruland and Franks, 1983). The oceanic distribution of mercury, especially with depth, is poorly understood (Bruland, 1983). At NELH, Chave and Green (1986) measured average zinc and cadmium concentrations of 5.2 nmol/kg and 1.4 nmol/kg, respectively, in water pumped from the 600 m depth.

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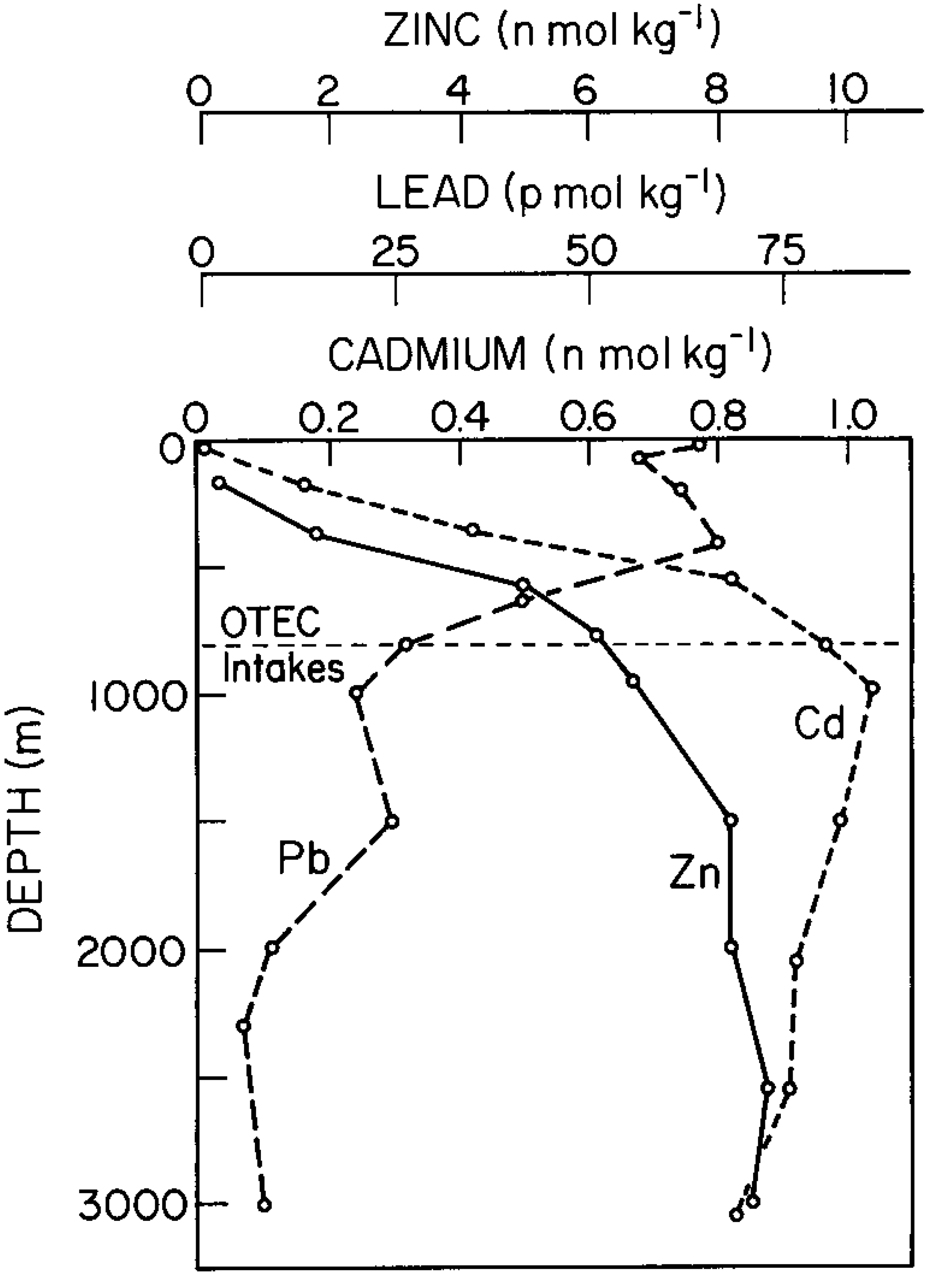

Figure 1. Depth distributions of zinc (Zn), lead (Pb), and cadmium (Cd) in waters of the North Pacific Ocean. Lead data are from Schaule and Patterson (1981); zinc and cadmium data from Bruland and Franks (1983).

Cold seawater from depths between 600 m and 800 m is commonly used to supply ocean thermal energy conversion (OTEC) plants. Water at this depth in Hawaii is derived from arctic subsidence water, which has been out of contact with the atmosphere for perhaps 1,000 years or more. In Hawaii these depths are also the depths of the dissolved oxygen minimum. Zooplankton fecal pellets, crustacean exuvia, and other particulate matter continuously rain down into the depths where they partially dissolve in the process (Bertine and Goldberg, 1972; Fowler, 1977; Elder and Fowler, 1977; Cherry and Higgo, 1978). These deep waters, therefore, have elevated concentrations of many dissolved substances relative to surface waters in the tropics.

Second, Bull et al. (1977) and Shulz-Baldes and Cheng (1980) found that an insect, *Halobates*, living on the water surface in areas of natural deep-water upwelling has a significantly higher concentration of cadmium than do specimens collected elsewhere. This suggests that animals reared in artificially upwelled waters may have higher concentrations of cadmium and perhaps other metals as well.

Lastly, Mencher et al. (1983) found that the seaweed *nori* (*Porphyra tenera*) cultured at NELH had higher concentrations of cadmium, lead, zinc, and chromium than did specimens of this same species collected from surface waters in Korea.

As a result of these observations, we decided to measure the selected metals content of salmon reared in OTEC-like waters at NELH and to compare the metals content of these fish with specimens of the same species collected from near-surface waters in their natural habitat.

MATERIALS AND METHODS

Eyed coho salmon (*Oncorhynchus kisutch*) and chinook salmon (*O. tshawytscha*) eggs were provided by the California Department of Fish & Game during December 1982 and January 1983. These eggs were flown to NELH, where they were incubated in a Heath-Techna incubator using a partial recirculation system. They hatched during January and February 1983. Sac-fry were placed in a partial recirculation system consisting of four 1.2-m diameter fiberglass tanks. The salmon were held in this freshwater system until smoltification occurred during June, July, and August 1983 and were then stocked in fiberglass tanks of the same dimensions but with flow-through seawater instead of recirculated freshwater. Stocking densities were 429 chinook and 235 coho salmon per tank. Barclay, Fast, and Katase (see paper on growth of coho and chinook salmon in this publication) and Grau et al. (1985) describe the handling of these fish in more detail.

The experimental design used to rear the salmon consisted of a 2x2 factorial: 2 species of fish and 2 water temperatures (11°C and 17°C). Water temperatures were achieved by varying the mixture of 9°C deep OTEC water drawn from the 600 m depth with warm surface waters (10 m depth) which ranged in temperature from 25°C to 29°C. The 11°C tanks in most cases contained 100% deep water owing to a 2°C warming of the water in the tank and heat gains during packed-column aeration. The 17°C tanks normally contained a mixture of 55% deep water and 45% surface water. Temperatures were maintained within 0.5°C for each treatment. Water flow-through rate was 130 l/min or 4 exchanges per hour. Barclay, Fast, and Katase describe the salmon-rearing system (see paper on growth of coho and chinook salmon in this volume) and Smith and Walsh describe the water quality of the seawater sources in more detail (see paper on water characterization in this publication).

Seawater growout under experimental conditions began in January 1984 and continued through November 1984. During this time, fish were fed pelleted feed from Rangen, Inc. At the completion of the experiment, the fish were sacrificed and length/weights were recorded. A fillet was also removed from one side of each of 30 fish from each of the 4 tanks for heavy metal analysis. The 120 fillets were frozen and then flown to Michigan State University for metal analysis.

Tissue preparation and analysis at Michigan State University consisted of thawing the fish at room temperature for approximately 12 hours, homogenizing a 100-g sample in a Waring blender, and storing the homogenate at -4°C in washed and tared plastic snap cap vials until use. For the determination of the mercury concentration, an approximately 2-g subsample of the thawed homogenized tissue was extruded into a tared 100-ml Erlenmeyer flask and the gain in weight recorded. To avoid contaminating the neck of the flask, a sample extruder was made from a 25-cm piece of 4-mm i.d. glass tubing. The homogenized sample was packed into the bore of the tubing and extruded into the flask with a piece of 4-mm solid glass rod which operated as a plunger. Five ml of concentrated sulfuric acid and 1 ml of distilled nitric acid were added to digest the fish tissue. The mixture was digested at 60°C to 70°C in a water bath for about 1 hour or until the sample tissues were digested completely as indicated by a clear, light yellow or brown solution. The mixture was cooled to room temperature, and 20 ml of a 4% potassium permanganate solution was added while gently swirling the flask. After this, the mixture was allowed to react at room temperature for 20 minutes and then was again placed in the 60°C to 70°C water bath until the reaction ceased. At this point the solution was clear except for a brown manganous oxide precipitate. The mixture was allowed to cool to room temperature. After cooling, about 5 ml of 10% hydroxylamine hydrochloride was added slowly with a swirling action until the solution became colorless. The solution was diluted volumetrically with deionized water and analyzed spectrophotometrically as described below.

For the determination of cadmium, lead, and zinc concentrations, an approximately 50-g subsample of the homogenized tissue sample was lyophilized for 2 to 3 days, and dry weights were determined to the nearest 0.01 mg. After lyophilization, samples were digested at 70°C in teflon digestion tubes with 1-ml or 5-ml redistilled nitric acid to give an approximate acid to tissue ratio (v/w) of 25 to 1. After the digestion was completed the samples were diluted volumetrically with deionized water and analyzed spectrophotometrically as described below.

Before use, all teflonware and glassware were soaked for 24 hours in 1% Alconox (Scientific Products) and rinsed three times in deionized water (Milli-Q Water Purification System, Millipore). The teflonware was then leached for 4 to 6 hours in heated (130°C) 50% redistilled nitric acid prior to storage in 10% redistilled nitric acid. Immediately before usage, digestion tubes were again rinsed twice in deionized water. Polyethylene bottles were soaked for 24 hours in 10% hydrochloric acid and rinsed twice in deionized water.

Cadmium and lead concentrations were measured by flameless atomization on a Hitachi polarized Zeeman atomic absorption spectrophotometer equipped with a flameless graphite atomizer and deuterium background continuum. Zinc concentrations were measured by flame atomization. Mercury concentrations were determined by first transferring an appropriate aliquot of the digested solution and stannous chloride reagent into the measuring cell of a Hitachi mercury reduction unit and then measuring the liberated mercury vapor by flameless atomic absorption.

Matrix interferences were evaluated by standard additions and measurements at nonabsorptive adjacent analytical wavelengths and eliminated by variation in charring and atomization parameters. Because of a persistent matrix interference from sodium, lead concentrations were measured using standard additions techniques even though much of the interference was eliminated by amnonium hydroxide additions. Standards were made from Fisher certified atomic absorption standards (Fisher Scientific). To evaluate for possible contamination, reagent blanks were used throughout all preparation and analytical procedures. Reagent grade nitric acid was redistilled in teflon before use, and amnonium hydroxide was prepared by isothermal distillation in teflon. Sample preparation and analytical procedures were evaluated and validated using U.S. National Bureau of Standards (NBS) bovine liver as a reference material. Our results were within the range of concentrations given by NBS for each metal studied.

The pelleted feed given to the NELH salmon was digested and analyzed at Michigan State University in the same manner as were the fish tissue samples. Fish condition factors were calculated according to Lagler (1952).

RESULTS

Coho salmon reared at the two temperatures averaged about the same length and weight (Table 1). They were slightly larger than chinook salmon, which may be a reflection of the lower stocking density for the former. Although coho salmon were on the average larger, chinook salmon had higher condition factors.

Mercury concentrations averaged 0.037 µg/g for all fish, but for coho and chinook salmon they were 0.030 µg/g and 0.044 µg/g, respectively (Table 1). Average mercury concentrations for coho plus chinook salmon reared at 11°C was 0.036 µg/g compared with 0.038 µg/g for those fish reared at 17°C. A 2-way ANOVA yields a significant difference between species means ($p < .01$; $F = 30.50$) but not between temperature means ($F = 0.51$). There is also a significant difference ($p < .05$) between average mercury concentrations of coho salmon at 11°C (0.025 µg/g) and at 17°C (0.034 µg/g). There was no significant difference between average mercury concentrations of chinook salmon reared at the two temperatures. A summary of significant differences is provided in Table 2.

Zinc concentrations averaged 7.64 µg/g for all fish or 7.84 µg/g and 7.44 µg/g for coho and chinook salmon, respectively (Table 1). Average zinc concentrations for coho and chinook salmon reared at 11°C was 7.40 µg/g compared with 7.88 µg/g for those fish reared at 17°C. A 2-way ANOVA yields no significant difference ($p > .05$) between either species or temperature means. Likewise, there were no significant differences between mean zinc concentration of either species reared at different temperatures (Table 2).

Cadmium concentrations averaged 0.11 µg/g for all fish or 0.12 µg/g and 0.010 µg/g for coho and chinook salmon, respectively (Table 1). Average cadmium concentrations for coho and chinook salmon reared at 11°C was 0.11 µg/g compared with 0.11 µg/g for those fish reared at 17°C. A 2-way

TABLE 1. LENGTH, WEIGHT, CONDITION FACTOR, AND HEAVY METAL CONCENTRATIONS IN MUSCLE TISSUE OF COHO AND CHINOOK SALMON REARED IN SIMULATED OTEC WATERS AT THE NATURAL ENERGY LABORATORY OF HAWAII

	Length (m)	Weight (g)	Condition Factor	Concentration (µg/g)			
				Mercury	Zinc	Cadmium	Lead
COHO SALMON							
11°C (n = 30)							
Mean	303.9	353.3	1.230	0.025	8.554	0.128	0.246
Standard Deviation	42.8	151.5	0.261	0.011	2.395	0.082	0.122
Minimum	225.0	191	0.686	0.010	5.810	0.030	0.080
Maximum	434.0	920	2.405	0.050	18.220	0.380	0.620
17°C (n = 30)							
Mean	303.2	342.6	1.173	0.034	7.116	0.113	0.258
Standard Deviation	32.2	139.4	0.131	0.007	2.025	0.135	0.149
Minimum	256.0	171.0	0.870	0.020	1.910	0.010	0.060
Maximum	378.0	707.0	1.355	0.050	13.820	0.430	0.620
CHINOOK SALMON							
11°C (n = 30)							
Mean	282.9	302.2	1.308	0.047	6.247	0.089	0.212
Standard Deviation	21.4	79.7	0.144	0.021	1.778	0.050	0.107
Minimum	245.0	175.0	1.007	0.030	3.410	0.020	0.040
Maximum	325.0	495.0	1.763	0.140	12.030	0.220	0.490
17°C (n = 30)							
Mean	284.6	336.5	1.460	0.041	8.639	0.110	0.230
Standard Deviation	29.8	111.0	0.522	0.013	4.817	0.057	0.110
Minimum	215.0	152.0	1.082	0.020	5.840	0.030	0.050
Maximum	357.0	670.0	4.105	0.070	33.000	0.240	0.470

TABLE 2. SUMMARY OF SIGNIFICANT DIFFERENCES FOR METAL CONCENTRATIONS (μg/g) IN COHO AND CHINOOK SALMON REARED AT TWO TEMPERATURES

	Mercury	Zinc	Cadmium	Lead
1. Differences between species (combine temperatures for each species)	+	–	–	–
2. Differences between temperatures (combine species for each temperature)	–	–	–	–
3. Temperature differences for coho salmon	+	–	–	–
4. Temperature differences for chinook salmon	–	–	–	–

+ = significant difference ($p < .05$)
– = nonsignificant difference ($p > .05$)

ANOVA yields no significant difference ($p > .05$) between either species or temperature means. Likewise, there were no significant differences between mean cadmium concentrations of either species reared at different temperatures (Table 2).

Lead concentrations averaged 0.24 μg/g for all fish or 0.25 μg/g and 0.22 μg/g for coho and chinook salmon, respectively (Table 1). Average lead concentrations for coho and chinook salmon reared at 11°C was 0.23 μg/g compared with 0.24 μg/g for those fish reared at 17°C. A 2-way ANOVA yields no significant difference ($p > .05$) between either species or temperature means. Likewise, there were no significant differences between mean lead concentrations of either species reared at different temperatures (Table 2).

Lengths, weights, and condition factors were analyzed for correlation with each metal at each temperature combination (Table 3). For coho salmon, only lead concentrations showed highly significant correlation ($p < .01$) with lengths and weights. There was a significant increase in lead concentration with increasing length and weight of coho salmon (Figure 2).

Chinook salmon had significant correlations among 10 combinations of variables (Table 3). Most of these correlations were less pronounced than for the coho salmon, and, in many cases, the

TABLE 3. SPEARMAN'S RHO AMONG LENGTH, WEIGHT, CONDITION FACTOR, AND HEAVY METAL CONTENT OF COHO AND CHINOOK SALMON REARED IN SIMULATED OTEC WATERS AT THE NATURAL ENERGY LABORATORY OF HAWAII

		Mercury	Zinc	Cadmium	Lead
COHO SALMON					
L	11°C	0.1248	-0.2350	-0.0498	0.6165**
L	17°C	0.0318	0.1274	-0.3482	0.7228**
W	11°C	0.1542	-0.2213	-0.0439	0.6487**
W	17°C	-0.1016	0.1538	-0.3134	0.6965**
CF	11°C	0.0945	0.0247	0.0071	-0.1374
CF	17°C	-0.2831	0.1315	-0.0324	0.2668
CHINOOK SALMON					
L	11°C	0.1942	0.5028**	0.0147	0.1694
L	17°C	-0.3866*	-0.0846	-0.2140	0.4529*
W	11°C	0.3172	0.5882**	0.0860	0.2550
W	17°C	-0.4855**	0.0211	-0.0529	0.6339**
CF	11°C	0.2338	0.4243*	0.0281	0.4076*
CF	17°C	-0.5048**	0.2272	-0.0436	0.4362*

Note: n = 30 for each correlation. L = length; W = weight; CF = condition factor
* = Significant (.01 < *p* < .05)
** = Highly significant (*p* < .01)

significant correlation with chinook salmon could be accounted for by a few "exceptional" values. The strongest correlation for chinook salmon was between fish weight and lead concentration.

The average heavy metal concentrations established for three replicate samples of pelleted feed was mercury, 0.002 µg/g; cadmium, 1.02 µg/g; lead, 0.010 µg/g; and zinc, 161 µg/g.

DISCUSSION

For the four heavy metals and two salmonid species tested at NELH, there was only one significant difference in average metals concentration for fish reared in 100% deep water (11°C) and for fish reared in a mixture of 55% deep water and 45% surface water (17°C). Coho salmon reared in deep water only had a significantly lower concentration of mercury than those reared in a mixture

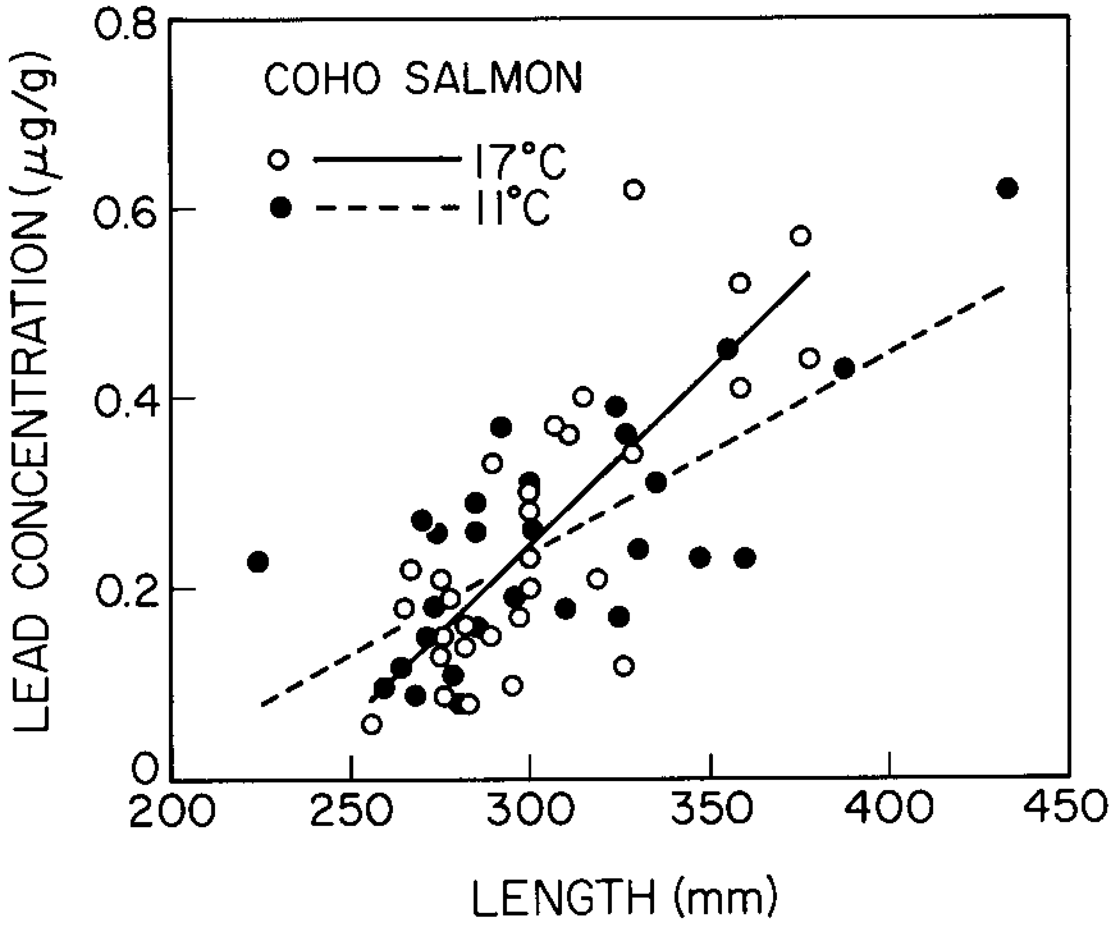

Figure 2. Length vs. lead concentration of coho salmon reared at NELH in simulated OTEC waters at 11°C and 17°C

of deep and surface waters (Table 3). In addition, there was only one significant difference between average metal concentration for the two salmon species. Again, the heavy metal involved was mercury. These results indicate that there could be direct uptake of mercury from the water by fish and that the uptake rate could be species-specific. Unfortunately, we were unable to analyze for mercury in the deep and surface waters, nor were we able to find reliable mercury data from the literature due to problems associated with mercury analysis in seawater at low concentrations (Bruland, 1983). If our conclusions about mercury uptake by salmon are valid, we would expect to find higher mercury concentrations in surface waters near Hawaii than in deep water.

Whatever the above case, mercury concentrations in salmon reared at NELH were below levels of concern. Not only were mercury concentrations in these fish below those considered a health risk, but they were also significantly lower than those concentrations found in fish captured from the Pacific Northwest. For comparison, we have plotted average metal content of wild-caught coho and chinook salmon from the Pacific Northwest (Alaska, Washington, Oregon, and California; Hall et al., 1978) against the metal concentrations of coho and chinook salmon reared at NELH (Figure 3).

In our NELH experiments, we found that chinook salmon had significantly higher mercury concentrations than did coho salmon. This trend is also present in the Pacific Northwest fish although there is not a significant difference between the two species (Figure 3).

Zinc concentrations were significantly higher in both salmon species at NELH compared with Pacific Northwest salmon (Figure 3), but the opposite situation occurs with lead. Cadmium concentrations in NELH and Pacific Northwest salmon were more like zinc, but significant differences occurred for coho salmon at 11°C and chinook salmon at 17°C.

Lower lead concentrations in salmon reared at NELH compared with surface-dwelling salmon from the Pacific Northwest probably reflect differences in concentration with depth of this element (Figures 1 and 3). In the Pacific Ocean, dissolved lead is found in much higher concentrations in surface waters than in deep waters. On the other hand, dissolved zinc and cadmium concentrations are higher in deep water. Fish reared in deep water at NELH had higher concentrations of these elements than did surface-dwelling salmon from the Pacific Northwest. Taken together, these data suggest that the dissolved forms of these metals are absorbed directly into the fish's flesh from the water.

Interpretation of our test results are confounded by many factors, not the least of which is food characteristics. Heavy metal concentration differences in fish between treatments cannot be correlated to size because all fish at NELH received the same feed and grew to nearly the same size. It does, however, make it difficult to draw strict comparisons with fish collected from the Pacific Northwest since the nature of the latters diet and its effects on the fish are unknown.

In summary, it appears that rearing fish in OTEC deep water poses no threat to people eating such fish. The concentrations of the four metals measured during our study were well below any Federal Drug Administration action level values. Furthermore, it appears that the concentrations of certain metals in fish flesh were influenced more by direct uptake from the water than from food chain events.

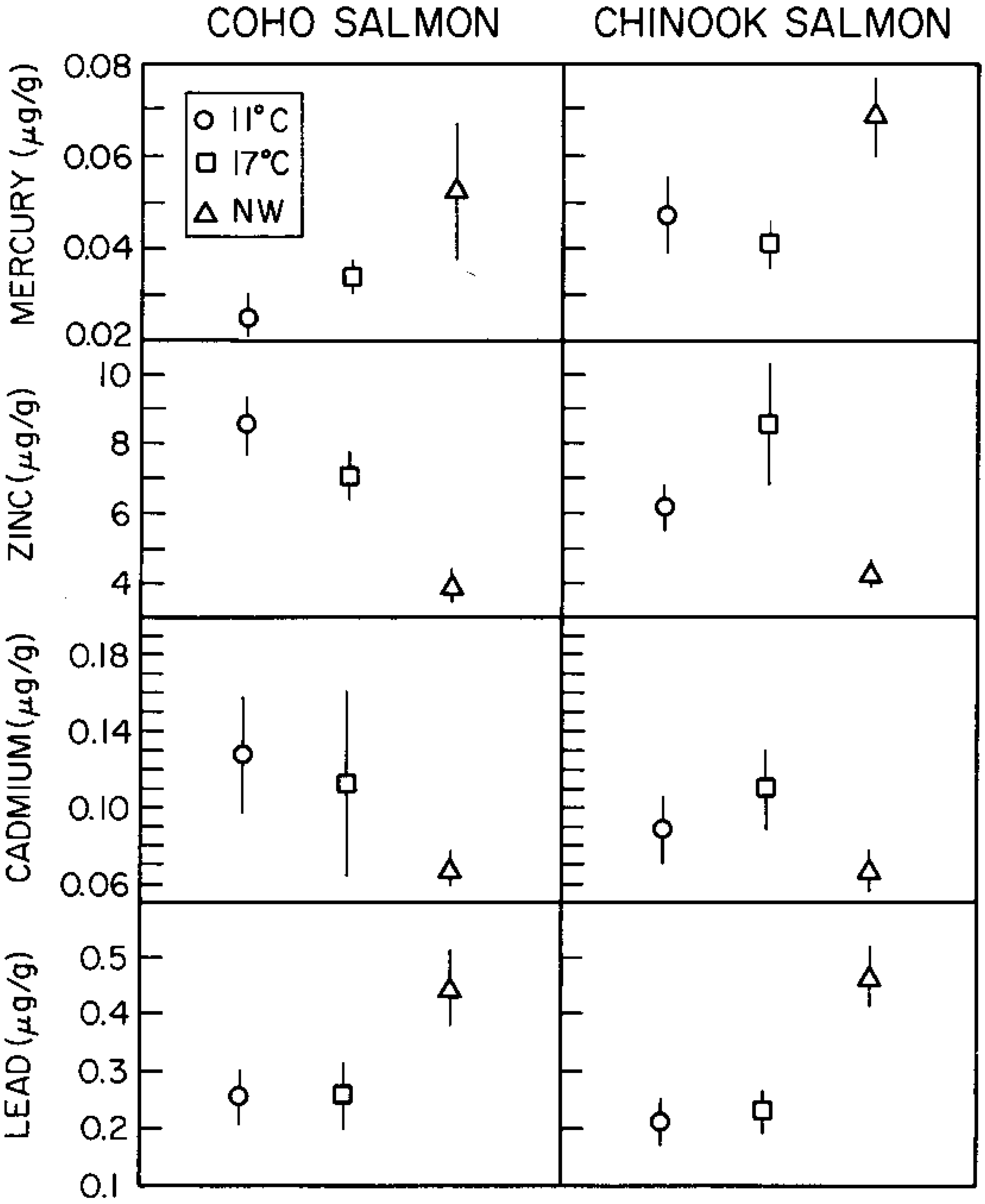

Figure 3. Average metal concentrations in coho and chinook salmon reared at the Natural Energy Laboratory of Hawaii in simulated OTEC waters, as well as in fish collected in the Pacific Northwest as reported by Hall et al. (1978). The 95% confidence limit is shown for each mean value.

ACKNOWLEDGMENTS

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THE ECONOMICS OF OTEC SALMON CULTURE IN HAWAII

Thomas A. Loudat
Arlo W. Fast
Gary L. Rogers

INTRODUCTION

The preceding four chapters contain technical feasibility assessments for salmonid culture using ocean thermal energy conversion (OTEC) water. They indicate that OTEC salmonid culture is technically feasible. This chapter assesses the economics of OTEC salmonid culture.

Three years of research on OTEC salmonid culture at the Natural Energy Laboratory of Hawaii (NELH) and a review of state-of-the-art salmon culture elsewhere, provide the basis for creating a hypothetical OTEC salmon culture operation (salmon farm) in Hawaii. It represents an optimistic scenario for a salmon farm since several assumptions made favorably affect the economics of operating such a farm. These include (1) a zero OTEC water delivery cost; (2) a zero water disposal cost; (3) a zero cost for the numerous permits required to operate aquaculture farms in the coastal zone; (4) no adjustment for known risks for aquaculture farms, especially large prototypes; and (5) egg costs based on conditions that existed 3 or 4 years ago. The typical price 4 years ago was $15 per 1,000 eggs. Today, disease-free egg prices range between $100 and $250 per 1,000 eggs.

This analysis is based on only one hypothetical case. There are other salmon farm configurations possible, the economics of which could differ significantly from those presented. The configuration chosen in our opinion, is reasonable and appropriate for conditions in Hawaii and similar to existent salmon farms elsewhere.

Our presentation is a synopsis of a larger economic analysis. The shortened version is included here for completeness of this publication on OTEC aquaculture in Hawaii. For more details, see Loudat et al. (in review).

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PRODUCTION SYSTEM DESIGN AND OPERATION

Coho salmon (*Oncorhynchus kisutch*) is one of three salmonids successfully cultured at NELH on an experimental basis. It is the most commonly cultured salmon worldwide. This salmon is the assumed species cultured for this analysis.

The assumed site for the OTEC salmon farm is NELH located at Keahole Point on the island of Hawaii. Required characteristics for the provision of large volumes of cold seawater exist at this location. Further, most legal and institutional requirements necessary for the installation and operation of the salmon farm have been met.

Technical details of the salmon farm are described in the literature (Leitritz and Lewis, 1980; Lindbergh, 1976; MacDonald et al., 1975; Nyegaard, 1973; Westers and Pratt, 1977). Appropriate adjustments were made to meet particular requirements of Hawaii salmonid production.

Expected average annual salmon production is 1 million fish approximately 13 inches long weighing 1 pound (Figure 1). This production size allows salmon feed purchase economies of scale.

The production system consists of two water delivery and culture systems, and a hatching system. One culture system — called the smolt growout system — grows fry to smolt size in freshwater (Figure 2). The second culture system — called the market growout system — grows salmon from smolts to market size in seawater (Figure 3).

COST OF PRODUCTION

Estimated construction and equipment costs for the salmon farm are summarized in Table 1. Raceway construction accounts for almost 25% of total construction and equipment costs. The smolt and market growout systems respectively account for 25% and 34% of the total construction and equipment costs. Noting that the market growout system contains the raceways, market growout system costs comprise almost 60% of total construction and equipment costs.

Fixed and variable annual operating costs are shown in Table 2 and summarized by major categories in Figure 4. The summary shows that feed cost makes up 40% of the total annual operating cost. Taken with interest on capital and electricity costs, these items make up almost 80% of total annual operating costs. Insurance, land lease, freshwater, eggs, packaging, feed, gross sales tax, and miscellaneous items comprise other operating costs.

ECONOMIC ANALYSIS

Expected average annual salmon production of 1 million pounds live weight could vary between 0.8 million and 1.2 million pounds, depending on mortality, disease, production/management, and other factors. Thirty percent live weight loss cause a removal of gills and viscera. Thus, processed production varies between 0.56 million and 0.84 million pounds.

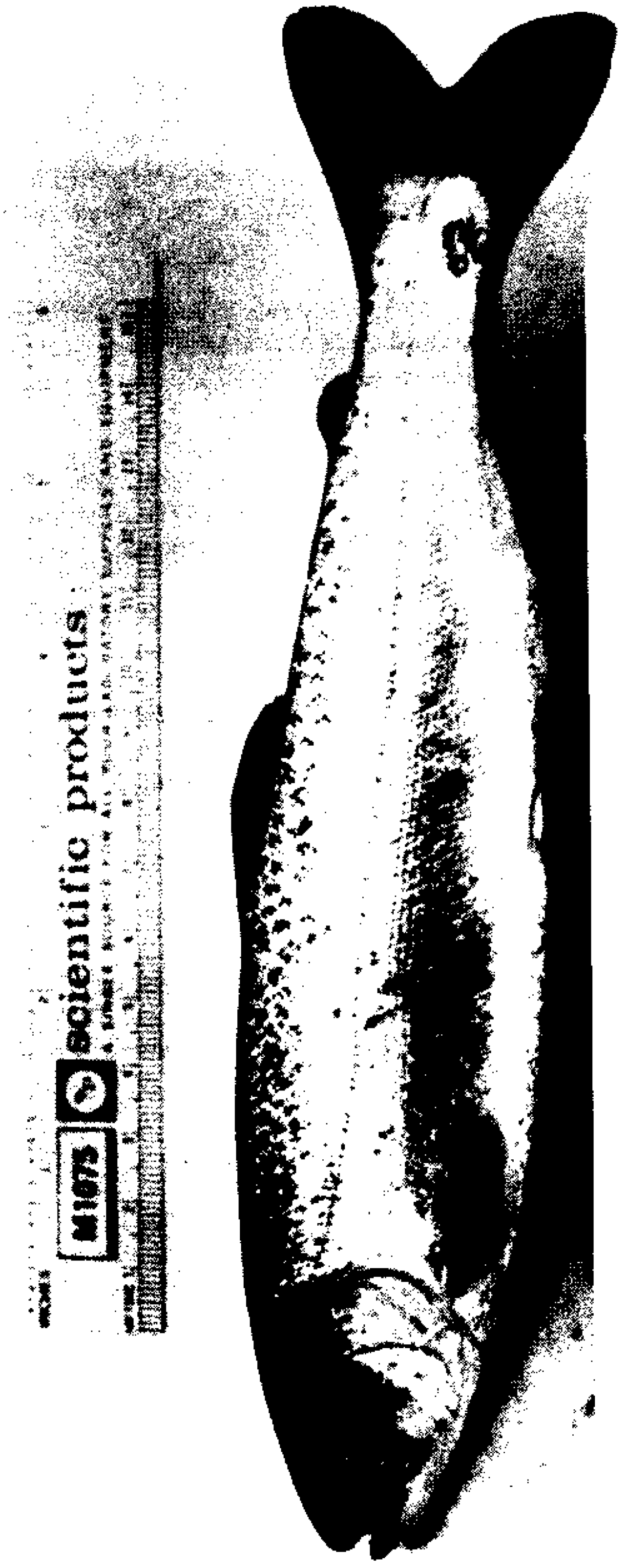

Figure 1. Pan-sized salmon. (Photo courtesy of California Sea Grant College Program)

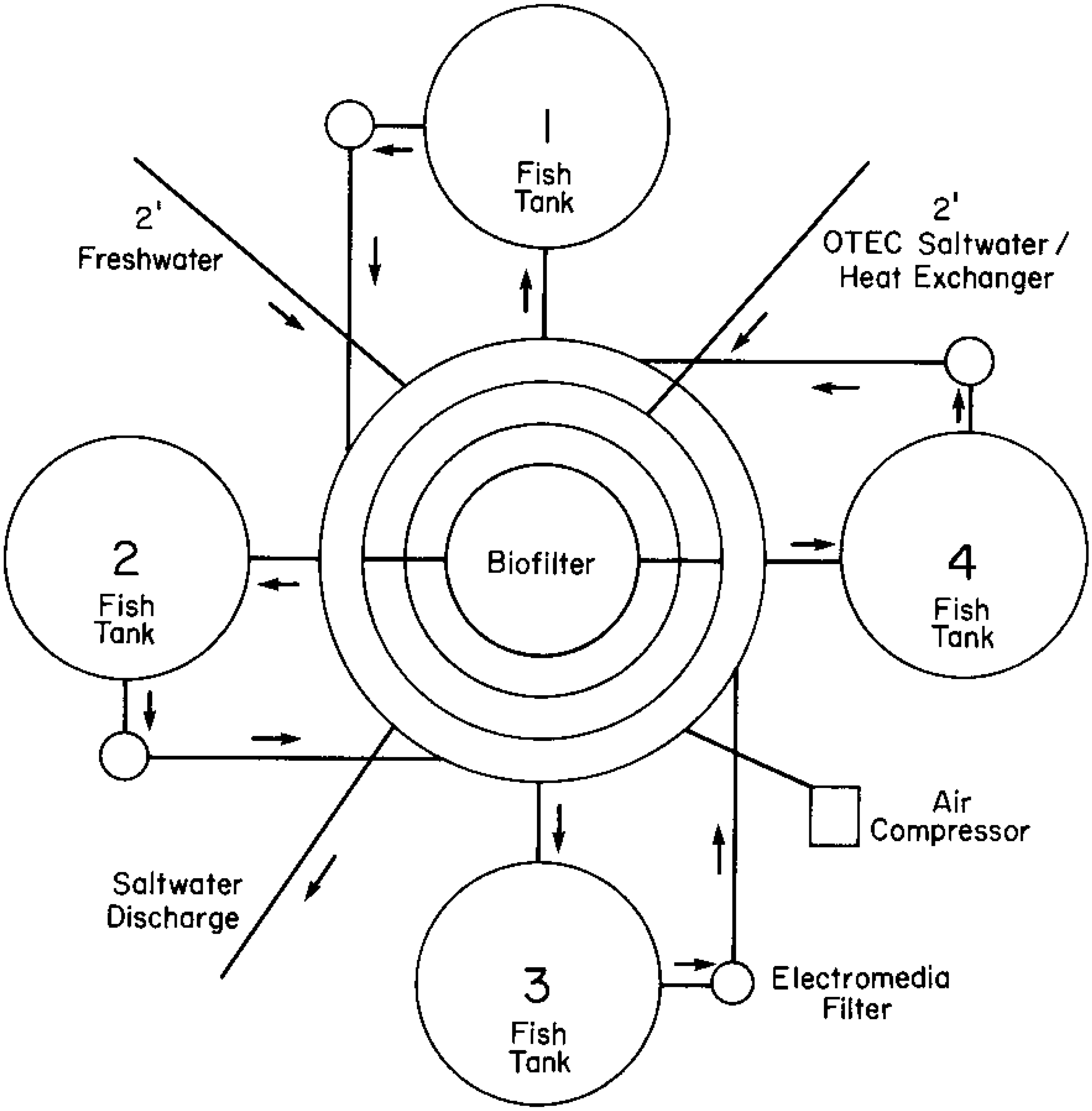

Figure 2. Freshwater recirculation system with biofilter used to rear salmon from fry stage to smolt stage before seawater entry. The biofilter serves four growout fish tanks and converts toxic ammonia to nontoxic nitrate

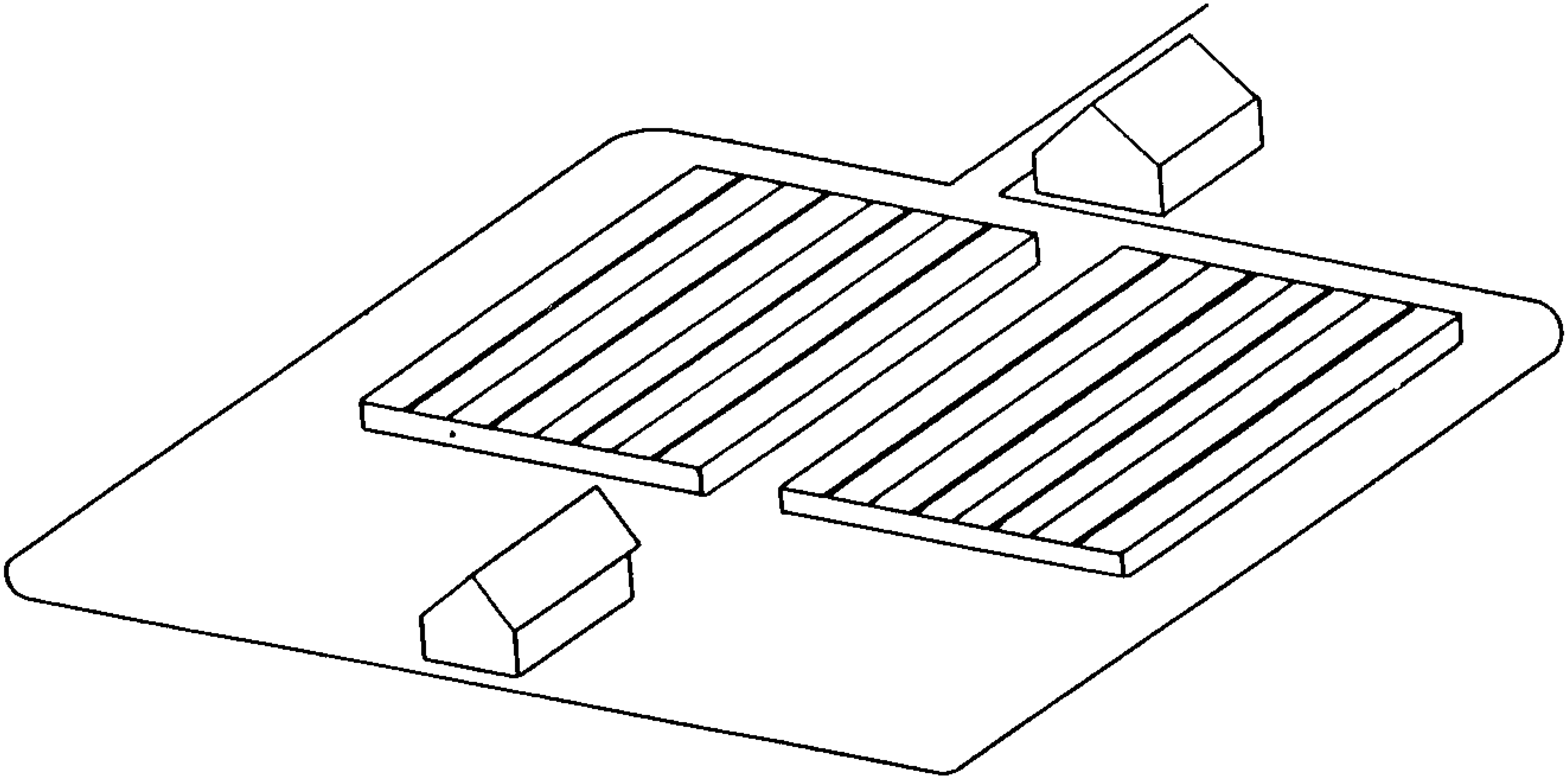

Figure 3. An artist's conception of a Hawaii salmon farm showing the raceways which are part of the market growout system

TABLE 1. ESTIMATED CONSTRUCTION AND EQUIPMENT COSTS FOR A HAWAII SALMON FARM

Item	Cost ($)	% of Total
Construction Costs	1,096,556	28.76
Building Permits	339	0.01
Site Preparation	34,000	0.89
Buildings	113,000	2.96
Raceways	897,000	23.53
Miscellaneous	52,217	1.37
Equipment Costs	2,716,103	71.24
Support	110,300	2.89
Lab	2,650	0.07
Incubation System	13,610	0.36
Smolt Growout System	942,215	24.71
Market Growout System	1,310,138	34.36
Processing	75,241	1.97
Electrical and Miscellaneous	261,950	6.87
TOTAL	3,812,659	100.00

TABLE 2. FIXED AND VARIABLE ANNUAL OPERATING COSTS FOR A HAWAII SALMON FARM

Item	Unit Cost or %	No. of Units or Value	Total Cost ($)	% of Total
Fixed Cost	—	—	679,535	32.99
Fixed Land Lease (acres)	100	6	600	0.03
Labor	—	—	82,500	4.01
Manager	35,000	1	35,000	1.70
Assistant Manager	17,500	1	17,500	0.85
Production Laborers	15,000	2	30,000	1.46
Fringe Benefits (% of total salary)	—	—	17,119	0.83
FICA	7.05%	—	5,816	0.28
Workmen's Compensation	12.50%	—	10,313	0.50
TDI	1.20%	—	990	0.05
Depreciation	—	—	209,695	10.18
Insurance	—	—	5,474	0.27
Fire and Theft	1,664	1	1,664	0.08
Liability	—	—	2,010	0.10
Bodily Injury and Property	110	1	110	0.01
Product (% of gross sales)	100	1	100	0.00
Vehicle	1,800	1	1,800	0.09
Interest	10.00%	3,812,659	381,266	18.51
Variable Costs	—	—	1,380,081	67.01
Variable Land Lease	1.50%	2,275,000	34,125	1.66
Processing Laborers (hours)	5	12,000	60,000	2.91
Fringe Benefits (% of total salary)	—	—	12,450	0.60
FICA	7.05%	—	4,230	0.21
Workmen's Compensation	12.50%	—	7,500	0.36
TDI	1.20%	—	720	0.03
Freshwater	—	—	6,642	0.32
Egg Hatching System (gal)	0.00069	18,000	12	0.00
Smolt Growout System (gal)	0.00069	9,275,622	6,400	0.31
Processing (gal)	0.00069	150,000	104	0.01
Other (gal)	0.00069	182,500	126	0.01
Eggs (1,000)	15	1,428	21,420	1.04
Feed	—	—	730,521	35.47
Smolt (lb)	0.37	254,889	95,074	4.62
Market (lb)	0.30	2,154,059	635,447	30.85
Packaging	—	—	54,838	2.66
Boxes 5 lb	0.10	140,000	14,000	0.68
Boxes 10 lb	0.25	23,350	5,838	0.28
Gel Paks	0.25	140,000	35,000	1.70
Electricity (kwh)	0.12	3,154,234	377,877	18.35
Gasoline (gal)	1.10	4,650	5,115	0.25
Gross Sales Tax (0.5%)	0.50%	2,275,000	11,375	0.55
Miscellaneous	5.00%	1,380,081	69,004	3.35
TOTAL ANNUAL OPERATING COSTS			2,059,616	100.00

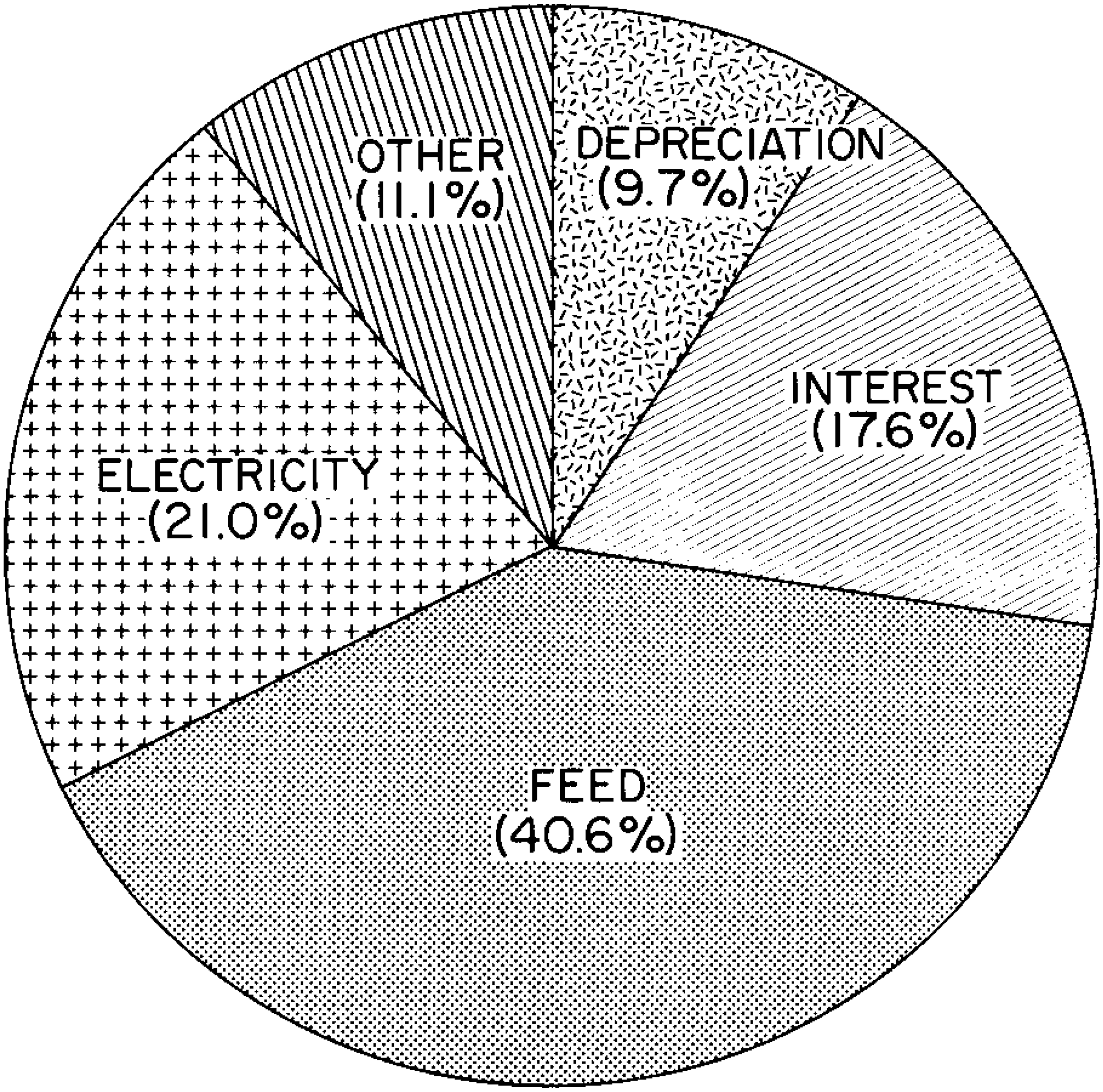

Figure 4. Annual operating cost summary for a Hawaii-based OTEC salmon farm

The current farm price of pan sized salmon ranges from $2.25/lb to $3.25/lb processed weight. For the analysis, prices range between $2.25/lb and $5.25/lb. The latter price is the upper bound of current point of production prices received for 6-pound to 9-pound fresh Atlantic salmon from Norway. Smaller salmon of all species command a lower price (Stern, 1984)

The economic analysis of profit, break-even price, and rate of return includes three different production levels and four different price levels within the above ranges. This allows a sensitivity assessment of these variables. The production levels are 0.56 million pounds, 0.70 million pounds, and 0.84 million pounds of processed fish; the price levels are $2.25, $3.25, $4.25, and $5.25 per pound processed weight.

Profit

Table 3 and Figure 5 show profit for the salmon farm for the price and production levels. At $2.25 per pound profit is negative. The farm is marginally profitable at the 700,000-pound production level when price is $3.25/lb, the high end of current prices for pan-sized salmon.

TABLE 3. FARM PROFIT BY PRODUCTION LEVEL AND FARM PRICE

Production Level (lb)	Salmon Price ($/lb)	Annual Profit ($)
560,000	2.25	(512,854)
	3.25	35,946
	4.25	584,746
	5.25	1,133,546
700,000	2.25	(470,616)
	3.25	215,384
	4.25	901,384
	5.25	1,587,384
840,000	2.25	(428,377)
	3.25	394,823
	4.25	1,218,023
	5.25	2,041,223

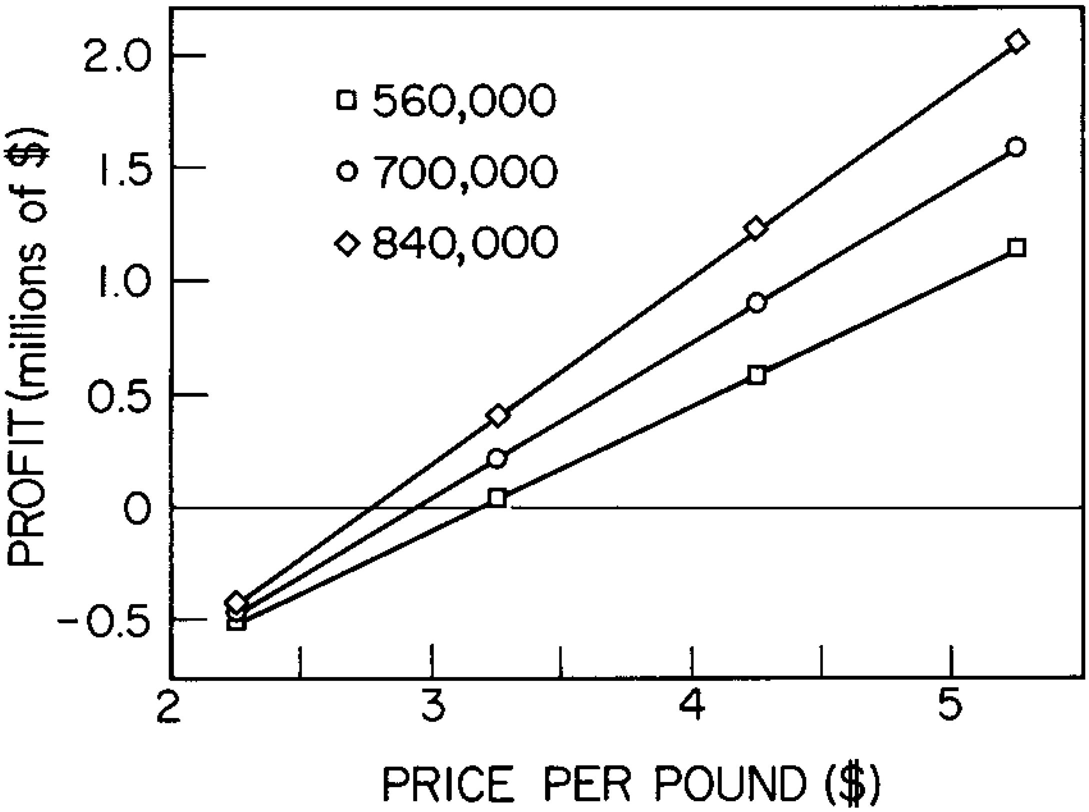

Figure 5. Profit levels for a Hawaii-based OTEC salmon farm

Break-Even Farm Price

The break-even farm price equals cost per pound of production. The calculation is:

$$\frac{\text{Break-even}}{\text{Farm Price}} = \frac{\text{Total Annual Farm Operating Cost}}{\text{Total Annual Farm Production}}$$

The break-even price for the three different production levels ranges from $2.78/lb to $3.19/lb (Table 4 and Figure 6). The farm would break even at 700,000 pounds production if pan-sized salmon prices are at the upper end of the current price range.

TABLE 4. BREAK-EVEN PRICE BY PRODUCTION LEVEL FOR A HAWAII SALMON FARM

Production Level (lb)	Break-Even Price ($/lb)
560,000	3.19
700,000	2.94
840,000	2.78

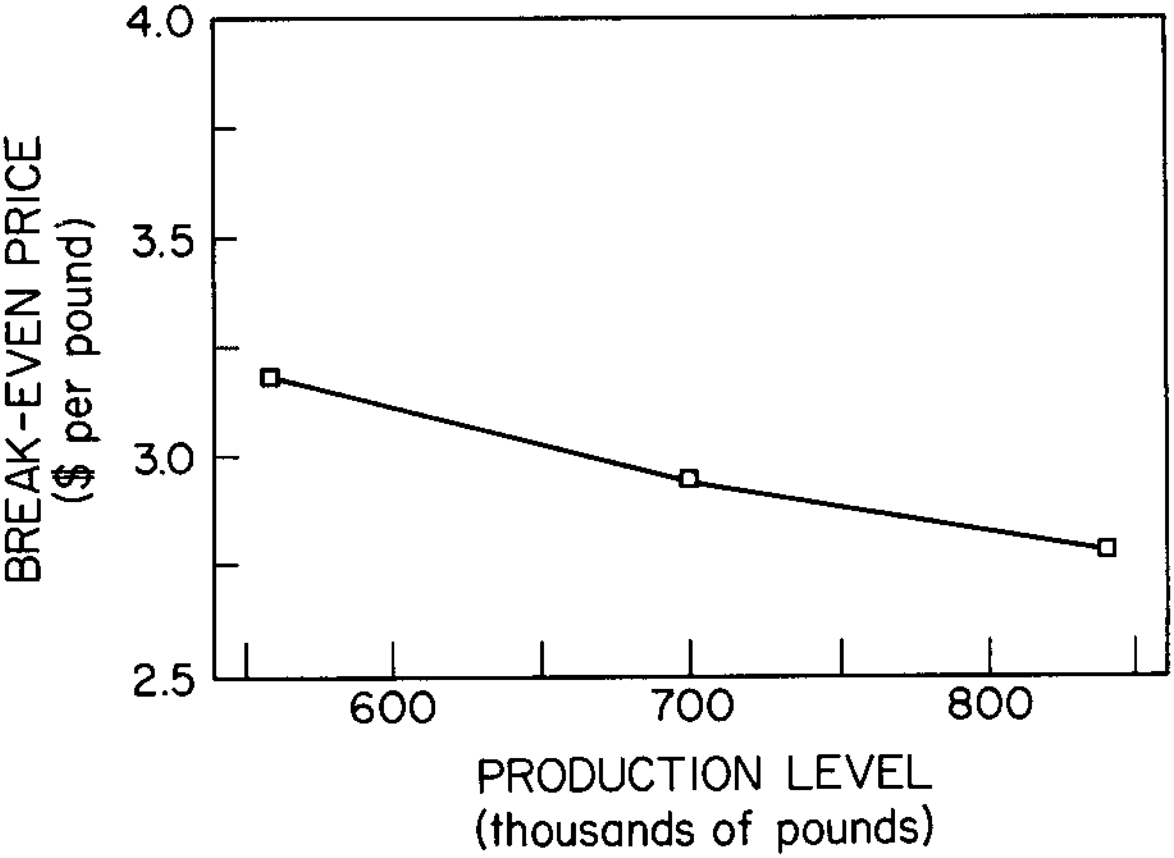

Figure 6. Break-even price levels for a Hawaii-based OTEC salmon farm

Break-Even Production

The break-even production indicates production required to achieve zero profit for a given price. The calculation is:

$$\text{Break-Even Production Level} = \frac{\text{Annual Operating Cost for the Farm}}{\text{Average Salmon Price Per Pound}}$$

Break-even production ranges between 0.40 million and 0.91 million pounds for salmon prices of \$5.25/lb and \$2.25/lb, respectively (Table 5 and Figure 7). The production level of 0.91 million pounds processed weight exceeds the expected growout system capacity of 700,000 pounds. Break-even production levels less than 700,000 pounds occur at price levels marginally below or above the upper limit of the current market range of \$3.25 per pound processed fish.

TABLE 5. BREAK-EVEN PRODUCTION LEVELS FOR DIFFERENT SALMON PRICES

Salmon Price ($/lb)	Break-Even Production (lb)
2.25	909,162
3.25	633,728
4.25	487,910
5.25	397,641

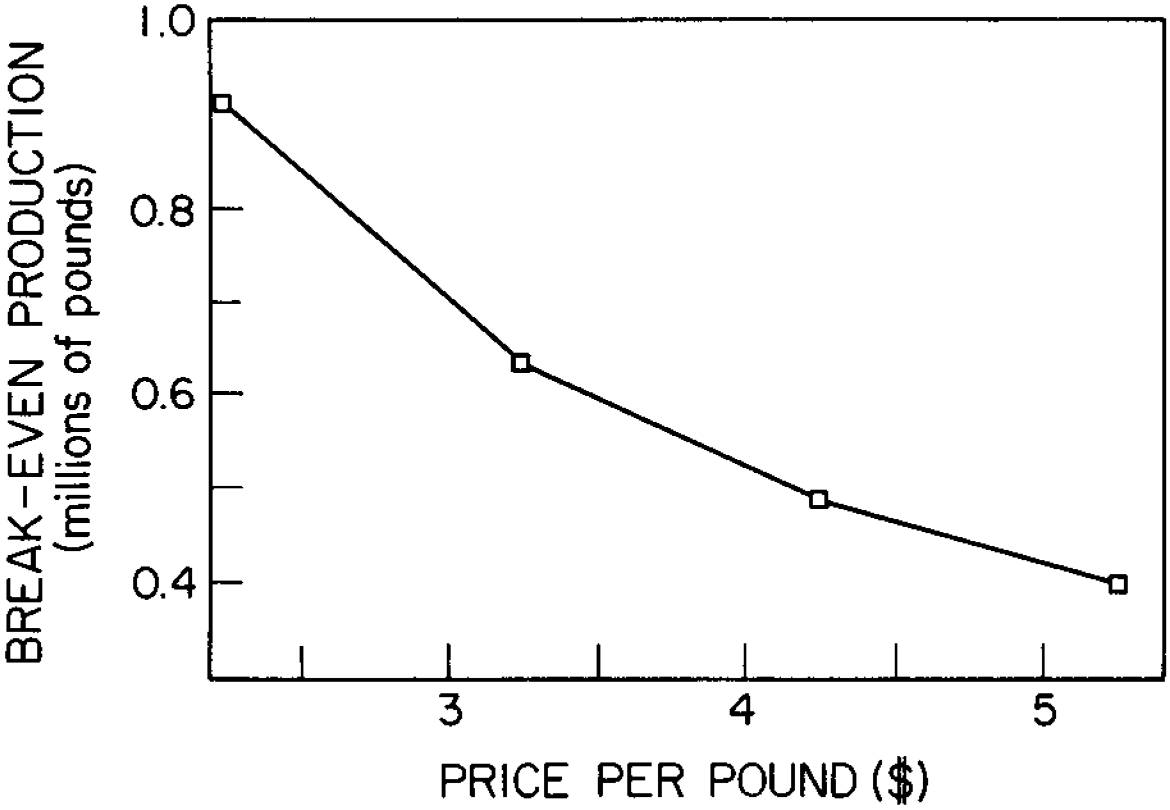

Figure 7. Break-even production levels for a Hawaii-based OTEC salmon farm

Rate of Return

Rate of return measures the annual earning power of an investment. Alternatively, it measures the earning power of annual operating capital. The respective formulas are:

$$\text{Rate of Return on Initial Investment} = \frac{\text{Annual Profit}}{\text{Initial Investment}}$$

and

$$\text{Rate of Return on Annual Operating Cost} = \frac{\text{Annual Profit}}{\text{Annual Operating Cost}}$$

Table 6 and Figure 8 and 9 present each respective rate of return for the different price and production levels. Both rate of return measures are negative or marginal over the current price range of pan-sized salmon. At high price levels, however, rates of return are significantly higher, suggesting some price-sensitivity.

TABLE 6. RATE OF RETURN BY PRODUCTION LEVEL AND SALMON PRICE

Production Level (lb)	Salmon Price ($/lb)	Return on Initial Investment (%)	Return on Annual Operating Costs (%)
560,000	2.25	-13.45	-28.93
	3.25	0.94	2.03
	4.25	15.34	32.98
	5.25	29.73	63.94
700,000	2.25	-12.34	-23.01
	3.25	5.65	10.53
	4.25	23.64	44.06
	5.25	41.63	77.60
840,000	2.25	-11.24	-18.48
	3.25	10.36	17.03
	4.25	31.95	52.54
	5.25	53.54	88.05

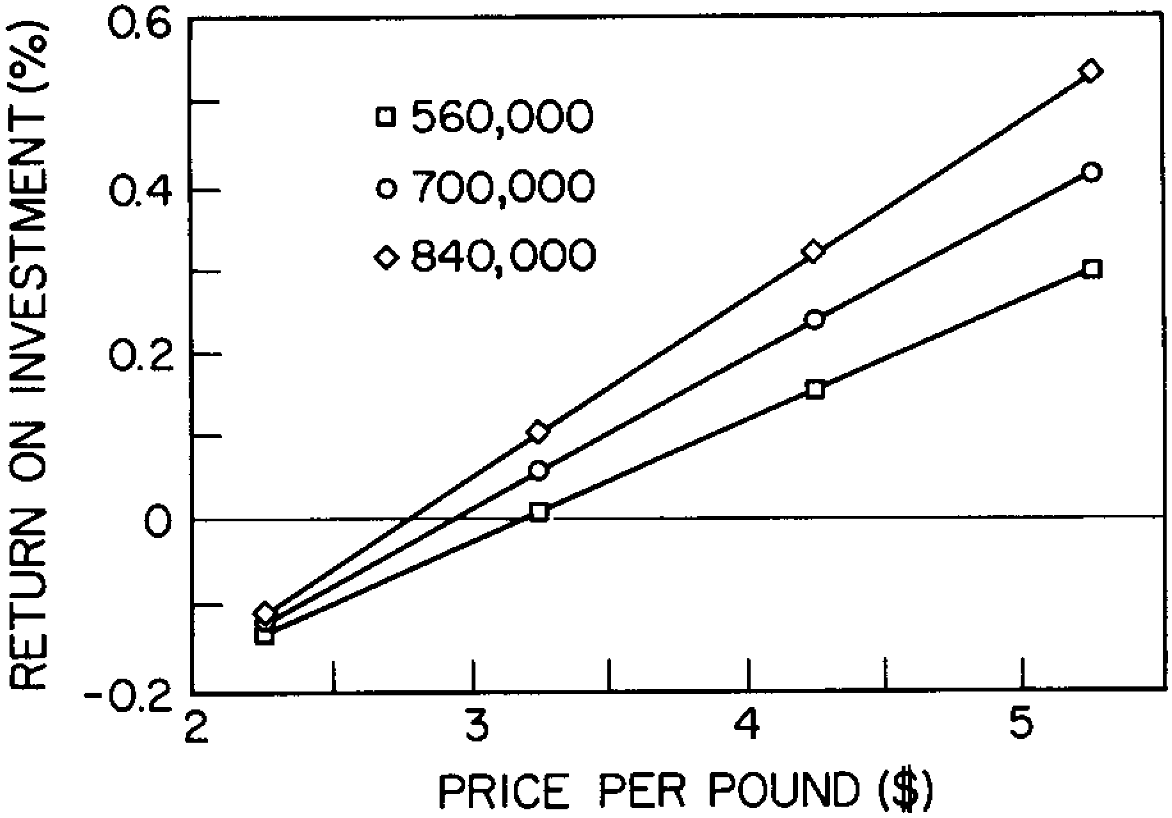

Figure 8. Rate of return on initial investment for a Hawaii-based OTEC salmon farm

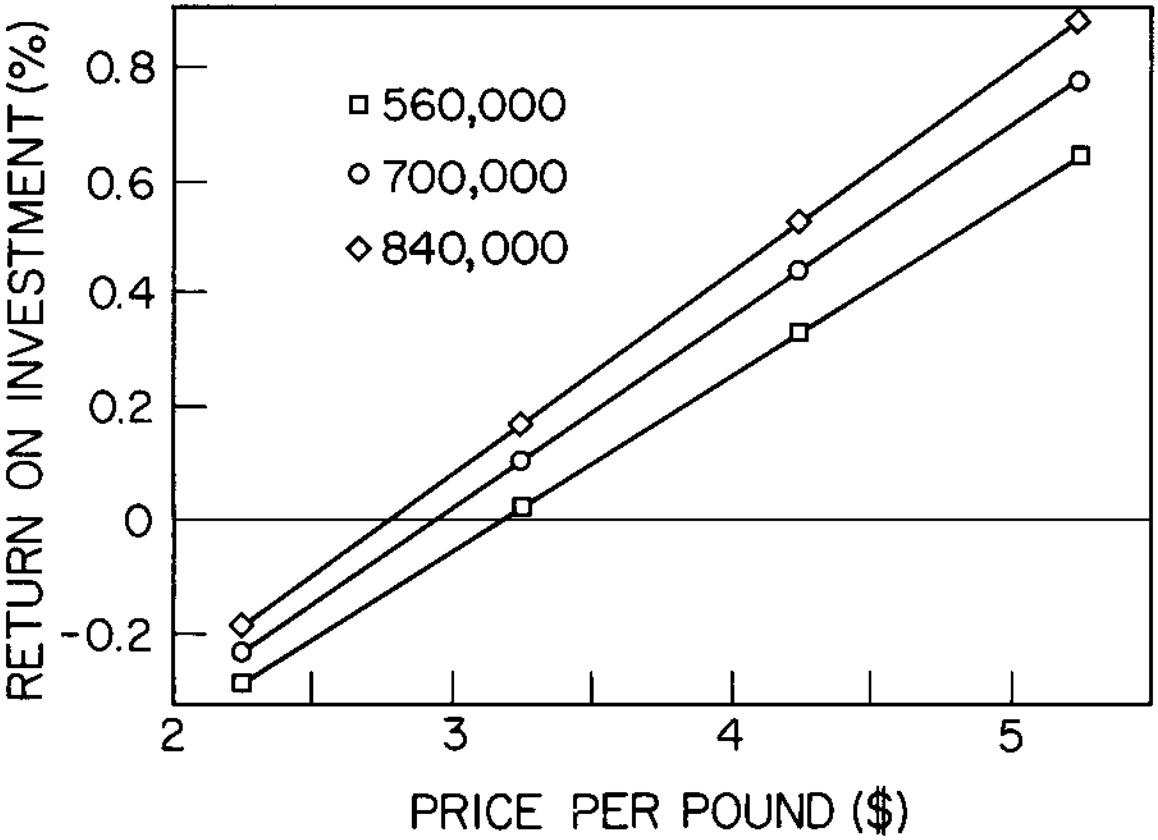

Figure 9. Rate of return on annual operating cost for a Hawaii-based OTEC salmon farm

Summary and Assessment

Table 7 contains a summary of salient points of the above analysis. It shows that for expected average annual production of 1 million pounds live weight, or 700,000 pounds processed weight, and the current price range of $2.25/lb to $3.25/lb for pan-sized salmon, that: 1) the break-even price is near the high end of this price range; 2) break-even production levels generally exceed expected average annual farm production; 3) acceptable rates of return only occur at prices exceeding this price range. In sum, the economics of salmonid culture as configured for this analysis, do not justify the installation and operation of a Hawaii salmon farm.

TABLE 7. SUMMARY OF ECONOMIC FEASIBILITY INDICATORS

Item	Break Even	Expected
Profit[1]	—	$470,616 to $215,384
Price (per pound)	$2.94	$2.25 to $3.25
Production (in pounds)[2]	633,728 to 909,162	700,000
Rate of Return[1,2,3]		
—On Investment	14%	-12.34% to 5.65%
—On Operating Cost	14%	-23.01% to 10.53%

[1] Assumes 1 million pounds of produced salmon and price range of $2.25 to $3.25 per pound of processed salmon

[2] For the current price range of $2.25 to $3.25 per pound of processed salmon

[3] Fourteen percent is the current rate of return on an alternative investment (Baa bonds) with assumed equivalent risk to a Hawaii salmon farm. It is used as a benchmark to assess Hawaii salmon farm rates of return.

This conclusion could change if: (1) costs of production could be reduced, (2) production could be increased, or (3) prices for the marketed product could be increased significantly above current levels. Achieving any one of these possibilities or some combination could alter the economics of a Hawaii salmon farm.

Annual operating costs could be decreased through various means. This includes: electricity purchase at rates less than those specified in the study; design changes to reduce materials, equipment, and construction costs; or, a different, less costly technological configuration. Such changes in system design or technology however, could alter other costs, leaving the net effect uncertain. In any case, any combination of such cost reducers would have to reduce annual operating costs by a minimum of 30% for the farm to break even at a price of $2.25 per pound, the lower end of the current price range for pan-sized salmon. Thus, cost reducers, if feasible and implemented, do not guarantee a significant change in the economics of the farm.

Annual farm production could be increased by using more intensive growout methods. This includes items such as oxygen injection and increased stocking densities. Such methods could increase both risk and operating costs which again leaves the net outcome uncertain. Regardless, farm profitability is not very sensitive to annual production level changes. At 840,000 pounds of processed production, 20% above expected levels, and a price of $3.25/lb, the farm would give a rate of return on investment and operating cost of 10.36% and 17.03%, respectively. This would not seem adequate compensation given risk inherent in such an investment and rates of return on stocks, bonds, and other securities.

An alternative method to intensively use the production facility would be to raise salmon year around. This posits the ability to obtain salmon eggs from April to June. Eggs for this period could come from sources in the southern hemisphere, such as New Zealand, Chile, or Australia where salmon runs are 6 months out of phase with the northern hemisphere. Alternatively, a Hawaii salmon farm could produce its own eggs from captive broodstock. This scheme would not only provide a steady source of eggs for the Hawaii operation when required, but it would also provide a separate source of income from the sale of excess eggs. If eggs could be obtained from either of these sources, it would allow two or more production cycles each year.

Increased annual production spreads the fixed costs over more units of production and consequently reduces the break-even farm price. Assuming all variable operating costs in Table 2 doubled, fixed operating costs remained constant, and production doubled over the projected level, the break-even farm price becomes $2.46/lb. This is less than the $2.94/lb break-even price at the projected 700,000 pounds annual production for one production cycle per year. Given current price ranges for pan-sized salmon, however, this does not guarantee profitability. Further, additional risk and uncertainties inherent for such a farm could reduce maximum production levels while increasing operating costs, leaving the economics virtually unchanged.

A different approach to positively affect the economics of a Hawaii salmon farm would be to increase the farm price. This might be achieved through a marketing program promoting "Hawaii" pan-sized salmon as a unique product or as a product of equivalent quality to large-sized salmon. Although this scheme may be good in theory, very few Hawaii-based aquaculture promoters have been successful with such programs. Additionally, other conditions would negatively affect this promotional effort. First, mainland-grown pan-sized salmon already have established markets at or near saturation. Second, consumer preference for larger-sized fresh salmon and derivative products have a long-standing tradition which pan-sized salmon would not likely supplant (Stern and Ure, 1984). Third, marginal benefits from any promotional program (i.e., increased prices) may not exceed the marginal cost of the program. Promotional programs may in fact be required for a Hawaii salmon farm to merely maintain current price levels in the face of increased market competition from (1) increased catches of wild Pacific salmon, (2) increased imports of high-quality Norway-grown salmon to U.S. markets, (3) increased production of mainland-grown pan-sized salmon, and (4) increased mainland production of low-priced pan-sized trout competing for the pan-sized market. In summary, it is unlikely promotional efforts could increase prices sufficiently above current levels to significantly alter the economics of a Hawaii salmon farm.

An alternate means to obtain higher prices would be to produce an alternative species of salmon and/or to grow the salmon to a larger size (e.g., 4 to 9 pounds). Alternative species are the Atlantic and sockeye salmon. The Norway-grown Atlantic salmon is the most popular cultured salmon currently marketed in the United States. The sockeye salmon is the most preferred species in the Japanese market because of its dark red flesh (Martin, 1985). Salmon sold in both markets obtain prices twice those for pan-sized salmon. The feasibility of growing alternative species of salmon to larger sizes in the facility as designed is unknown and beyond the scope of this evaluation. Additionally, if successfully grown, increased revenues from the sale of larger-sized salmon may not exceed increased production costs to raise them.

CONCLUSION

The installation and operation of an OTEC salmon farm in Hawaii does not appear economically justifiable at this time. Profitable price and production levels are above those projected for the farm as configured. Other technologies, sites, configurations, and operational strategies may increase production and/or reduce costs. Additionally, market strategy and promotional efforts may raise prices. Any one of these factors or some combination of them could significantly alter the economics of a Hawaii OTEC salmon farm. However, assessing their feasibility and whether they would have net positive economic effects is beyond the scope of this analysis. This suggests additional research be conducted to demonstrate the technical and operational feasibility of the production factors, whether marketing and promotional efforts could raise prices above current levels and, most important, if these variables would significantly alter the economics of a Hawaii OTEC salmon farm.

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EPILOGUE

OTEC aquaculture research at the Natural Energy Laboratory of Hawaii and the prior related research in the U.S. Virgin Islands provide a solid foundation for commercial OTEC aquaculture ventures and for additional research and development. As a result, there are currently three prototype commercial aquaculture ventures at NELH, with other prospects in the wings. The existence of these ventures is either directly or indirectly related to the pioneering research collectively done at NELH during 1982–84.

Whether or not one concludes that aquaculture is now the dominant physical presence at NELH, one can safely say that the aquaculture presence is pervasive. This situation was unforeseen when NELH was originally conceived. The original thinking was that NELH would serve primarily as an engineering test-bed for OTEC and other alternative energy production schemes. Although aquaculture was given its due in the original plans, neither the course nor the magnitude of aquaculture ventures was fully anticipated.

The existing commercial ventures notwithstanding, there are further, new prospects to be explored such as aquaculture "seed" production. Specifically, hatchery operations to produce salmonid eggs, bivalve larvae and spat, and shrimp postlarvae hold great promise because of the low water costs involved and the small size, low shipping weight of the product which strengthens their export potential.

In addition to aquaculture seed production, other bright prospects include additional kinds of algal and seaweed production; bivalve production; bivalve depuration; and holding operations for lobster and/or other imported live products enroute to markets. Some of these possibilities have been considered; others have not. In some cases, an appropriate technology needs to be developed through on-site research and development which will tailor existing technology to OTEC conditions.

On the OTEC engineering side, much is still left to be done, as Tom Daniel has pointed out. Much of the original alternative uses of the deep water still remain untapped. The use of the cold deep water for air conditioning and freshwater production are two such ideas.

The NELH facilities offer unique and important research opportunities in engineering, physical/chemical oceanography, marine biology, and aquaculture. Some of these unique features and opportunities have been identified in this publication; other opportunities remain unidentified and unexplored.

All things considered, however, the future for OTEC aquaculture in particular looks bright. The rapid development of commercial aquaculture ventures at NELH bodes well for the future. This is particularly impressive given the relative newness of OTEC-style aquaculture and the limited research and development undertaken specifically for this fledgling industry.