The Center for Marine and Coastal Studies — North Carolina State University

CONFERENCE PROCEEDINGS

ENERGY FROM THE OCEANS FACT OR FANTASY?

JANUARY 27-28, 1976
RALEIGH, NORTH CAROLINA

Edited By
JEROME KOHL

REPORT NO. 76-1
UNC-SG-76-04

CENTER FOR MARINE AND COASTAL STUDIES
NORTH CAROLINA STATE UNIVERSITY
RALEIGH, NORTH CAROLINA

CONFERENCE PROCEEDINGS

ENERGY FROM THE OCEANS FACT OR FANTASY?

JANUARY 27-28, 1976
RALEIGH, NORTH CAROLINA

Edited By

Jerome Kohl
Extension Specialist
North Carolina State University

Report No. 76-1
UNC-SG-76-04

Conference Sponsored by Coastal Plains Center for Marine Development Services; UNC Sea Grant Program; NCSU Center for Marine and Coastal Studies; NCSU Division of Continuing Education, Industrial Extension Services.

Copies may be obtained at $3.00 from Al Lanier, Division of Continuing Education, NCSU, Raleigh, North Carolina 27607

CONTENTS

FOREWORD

These proceedings represent papers presented at the program titled "Energy From The Oceans Fact Or Fantasy?" held January 27-28, 1976 in Raleigh, North Carolina. This program was sponsored by the Coastal Plains Center for Marine Development Services; the University of North Carolina Sea Grant Program, the North Carolina State University Center for Marine and Coastal Studies; the North Carolina State University, Division of Continuing Education and the North Carolina State University Industrial Extension Service.

The objectives of the program were:

(a) Provide information on the Ocean as an Energy Source including as sources: Waves, Tides, Salinity Gradient, Wind, and Ocean Thermal. The information included a discussion of each resource, its prospect and problems.

(b) Provide information on the present government support program for Energy From the Oceans and an input on needed research and development.

(c) Provide information on possible environmental, political, economic and legal effects of Ocean Thermal Energy Conversion Plants.

(d) Provide information on the possibility of Ocean Thermal Energy Conversion Plants off the Southeastern Atlantic coast.

The program was intended for:

(a) University faculty in scientific, engineering, political, legal and economic fields who are interested in programs for obtaining energy from the oceans and their possible involvement in such programs.

(b) Regional, state, federal, and local government individuals involved in the administration or support of marine and/or energy programs and who wish to be informed on the status and prospects of Energy From the Oceans.

(c) Representatives from industries that would be affected by Ocean Energy Plants. Industries could include shipbuilding; coastal engineering; marine surveys and environmental studies; electric utilities.

This program had its origin in May of 1975 when a planning meeting was held to discuss the possibilities of a program on Energy From The Oceans. Participants in this planning meeting included:

Leigh Hammond
  Assistant Vice Chancellor, University Extension, North Carolina State University
Dirk Frankenberg
  Director, Marine Sciences Program, University of North Carolina at Chapel Hill
B. J. Copeland
  Director, Sea Grant Program, North Carolina State University
Phillip Hill
  Coastal Plains Center for Marine Development Services
L. Jay Langfelder
  Director, Marine Sciences Program, North Carolina State University
Daniel Textoris
  Associate Administration Dean for Research, University of North Carolina at Chapel Hill
R. A. Mabry
  Director, Continuing Education, North Carolina State University
Wayland Griffith
  Director, Engineering Design Center, North Carolina State University
George Holcomb
  Dean Research Administration, University of North Carolina at Chapel Hill
Paul Taylor
  Head Science Education Division North Carolina Department of Public Instruction
Jerome Kohl
  Extension Specialist, Nuclear Engineering, North Carolina State University
John Canada
  Associate Dean for Extension, North Carolina State University
Charles Cooper
  Industrial Extension Services, North Carolina State University

Following the planning meeting, I made a visit to Washington and obtained suggestions on possible speakers from Dr. Robert Cohen of the Division of Solar Energy at ERDA and from Frederick E. Naef, Lockheed Missiles and Space Corporation. These suggestions were brought back to a program committee comprised of the following:

B. J. Copeland
  Director, Sea Grant Program, North Carolina State University
Dirk Frankenberg
  Director, Marine Sciences Program, University of North Carolina at Chapel Hill

Wayland Griffith
    Director, Engineer Design Center, North Carolina State University
Jerome Kohl
    Extension Specialist, Nuclear Engineering, North Carolina State University, Chairman of Program Committee
L. Jay Langfelder
    Director, Marine Sciences Program, North Carolina State University
Bruce Muga
    Head, Civil Engineering Department, Duke University

The program committee developed the program, the papers for which are included in these proceedings. The design of these proceedings follows the pattern set by Dr. Gordon L. Dugger of the Applied Physics Laboratory of The John Hopkins University in the excellent proceedings he produced for the Third Workshop on Ocean Thermal Energy Conversion, Houston, Texas, May 1975.

Our ability to put on the program and to print these proceedings is in no small measure the result of the assistance provided by Beverly C. Snow, Jr., Executive Director of the Coastal Plains Center for Marine Development Services who assisted in funding of the program and in its presentation. Drs. B. J. Copeland and L. Jay Langfelder provided continuing guidance as the program details evolved. Mrs. Johnnie Braswell handled the typing of many of the papers. I am responsible for actual selection of speakers and topics and for the final assembly of the program. I hope that you find this material useful and as interesting as did those who participated in the workshop itself.

Jerome Kohl, Program
Chairman, Engineering
Extension Specialist,
North Carolina State
University

Michael E. McCormick
Professor of Ocean Engineering
U. S. Naval Academy
Annapolis, Maryland

and

Robert Cohen
Chief, Ocean Thermal Branch
Division of Solar Energy
Energy Research and Development
 Administration
Washington, D. C.

Abstract

An overview of renewable ocean energy resources is presented, including waves, tides, currents, salinity gradients and thermal gradients, along with the utilization of ocean coolness and the use of the ocean as "real estate" for the conversion of solar radiation and wind energy.

Introduction

The world's oceans provide at least five renewable energy resources: thermal gradients, waves, tides, currents, salinity gradients. These resources are derived from energy that originates as solar radiation or, in the case of tides, from gravitational forces. This paper is a discussion of the potential applicability of these resources to U. S. energy needs.

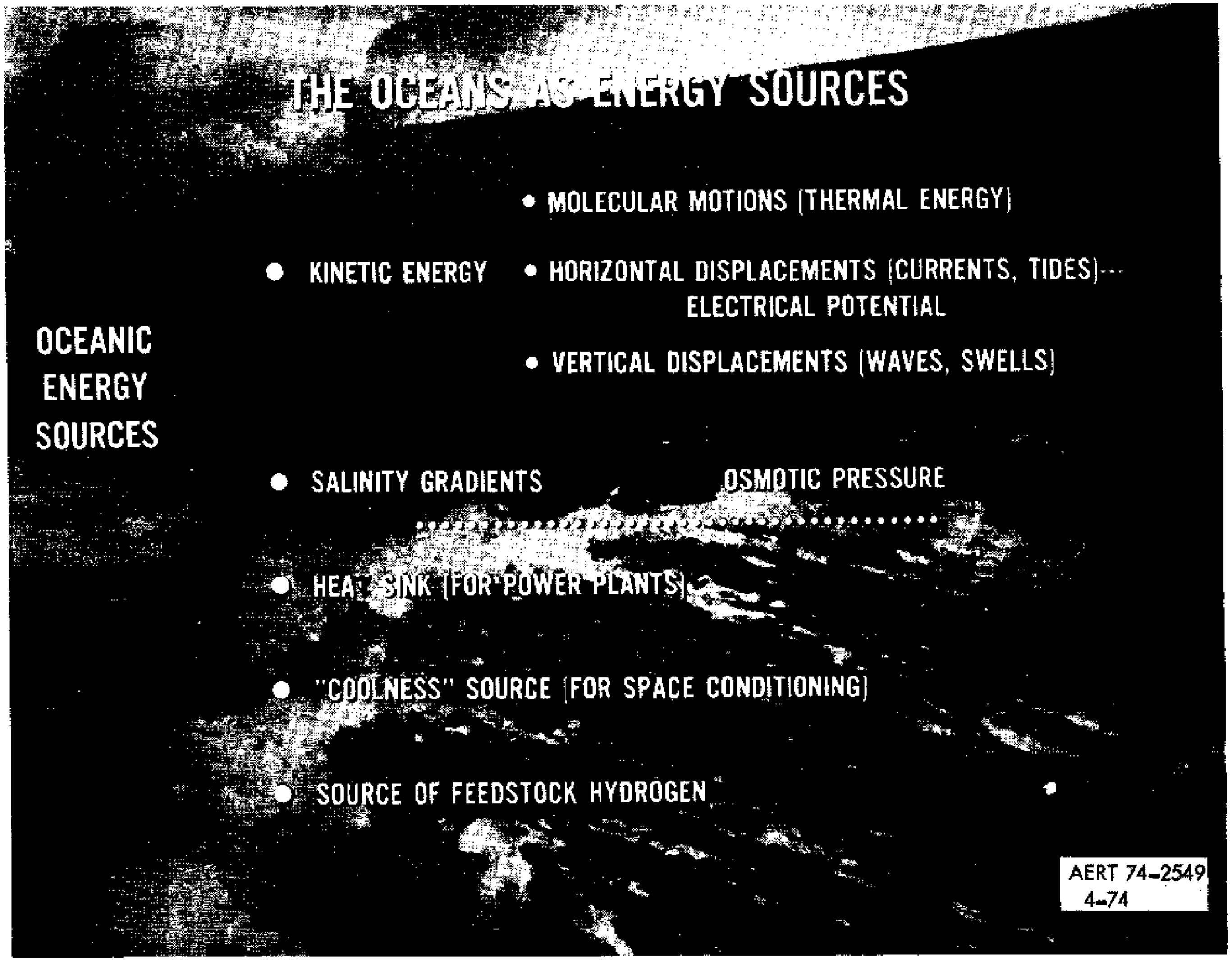
Ocean Energy Sources

The oceans serve as natural collection and storage devices for solar and gravitational energy. The resulting energy is manifest as waves, tides, currents, salinity gradients and thermal gradients. The first three of these energy resources are conspicuous forms of kinetic energy; the last two are inconspicuous. Accordingly, man has recognized and succeeded in utilizing these kinetic energy forms throughout recorded history, and they are still of interest in the quest for alternative energy resources. Figure 1 is an attempt to catalog the oceanic energy sources.

The surface of the ocean converts solar radiation into thermal energy, and the resulting warmed surface water is maintained at a temperature significantly greater than the cold, nearly freezing water at depth. This temperature difference, known as a thermal gradient, can be used as an energy source. Similarly, differences in salinity--i.e., salinity gradients -- between the surface water and water at depth, or between river water and ocean water at mouths of rivers, correspond to differences in osmotic pressure from which energy can be derived.

Besides the five renewable ocean energy sources mentioned above, the oceans provide several less direct sources of energy, as summarized in Figure 1. For power plants located near or on the ocean, the cooling water that can thereby be made available constitutes a "heat sink", an indispensable adjunct to the operation of a power plant. Similarly, cooling water from the ocean can be circulated for space conditioning of buildings. Also, the ocean provides a ready source of feedstock hydrogen for energy storage once energy is provided to dissociate sea water.

The oceans can further be utilized as "real estate" for the technological collection and conversion of solar radiation, such as by using photovoltaics or thermal collectors. Also, wind energy can be harnessed at sea, submarine geothermal energy can be extracted,



THE OCEANS AS ENERGY SOURCES

OCEANIC
ENERGY
SOURCES

- KINETIC ENERGY
  - MOLECULAR MOTIONS (THERMAL ENERGY)
  - HORIZONTAL DISPLACEMENTS (CURRENTS, TIDES)--- ELECTRICAL POTENTIAL
  - VERTICAL DISPLACEMENTS (WAVES, SWELLS)
- SALINITY GRADIENTS OSMOTIC PRESSURE
- HEAT SINK (FOR POWER PLANTS)
- "COOLNESS" SOURCE (FOR SPACE CONDITIONING)
- SOURCE OF FEEDSTOCK HYDROGEN

AERT 74-2549
4-74

FIGURE 1

and energy crops can be produced by photosynthesis from solar radiation through open-ocean mariculture.

The global power dissipation in the five key renewable ocean energy resources has been estimated by Isaacs and Seymour (1973), and is summarized in Figure 2. Thus, Figure 2 gives some idea as to the resource potential of these forms of energy. However, regional considerations also need to be introduced into such estimates.

Salinity gradients, tides and waves will be discussed further at this Workshop in a paper by McCormick (1976); thermal gradients will be discussed in several other papers to be presented at this Workshop; currents--especially the potential of utilizing the Florida Current--have been discussed in the Proceedings of the MacArthur Workshop (1974). The remainder of the present paper provides a brief overview of the five renewable ocean energy forms.

Wind waves

The wind blowing over the ocean surface generates surface waves through the action of shear stress and turbulence. There have been many attempts to utilize the energy of surface waves, some of which have been moderately successful. It has yet to be resolved whether wave energy represents a potentially substantial energy source for the United States that is also technically and economically attractive. Some studies are now underway to clarify these matters. Those studies are being sponsored by the Energy Research and Development Administration (ERDA), and their results will be presented at a Workshop to be held at the end of May, 1976.

Tides

There have been two successful attempts to utilize the tides. One of these is a demonstration facility that has been constructed in the U.S.S.R. The other is an operational power plant that was constructed on the mouth of the Rance River in France. That plant produces an average power output of about 240 Megawatts. The exploitation of tidal power is usually feasible if the tidal range exceeds about 5 meters. In the continental United States, this criterion is met only in the vicinity of Maine and Alaska. ERDA and the Corps of Engineers are presently reviewing United States tidal energy possibilities.

Currents

The technology for utilizing the energy contained in ocean currents was examined at the MacArthur Workshop on Energy from the Florida Current, and is reported in the Workshop Proceedings (1974). The Florida Current was estimated to contain a kinetic

ESTIMATES OF POWER DISSIPATION RATES IN THE OCEANS

JOHN D. ISAACS AND RICHARD J. SEYMOUR

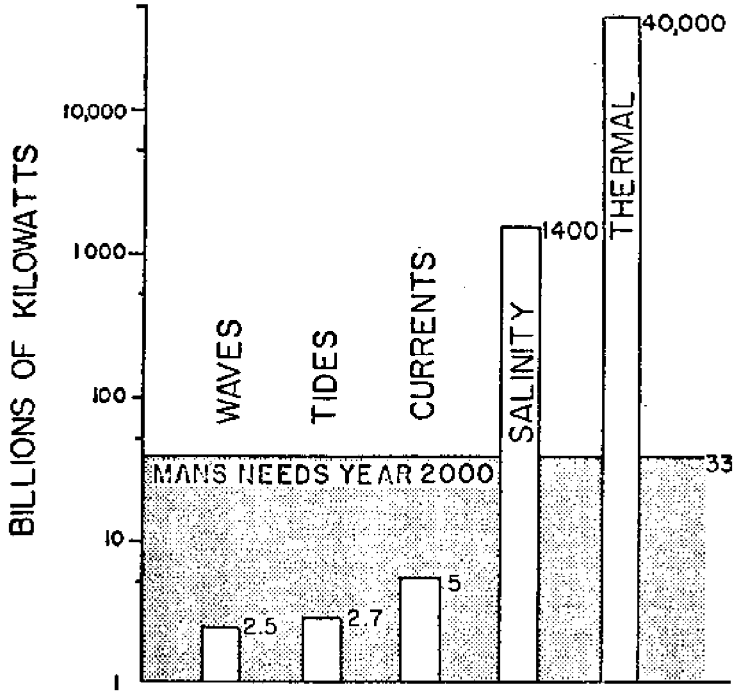


Figure 2

AERT 74-2569
4-74

power of about 25,000 Mw. if 8% of that power could be harnessed at an efficiency of 50%, this would provide a net power of 1000 Mw.

Salinity gradients

Although the energy available in the form of osmotic pressure arising from salinity gradients is appreciable, it is most feasible to extract it at mouths of rivers. Accordingly, the estimate in Figure 2 of power dissipated in salinity gradients corresponding to the amount available at mouths of rivers would be comparable to that available from waves and tides. Conversion and utilization of this energy source, however, would be complicated with both technological and environmental problems. The largest salinity gradients occur where fresh water rivers empty into hypersaline bodies of water, such as the Great Salt Lake. Much smaller, yet significant, gradients occur where rivers empty into oceans. Four studies are presently being supported by ERDA to investigate technical, economic, and environmental aspects of this subject, and the results will be presented at a Wave/Salinity Gradient Workshop to be held at the end of May, 1976.

Thermal gradients

The possibility of exploiting thermal gradients between warm ocean surface waters and cold waters at depth to produce electricity is presently being explored by the ERDA Ocean Thermal Energy Conversion (OTEC) program. That program is now entering a hardware phase, leading to testing and engineering development of components, subsystems and systems for harnessing the extensive amounts of low-quality heat that are available, provided that this process can be accomplished at competitive cost and is technically and environmentally viable. The thermal resource is available at tropical and sub-tropical latitudes, and could be converted into electricity as an end-use, and/or the energy can be utilized to produce energy-intensive products such as hydrogen, ammonia, and aluminum.

References

1. Isaacs, John D. and Syemour, Richard J., "The Ocean as a Power Resource", Intern. J. Environmental Studies, 4, 201-205 (1973).

2. Proceedings, MacArthur Workshop on the Feasibility of Extracting Usable Energy from the Florida Current, held at Palm Beach Shores, Florida--1974 Feb. 27-March 01--Available from Harris B. Stewart, Jr., Editor--Director, NOAA AOML, 15 Rickenbacker Causeway, Virginia Key, Miami, Florida 33149--(1974).

3. McCormick, Michael E., Salinity gradients, tides and waves as energy sources, these Proceedings (1976).

WAVE POWER - NODDING DUCK WAVE ENERGY EXTRACTORS

S. H. Salter, D.C. Jeffrey and J.R.M. Taylor

Department of Mechanical Engineering,
University of Edinburgh,
Mayfield Road, Edinburgh 9

Abstract

Advocates for all energy technologies must answer the following questions:

Is there enough?

Is it safe?

Is it secure?

Is it environmentally acceptable?

How do we get it and what will it cost?

This paper attempts to answer the questions for wave power.

Is there enough?

Waves cannot approach solar radiation in total amounts of energy but they provide greater power density than is available to wind machines. A wave installation is the second stage of a windmill of which the first stage is the open sea. The size of waves depends on the fetch of sea as well as the strength and duration of the wind. Instrument observations of waves in British waters have been made by Draper of the British Oceanographic Data Service(1). I based my first estimate of power levels on his findings. I concluded that the average power density in the North Atlantic was about 80 kilowatts per metre(2). Work in progress by Mollison and Buneman using more refined techniques suggests that it is actually more than 90 kilowatts per metre. The peak of supply is in winter. Waves are directly complementary to sun.

Visual observations from around the world have been collected by Lewis(3) and by Hogben and Lumb(4). They show that power densities in open oceans are nearly always greater than 10 kilowatts per metre. Draper(5) presents a table which shows that a fetch of 100 kilometres is sufficient to produce large enough waves to be worth harvesting. North Atlantic waves on a 500 kilometre front could produce all the electricity now used in the U.K. If ways can be found of transporting energy from offshore stations then the world wave potential is several times the present world demand for all forms of energy.

Is it safe?

Our designs for wave power installations are unmanned but from time to time plant will need to be brought in for servicing. This activity will be like fishing. Men's lives will be part of the price of wave power just as we pay in Britain about one life per week for coal and twenty lives a day for road transport. With money and commonsense and sound legislation we can reduce this price. Most of the accidents will happen to yachtsmen attracted by calm water and good winds.

Ships usually keep to the economical line between two points. This leaves very large infrequently visited polygons inside the great circle routes. Wave power installations will be more or less stationary in marked chart positions and well equipped with navigation warnings. They should be less of a hazard to ships than other ships or the land itself. However no system of human devising is perfect and there will be many small accidents, some medium ones and a few large ones.

Is it secure?

Security is affected by the interruption or exhaustion of the flow of some ingredient. These days we have to consider interruption by political or terrorist activity. A widely dispersed target with parallel redundant connections and controls is not attractive to terrorists. Indeed, it would take a hard-working group to make much impression on 500 kms of wave plant. There are no secondary hazards.

In the very long term, wave power is as secure as we could wish. We know that the winds will blow for ever. In the very short term, wave power is at least predictable. We know enough to prepare reliable forecasts for twenty-four hours ahead so that stand-by plant should have plenty of warning. In the medium term, wave power security can be expressed in terms of a statistical probability. Figures 1 and 2 show summer and winter scatter diagrams with wave power density contours for the North Atlantic. Each entry gives the probability in parts per thousand of the occurrence of particular combinations of significant wave height and zero crossing period. In British waters, wave power is worth having for 80% of the time and in the winter this figure moves to 90%. The probability of zero power is not zero. The Central Electricity Generating Board have found a week in May 1961 in which there was no wave power at a station in the Atlantic. A secondary source must be provided. There is no diurnal variation and so no match with daily pattern of demand. Methods of short and medium storage will become important when the amount of wave power exceeds the base load.

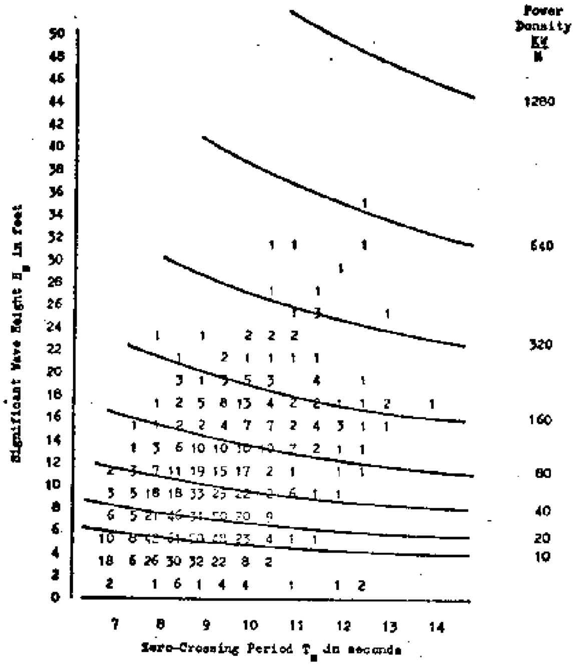
Is it environmentally acceptable?

Wave power introduces no new chemicals or heat into the biosphere. But it does introduce a temporary diversion of heat. There will be a very slight cooling of water on the beaches. We could measure the effects by putting a sufficient number of electric fire elements into the surf zone and noting the rise in temperature. This rather extravagant experiment is now done continuously by those generating boards who draw cooling water from the sea and put into it twice the energy that they deliver to consumers.

The size of wave to leeward of a wave power installation will be reduced. When incident power density is less than 80 kilowatts per metre there will be a calm. When it is greater than 320 kilowatts per metre the reduction will be negligible. Figures 1 and 2 show how often these conditions will occur. People using the sea lanes inshore will find life less exciting and the requirements for hardihood and seamanship will be less exacting. I do not believe that the present causes of beach formation and erosion which make such a difference between the east and west coasts of the Hebrides should be much affected. But if they were, then we have many examples of beaches in sheltered seas to help us predict the outcome. The wave power engineer will, if he can, avoid sites with high current flow. If mistakes are made and silting of harbours results then the machinery may be resited.

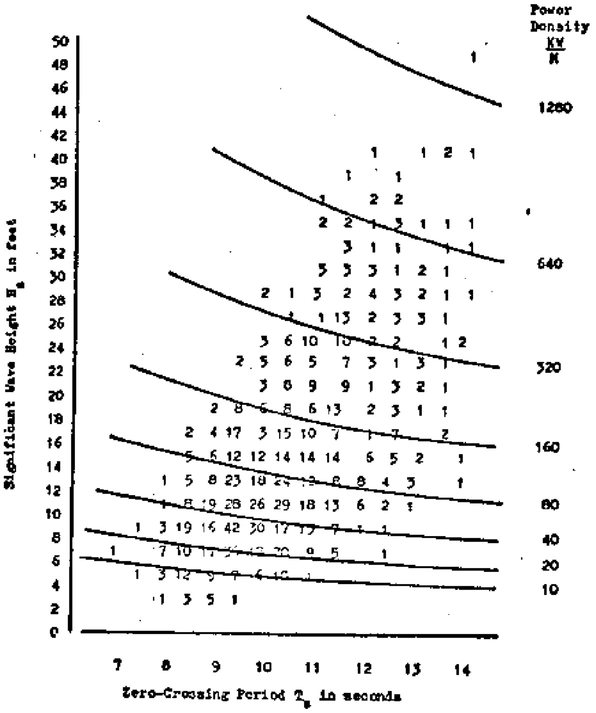
The difference in cost between overhead cables and buried or submerged ones is so large that there is very little question about which will be used. In Britain the rich wave fields are off the Hebrides in a depopulated area. Lines will have to be built to take the power to the hydrodynamically underprivileged high-consumption areas like London and the South-East. They will affect the breathtaking beauty of the Scottish Highlands.

FIGURE 1.



SUMMER SCATTER DIAGRAM
I.O.S. DATA FROM STATION 'INDIA'

FIGURE 2.



WINTER SCATTER DIAGRAM
I.O.S. DATA FROM STATION 'INDIA'

Among the many requirements of modern industry are power, cooling water, deep harbours and easy disposal of waste. Some industrialists may feel that threats of nationalisation and factory regulations restrict their freedom and they might be tempted to set up at sea. I believe that waste disposal from an offshore installation in international waters could be dangerous and difficult to regulate in the present state of law, and that this is the only serious environmental risk inherent in wave power. Perhaps this risk is really inherent in having industrialists.

<u>How do we get it and what will it cost?</u>
To calculate the cost one should add up the cost of research and development, land, factories, processing plant, fuel, labour and interest charges that can fairly be carried by the project and divide this by the output produced over some period of time. This tedious exercise is not always done amid the excitements of technological advance. The answer is most needed at the start to help in deciding between competing proposals but cannot be known with any certainty until the end. It is particularly difficult to decide whether or not some piece of research done many years before has to be paid for by this account or another.

We set out to build Atlantic plant rated for an average of 50 kilowatts costing £20,000 (1974) per metre, giving a target capital cost of £400 per kilowatt. After considering a wide number of possible mechanisms and conducting model tests of several, we settled on the one shown in Figures 3 and 4.

It consists of a number of 'duck'-shaped segments rotating about a common backbone. Each duck is designed to be slightly heavier than the water it displaces so that if it should break it will sink. The whole structure has a very low freeboard so that it could be easily submerged. The rear surface of each duck is a cylinder coaxial with the centre of rotation so that no water is displaced behind and no rear wave created. The front curve is designed to match the displacements of water in approaching waves. The natural 'nodding' period is designed to coincide with the wave period where maximum efficiency is required and attempts are made to broaden the frequency response. Laboratory tests on single units on a fixed mounting show an extraordinary efficiency for monochromatic and mixed spectrum waves. Figure 5 shows the preferred model curve achieved by September 1975. (6)

In full scale designs prepared by my colleague Eric Wood each duck runs on rollers which are the bodies of commercially available rotary hydraulic pumps(7). High pressure oil drives hydraulic swash plate motors coupled to electrical generators at sea. Whittington is studying the problems of transmission of electricity to land(8). There are about ten undersea electrical routes in the world. A.C. transmission uses cheaper terminal equipment but needs extra copper to carry the large capacitive charging currents. D.C. requires rectification and inverting terminals but evades synchronisation problems. Cheaper D.C. cables are better for long links but it seems that the change-over distance is quite close to

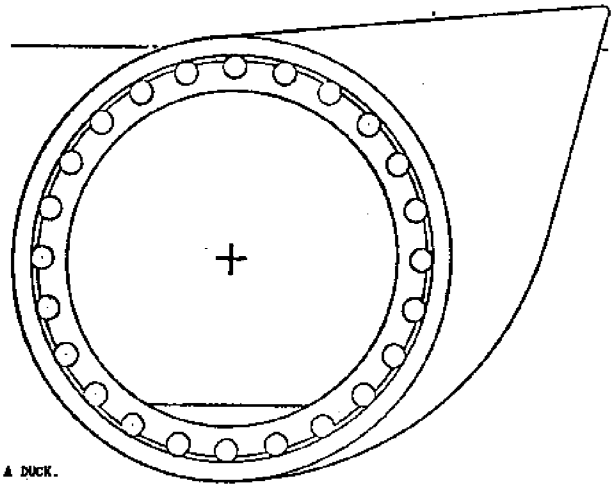


FIGURE 3.
A CROSS SECTION OF A DUCK.

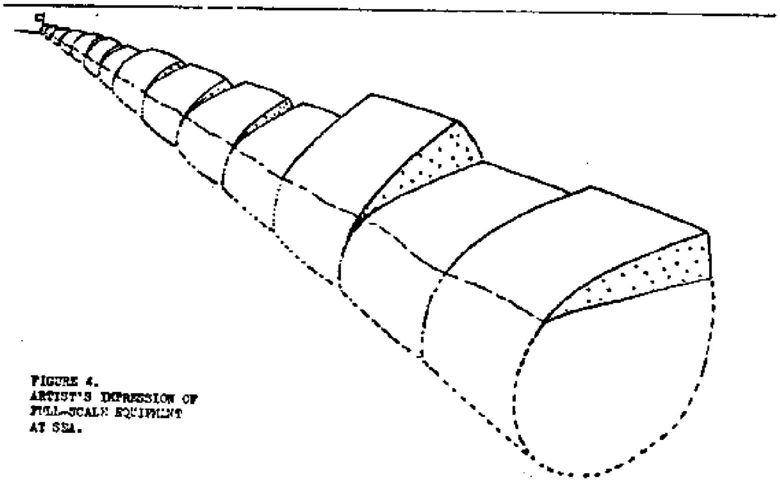


FIGURE 4.
ARTIST'S IMPRESSION OF FULL-SCALE EQUIPMENT AT SEA.

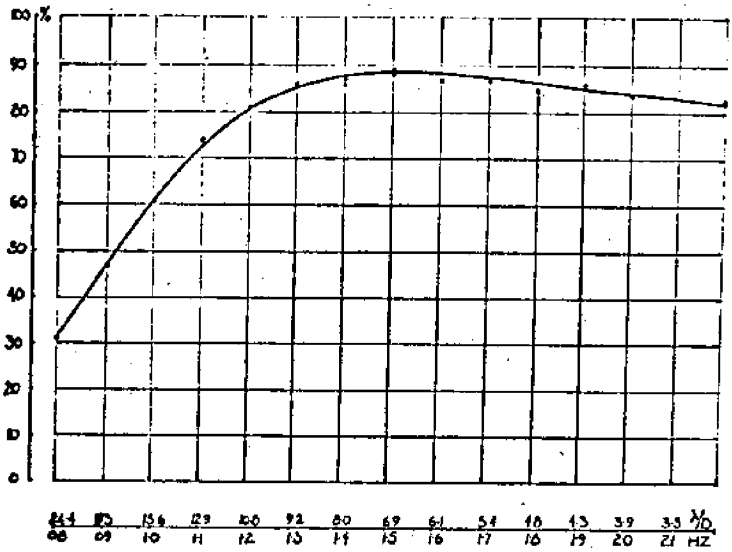


FIGURE 5. EFFICIENCY CURVE FOR SINGLE 100 mm DRAUGHT MODEL ON FIXED MOUNTING. SEPTEMBER, 1975

the distance we expect to use.

Each metre length of structure displaces just over one hundred tons. One string of ducks will be about 500 metres long. The concrete, electrical generating plant, hydraulic parts and labour can all be costed fairly accurately. The result is within the target. The only problem lies in the strength requirements of the common backbone. The laboratory models are mounted on fixed bearings. At sea this reference must somehow be synthesised. It is clear that a sufficiently long backbone would span a large enough sample of wave phases so that it would average the alternating components of wave force. But the resulting structure would suffer a dangerous bending moment in the centre. We calculated that the really extreme '50 year wave'(9) would require steel costing ten times more than we could afford. The crucial question was whether we could find ways of evading those bending moments. The key to the problem has been found by Eric Wood. His design gives a rigid backbone for low bending moments which turns into a flexible one for high bending moments. A model tested in a multi-directional sea behaved as we had hoped.

Our approach is by no means the only one, and efficiency itself is of no concern when the gods pay for the waves. But in structures of this size the wave forces depend on the displacement, and the cost depends on strength, so that there are powerful economic incentives to get the most power out of the lowest displacement. We are certainly interested in the highest possible efficiencies for those times when wave power levels are low.

Wave power plant can be added in amounts of £10,000,000 at a time. All engineers make mistakes. If we are wrong we can be stopped early. Wave power plant consists of multiple small modules which will have the advantage of repetitive production. Each will take only a few months to build so that interest during construction is low. The makers of the hydraulic parts advise us that we will need to replace bearings and seals after six years. Ships need antifouling treatment after two years. This work will have to be done in protected water and will be the major running expense. Ships can be made to last for forty years and indeed, the first ferro-cement boat made in 1855 is still in perfect working condition. It is an obvious disadvantage of wave power that almost all the costs come at the beginning but that benefits may accrue to future generations.

Chapman(10) gives figures for the energy content of raw materials. Structural steel consumes 132,000 kilowatt hours per ton, while cement needs 2,200 kilowatt hours. If we use a five to one aggregate ratio, we will need to run our plant for 2,000 hours to earn the energy to build the main structure.

Conclusions

I claim that the answers to the questions at the beginning of this paper are as follows:

There is enough wave energy.

Its safety is acceptable. The dangers are clear and well understood.

Its security is as good or better than other technologies.

Wave power is clean and cool.

There are at least four possible techniques for getting energy from waves under active study in Britain. I think that nodding ducks are best but I am hardly a detached observer. As our model work continues the cost estimates fall. At least the costs of finding the costs are low.

I rest my case. Let the ultimate judges be our children and, of course, the sea.

Acknowledgment

This work was supported by The Department of Industry.

References

(1) Draper, L. & Squire, E.M., Waves at Ocean Weather Ship Station 'India' (59°N, 19°W), Trans. Inst. Nav. Arch., 109, 85-93 (1967).

(2) Salter, S.H., Wave Power, Nature, Vol. 249, No. 5459, 720-724, June 21, 1974.

(3) Principles of Naval Architecture, (Ed. John P. Comstock) for E.V. Lewis on Motion of Ships in Waves, Chap. IX, 624-626, (S.N.A.M.E., New York, 1967).

(4) Hogben, N. & Lumb, F.E., Ocean Wave Statistics. (H.M. Stationery Office, London, 1967).

(5) Darbyshire, M. & Draper, L., Forecasting wind generated sea waves, Engineering, Vol. 195, 482-484, April 5, 1963. (Reprinted as Paper No. 1, Symposium of Offshore Drilling Rigs 1970, by Roy. Inst. Nav. Arch.).

(6) Salter, S.H., Jeffrey, D.C. & Taylor, J.R.M., The Architecture of Nodding Duck Wave Power Generators, The Naval Architect, 21-24, January, 1976.

(7) Hydrostatic Transmission Systems, (Ed. J. Korn) (Intertext Books, London, 1972).

(8) Whittington, H.W., Transmission of Electricity from Wave Power Devices, Edinburgh Wave Power Project Report 33.

(9) Draper, L., Extreme Wave Conditions in British and Adjacent Waters, Proc. 13th Coastal Engineering Conference 1972, Vancouver, Canada. (Reprinted by Am. Soc. Civ. Engrs.).

(10) Chapman, P.F., Energy Policy, March, 1975 Vol. 3, No. 3, 231-243.

OCEANIC WINDPOWER

William E. Heronemus, Professor of Civil Engineering
in the University of Massachusetts (Amherst)

Abstract

The oceanic windpower resource is examined macroscopically. One region in which that resource is known to be rich is then examined in greater detail. Six different products associated with the U.S. energy industry are then proposed as products that could be provided from windpower systems. A closer look at the possible size of that Atlantic Coast resource is taken and an estimated total annual productivity is weighed against the last year's 73 Quad U.S. energy budget: a 12 percent impact from this one solar replenished resource alone is predicted. Statements as to system Energy Budget and Environmental Impact are made. Conclusions suggest that windpower systems, including oceanic windpower systems, should be advanced rapidly by the United States.

1. The Resource

Most of the atmosphere surrounding Earth is in constant motion. The summation of its kinetic energy at any time yields numbers of the order of 10^{14} kilowatts. This energy flux usually increases with height above surface up to some level measured in tens of kilometers above which it decreases to zero by the time the upper edge of the atmosphere is reached. The vast preponderance of that energy will be found in the layers above 1000 feet of altitude. But, fortunately for the windpower enthusiast, an astronomically large amount (compared against all of man's energy demands) lies below the 1000 foot level, and is therefore in many instances available to practical windpower extraction systems.

The windpower resource is a seasonal resource and a regional resource as well as one whose energy distribution varies with altitude. The windpower engineer has one other natural phenomenon going for him: natural dissipation of kinetic energy into low grade heat at the earth-atmosphere interface. This is one of the mechanisms by which nature maintains the heat balance of Earth within the solar system. A significant amount of wind energy must be constantly frittered away into low grade radiant energy that can find its way back away from Earth into space. The energy content of a column of atmosphere above the Earth's surface tends to flow downward: this is the natural replacement mechanism for the frittering process. The windpower enthusiast places his device into that natural frittering process and thus makes a very tiny human footprint on a global system while satisfying his man-made demands. The extraction of wind energy is in a sense almost self-healing, (up to a reasonable level, of course).

The energy content of the winds is a regional phenomenon. The ocean in the temperate zones, because of its generally low surface temperature, seems to be able to intensify the velocities of the winds, particularly where they tend to blow across the coast line to seaward in a strongly ordered prevailing pattern. This phenomenon appears to prevail along the U.S. Atlantic coast in the path of the Westerlies, from the Canadian border in the north to the Virginia-Carolina region in the south. Those winds move with increasing velocities on out toward that "big vacuum pump" which operates to the south of Iceland. They will have come across the eastern mountain chain where they have been converged upward, then they diverge downward toward the coast, cross the coastline and blow out to sea with ever increasing energy.

There are, of course, the seasonal, and in some seasons, daily, and in any season, the unpredicted deviations from that pattern where energy diminishes, or where the prevailing pattern fails. But, all-in-all, to a station out in 600 feet or so of water near the edge of the continental shelf, from Charleston to the Canadian-U.S. boundary off Halifax, there is a very long vertical plane in which the energy content of the winds is of large-scale significance to the windpower enthusiast. It is to that region that the preponderance of this report will address itself. Figure (1) shows that line along the edge of the shelf. Figure (2) taken from Jack Reed's work[1] gives some clue as to the energetics of the wind out there. Figure (3), going back to Sverre Peterrssen in 1938[2], adds to the evidence of intensifying wind energetics moving from the U.S. Atlantic coast eastward.

2. <u>Offshore Windpower System Products</u>

A. Jumping all the way from the resource across the system diagram to the right hand side, the delivered product, it is suggested that one finds at least these products appropriate for windpower systems moored along our Atlantic shelf-edge:

(a) Electricity for heating and cooling buildings
(b) Electricity, firm-power-on-demand
(c) Electricity, peak-power
(d) Hydrogen, for the fueling of aircraft and other transportation systems
(e) Nitrogenous fertilizer
(f) Dispersal of stack effluents from ocean sited dirty coal burning central stations.

There is considerable diversity in that short list, and perhaps the last item raises the highest level of curiosity: we will come to that later.

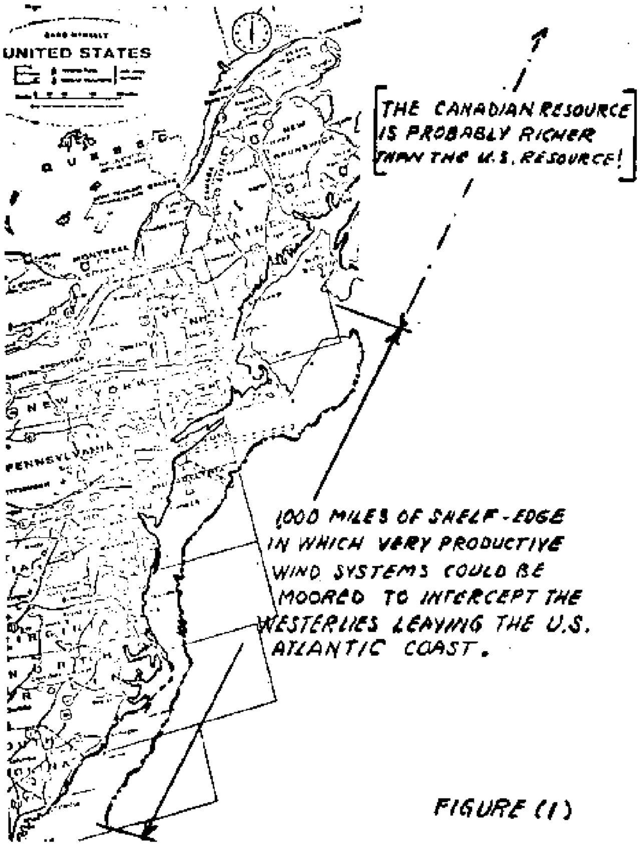
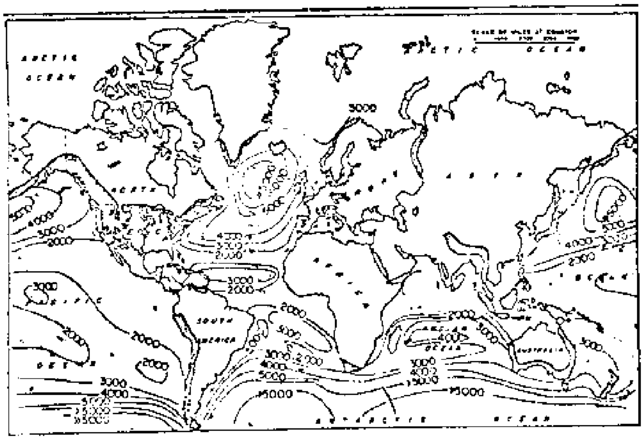
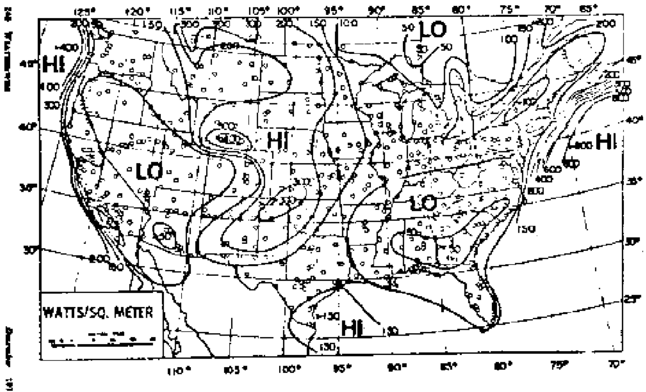


FIGURE (1)



ESTIMATED PRODUCTIVITY, KWH PER YEAR, FOR EACH KW OF WIND GENERATOR AT 150'. -Sverre Petterssen-

FIGURE 2



AVAILABLE WIND POWER-ANNUAL AVERAGE

FIGURE 3

B. Heating and Cooling Buildings with Offshore Windpower

Well over 30 percent of the U.S. population (at one time it was close to 40 percent) live on 2 percent of the area of the contiguous 48 states in the Northeast Corridor. Most of the buildings occupied by those people require warmth in the heating season and many of them require mechanical cooling and ventilation at the peak of the summer. The possible advantage of some combination of windpower and solar thermal power system for such buildings, particularly those in the colder end of that corridor, was first suggested by the U.Mass Energy Alternatives program[3], and is the subject of an investigation now underway on the Amherst campus. That project is interested in the first instance with small single-building Wind Furnaces located immediately adjacent to those buildings (in most cases) as suggested by Figure (4). Many numbers have been made for that system throughout the rural, widely spaced suburban, village and town institutional places to permit saving of almost 600 million barrels of petroleum per year. [Our current import level totals about 2500 million barrels per year.] While thinking of this as a land-based system for coastal towns and for the varied features of Long Island, New York, interest was immediately aroused as to what might be done with the systems moored offshore in the more productive winds[4]. One suggestion comes from a study of Figure (5). The Harbor Campus of the University of Massachusetts is on the coast in a rather windy place. It is an all-electric campus whose electricity bill is almost one-fourth of its total annual budget! (As John Kenneth Galbraith might say, it is not an institution of higher education, but rather just another CONSUMER in our affluent society!) Figure (5) shows the 1974 electricity consumption and the 1975 consumption, reflecting significant savings (and concurrently creating some minor discomfort). Superimposed thereon, dash-dot, is the calculated monthly productivity of a wind generator at that site. Also, superimposed thereon, dot-dot-dot, is the calculated monthly productivity of the same size wind generator at the same height above surface, but down over Nantucket Shoals at the site of Texas Tower Three. The coincident shapes of the curves are the significant features of Figure (5), as well as the relative quantities produced by the machine at sea at Nantucket Shoals compared against the machine ashore at Columbia Point. The shapes suggest that raw energy, as the wind will blow, has an excellent chance of matching northeast coast building heating loads with very little storage buffer between resource and load. And therein lies the major element of economic success for this application of oceanic windpower. The heating system is perhaps as simple as floating wind generators paralleled into high voltage d.c. undersea cable feeding a completely separate distribution network ashore. There may be a need for relatively small thermal

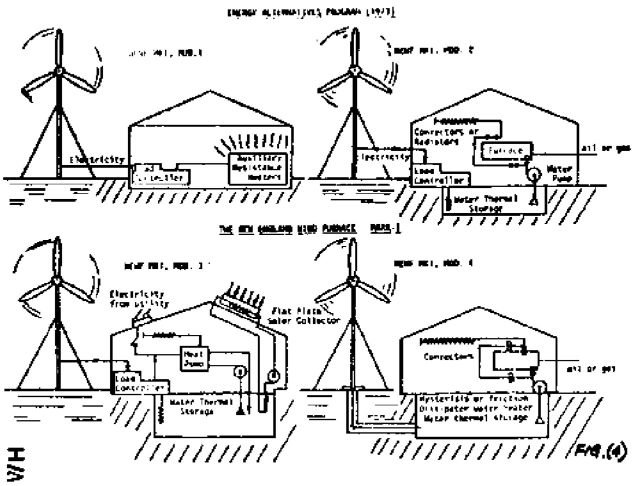
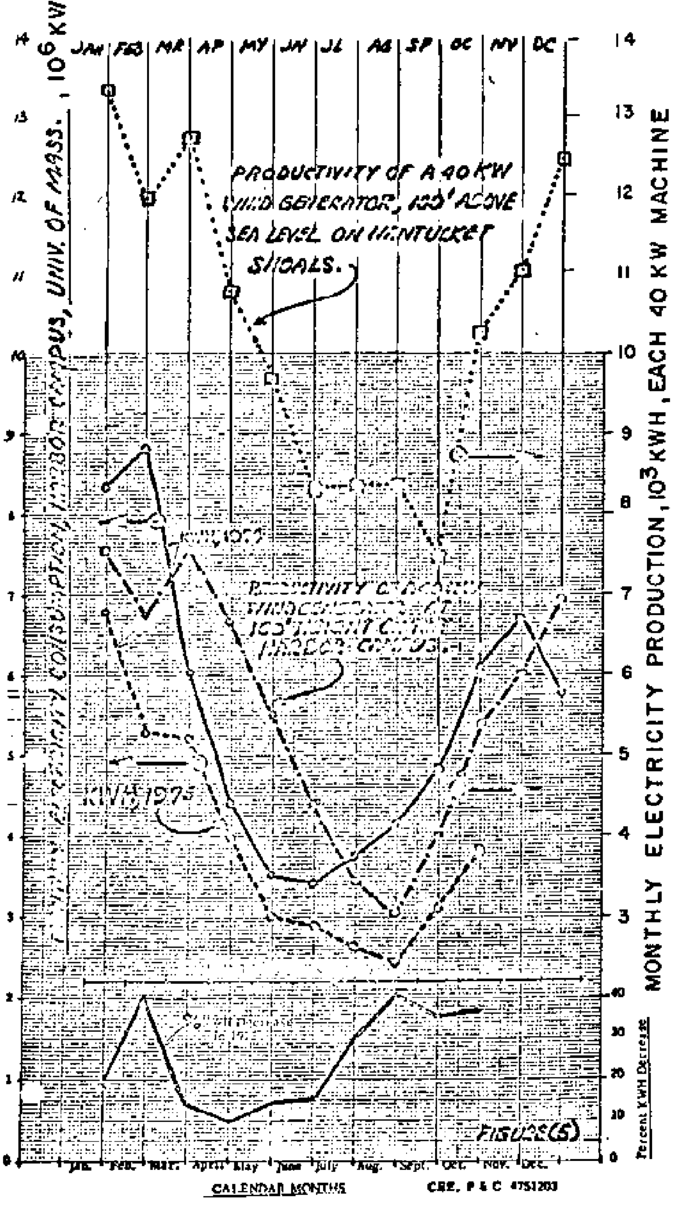


FIG.(4)



FIGURE(5)

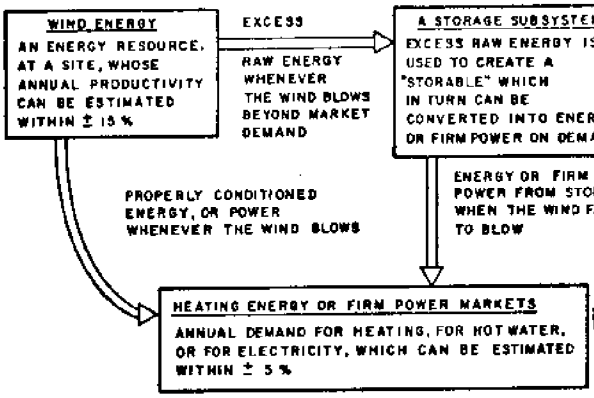
storages in each customer's building, to guard against some number of hours' continuous period of very low wind. (Examination of tables of hourly data from Texas Towers 2, 3, and 4 suggest, however, that during the heating season, the need for even 4 hours of storage is questionable.) For the air conditioning months, some storage may be required: the least expensive version may be underwater compressed air storage adequate for 48 hours' operation.

C. Providing Electricity, Firm-Power-On-Demand, with Offshore Windpower

The resource along that line of Figure (1) is huge, and its energy content over a year's time can be expected to be reproducible within at most a ±15% variability, and probably as little as ±3% variability[5]. Dambolena's work[6] with tables of hourly data, four years' experience, showed the smaller number. But second-by-second assurance required in a system which offers electricity, firm-power-on-demand makes mandatory a very dependable storage buffer between resource and market. Figure (6) suggests the nature of the problem and its possible solution, and Figure (7) adds detail to one suggested solution. This of course was the problem which intrigued HERONEMUS the most when he prepared the 1972 paper "Pollution-Free Energy from Offshore Winds"[7], and it was the major subsystem concern of Dambolena during his 1974 work[6].

The hydrogen storage subsystem has received attention for this purpose at UMass.; unfortunately the most useful results are not yet published but will come out in the thesis of Wm. J. Rowan, Spring 1976. For the purpose of this discussion Figures (8) and (9) suggest the basics of the system. The firm-power-on-demand pattern must always be met. There may be short intervals in which essentially all of the peak demand of the market must be satisfied from the hydrogen store. That requirement, though very large, still does not set the size of the storage. The size is set by calculating a running sum of required flows out of station 4 in Figure (9), while satisfying second after second of the year's load demand, and being fed, second after second at 1, the wind system's productivity. A pseudo load demand curve like Figure (8) for one whole year assists in matching inputs to outputs. Using a very crude approximation and simplified calculation procedure, Heronemus in [7] estimated that 40 percent of the annual energy product had to enter the storage subsystem. Using tables of hourly wind data and synoptic hourly load-demand data, Dambolena showed that number to be closer to 12 percent [6].

Since both [6] and [7] were completed, there has been some thought that no hydrogen should ever come ashore, i.e., the reconversion of hydrogen to electricity should be done at sea, possibly within the same hulls that house the electrolyzer units, and only electricity-in-cable would be sent ashore. Among other things, this opens up the possibility of using the reversible H_2-O_2 electrolyzer fuel cell,


WIND ENERGY
AN ENERGY RESOURCE, AT A SITE, WHOSE ANNUAL PRODUCTIVITY CAN BE ESTIMATED WITHIN ± 15 %

EXCESS
RAW ENERGY WHENEVER THE WIND BLOWS BEYOND MARKET DEMAND

A STORAGE SUBSYSTEM
EXCESS RAW ENERGY IS USED TO CREATE A "STORABLE" WHICH IN TURN CAN BE CONVERTED INTO ENERGY OR FIRM POWER ON DEMAND

PROPERLY CONDITIONED ENERGY, OR POWER WHENEVER THE WIND BLOWS

ENERGY OR FIRM POWER FROM STORAGE WHEN THE WIND FAILS TO BLOW

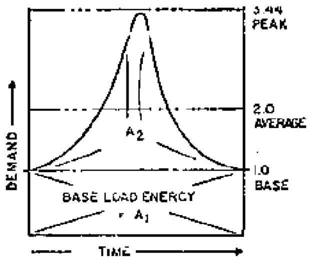
HEATING ENERGY OR FIRM POWER MARKETS
ANNUAL DEMAND FOR HEATING, FOR HOT WATER, OR FOR ELECTRICITY, WHICH CAN BE ESTIMATED WITHIN ± 5 %

Fig. (6)

CANDIDATE STORAGE SYSTEMS FOR WIND POWER SYSTEMS

Fig. (7)

1. THE HYDROGEN LINK
   - (a) ELECTROLYSIS OF DISTILLED WATER YIELDS HYDROGEN GAS
   - (b) HYDROGEN CAN BE STORED AS A GAS, AS A LIQUID, CHEMICALLY BOUND IN METAL HYDRIDES, OR CHEMICALLY COMBINED TO PRODUCE METHANE GAS OR WOOD ALCOHOL
   - (c) HYDROGEN CAN BE BURNED AS FUEL IN MANY HEAT ENGINES OR COMBINED WITH ATMOSPHERIC AIR TO PRODUCE ELECTRICITY IN FUEL CELLS.
2. COMPRESSED AIR
   - (a) CAVERN OR UNDERWATER BUBBLE STORAGE OF WIND COMPRESSED AIR
   - (b) EXPANSION OF COMPRESSED AIR VIA TURBINES TO DRIVE GENERATORS -- TURBINES CAN HAVE FUEL ADDED IF DESIRED
3. HEAT
   - (a) STORAGE BY ELECTRICALLY HEATING WATER OR ROCK TO LOW TEMPERATURE, OR BY HEATING PHASE-CHANGE SALT TO HIGH TEMP.
   - (b) LOW TEMP. OR HIGH TEMP. STORED HEAT CAN BE USED FOR WATER AND BUILDING HEATING. HIGH TEMP. CAN BE USED TO DRIVE HEAT ENGINES.



$A_1 = A_2$.

FIGURE (8)

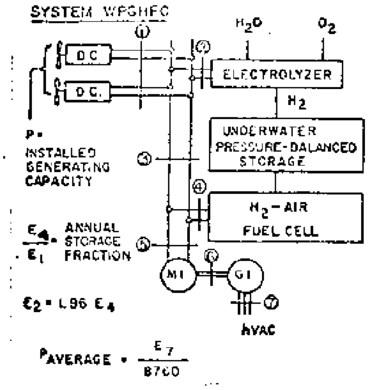


FIGURE (9)

probably reducing total cost considerably, as well as other possible cost savings should new underseas cables of the high voltage high power size be found more attractive than pipelines. Rowan's work to date shows pipelines up to 44 inches in diameter, built and emplaced to 1974 technology standards, as quite reasonable in cost. More cable data will be required to complete that trade off.

The nature of the offshore wind stations is a wide-open matter in our opinion. The three-wheel large diameter two-bladed wind stations of [3], repeated here in Figure (10) are probably not the way to go. As a minimum, three blades rather than two would be called out by UMass. at this time. Quite a number of variants on the arrays of smaller diameter 3-bladed machines are being considered by us at this time. Perhaps the first wind station to go to sea may comprise a star array of six 35 foot diameter 3-bladed wind wheels, each turning a 60 kilowatt generator for a total maximum station output of only 360 kilowatts. Such a design in considerable detail will be published soon. Toward the other end of the spectrum we are looking at a floating wind factory ship, conceived in the first instance to drift slowly on the end of a dragging anchor line out in the relatively shallow high seas, but very amenable to fixed mooring along that 1000 mile line of Figure (1). Each of those stations could carry as many as 48 megawatts of generators arrayed in "masts and yards" configuration. Indeed, the basics of masts, yards, shrouds, stays, and spreaders must be understood, then injected into structural features that can capitalize on them as well as on circa 1976 materials. We think that the semi-submersible hull has a great deal to offer, hulls with a minimum of surface-penetrating displacement and a maximum of pendular stability, which means displacement as near the surface as possible without unacceptable surface excitation as well as huge quantities of low-cost deep ballast weight.

The projected economics for large-scale firm-power-on-demand systems were probed in both [6] and [7]. Dambolena gives the wider spread of results some of which are reproduced here in Figure (11). Heronemus has been criticized for his "low cost estimates" in certain quarters: before 1976 is over it is planned to have demonstrated in working hardware that wind generators in the 3-bladed 35 foot diameter size driving generators up to 100 kilowatts in size may cost as little as 100 dollars (1976) per kilowatt (everything that is carried aloft in the support structure but sans the support structure). Such heavy loadings on that swept diameter make no sense at all in near-ground shore-side windfields, but make much sense out where the winds are really energetic.

D. Providing Electricity, Peaking Power

It is quite easy to see that once one has provided the storage subsystem which must be associated with an offshore windpower firm-power system,

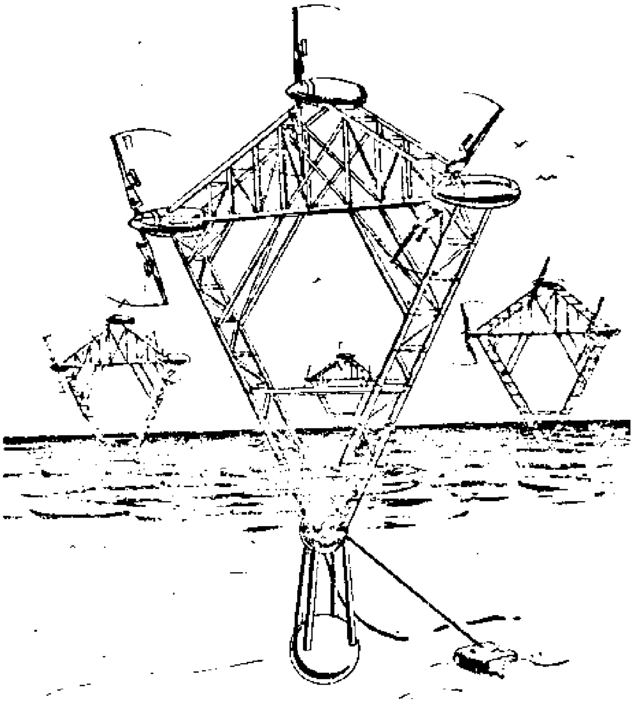


FIGURE 10

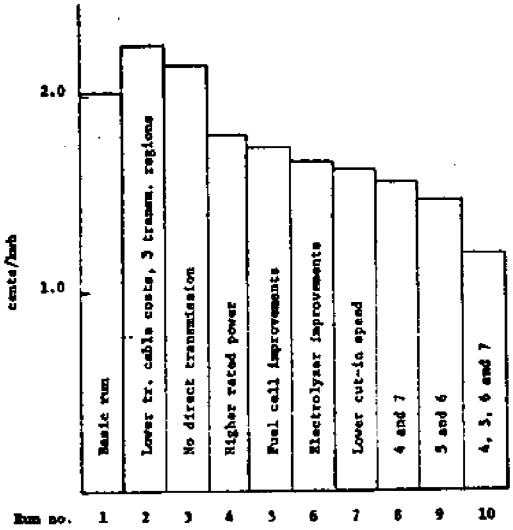


Figura IV.4 Selected Computer Runs Compared

FIGURE 11

one is in an excellent position to sell peaking power which commands a handsome price differential over the average kilowatt hour price. This may be a good ploy to improve the economics or reduce the apparent risk of the first systems. If the least-cost available base-load electricity is converted to peak power by a pumped-back hydraulic system, the peak power product is usually worth 1.7 times as much as the baseload kWh. Other peaking systems which consume fossil fuel may show an even higher ratio now that fuel costs have escalated so much.

E. Providing Hydrogen, for the Fueling of Aircraft and Other Transportation Systems

Assume that the Offshore Windpower System of references [6] and [7] was modified so that:

(a) only electricity flowed ashore via transmission cable,
(b) the electrolysis units were located at Logan Airport, Boston Harbor, and were fed pure distilled sea water,
(c) enough hydrogen liquefaction plant also were installed at Logan to liquefy hydrogen at the maximum power rate of the system, capable of delivering that Liquid H_2 to tanks at Logan, thence to aircraft (or buses and trucks).

What would be the cost per pound of that liquid hydrogen at that sea coast refueling location?

That OWPS [7] has an installed generating capacity of 82.17 x 10^6 kilowatts.

Assume that the electrolyzers to be used are of the currently available type which use 22.5 kWh to produce one pound of hydrogen gas [6],[7]. We will assume that the liquefaction-purification plant is similar to that described in 1975 by the Linde Division of Union Carbide [8]. That liquefaction plant requires 5.7 kWh of electricity to convert 1 lb. hydrogen into liquid hydrogen. Allowing for some pumping power, each pound of liquid H_2 (LH_2) will then use up 29 kWh of electricity sent to it by cable from OWPS. The annual productivity (gross electricity) of that OWPS is 335 x 10^9 kWh. Therefore 11.55 x 10^9 lbs of LH_2 will be produced per year.

It is improbable that that much LH_2 could be used at Logan alone, but the analysis will assume such is possible.

The maximum possible rate of production of hydrogen, when every installed kW of generating capacity is producing at 100% load factor, would be 82.17 x 10^6 divided by 29 = 2.833 x 10^6 lbs per hour. To handle that rate of H_2 flow, a total of 33,996 tons LH_2 per day, 13.6 of the Linde 2500 Ton Per Day Liquefaction Complexes would be required. Each of those complexes per [8] require $0.649 x 10^9 capital investment, a total investment here of $8.826 x 10^9. The annual operating costs, people and expendables, for those 13.6 complexes would be $0.399 x 10^9.

Going back to Section 9 of the OWPS paper [7] we describe this new LH_2 producing system as:

(a)	83 wind units plus electrolyzers plus interconnecting cables, etc, in place:	$17.050 x 10^9
(b)	Transmission cables adequate to bring the entire electricity production into Boston Harbor:	2.398 x 10^9
(c)	13.6 Liquefaction Complexes at Logan Airport, in Boston Harbor:	8.826 x 10^9
	Total Capital Investment:	$28.274 x 10^9

Assume a cost of money of 8.5%, 1% amortization (25 year life), 0.5% for insurance, 1% for taxes and 0.5% for interim replacement. Fixed charge rate = 11.5%:

$$\text{Fixed Charges} = \frac{(0.115)(28.274 \times 10^9)}{11.55 \times 10^9} = \$0.281 \text{ per pound of } LH_2$$

Annual operating expense for OWPS = 0.09 cents per kWh = 2.61 cents per lb. LH_2.

Annual operating expense for the Ashore Liquefaction Complex = $\frac{\$0.399 \times 10^9}{11.55 \times 10^9 \text{lbs.}}$ = 3.45 cents per lb of LH_2. Total cost per lb. of LH_2 = $0.281 + $0.034 = $0.341 per pound.

Reference [8] says that Liquid Hydrogen produced from coal costing $0.75 per 10^6 Btu (which corresponds to $19.50 per ton for 13,000 Btu per pound coal, their estimate for the highest coal price in the 1985-2000 period), would cost essentially the same, 34.18 cents per pound. That coal price must mean mine-mouth, however, because 13,000 Btu per pound coal cost an average of $51.00 per ton delivered in large quantity to the UMass. (Amherst) campus in FY '75, and probably costs at least $30 per ton received pierside in Boston Harbor. $30 per ton coal would boost the 34.18 cents per pound cost of LH_2 up to 49.44 cents per pound LH_2.

LH_2 @ 34.1 cents per pound and a higher heating value of 55,000 Btu per lb. corresponds to gasoline at 19,000 Btu per lb. sold for 11.8 cents per pound or about 83 cents per gallon. 11.55 x 10^9 lbs. of LH_2 per year would provide the fuel equivalent of 0.635 x 10^{15} units of thermal energy (0.635 Quads), about 1 percent of the 1975 total U.S. energy demand.

The Linde study team also suggest[8] that the capital cost of those Liquefaction Complexes could go down by 20% if numbers of them were built. Others working on electrolyzers suggest a total energy cost of as little as 15 kWh per lb. of hydrogen released plus a significant drop in electrolyzer cost in the future. The 5.7 kWh per pound of hydrogen electrolyzed includes 4.0 kWh for various inefficiencies in available systems, some of which could certainly be reduced if a large market for such systems existed. And some modest investment in even shallow-water pressure-balanced on-the-line gaseous hydrogen storage could probably halve the size of liquefaction plant required by smoothing out incoming hydrogen flow. When any or all of those feasible future improvements are injected into the calculation, the cost of windpower produced liquid hydrogen at a north-east Atlantic coastal station can be dropped down into the 22 cents per pound category. 22 cent per pound LH_2 "corresponds" on a straight energy content basis to 54 cents per gallon gasoline. There are some factors which NASA would apply which favor the LH_2 over gasoline aviation fuel, thus further increasing the relative value of the LH_2, but those factors are not readily at hand, therefore not used here.

E. Providing Electricity for the Production of H_2 from Distilled Sea Water Plus the Production of Nitrogen from Air, Then Their Combination into Nitrogenous Fertilizer

The cost of ammonia and ammonium nitrate fertilizers, produced today around the world principally from hydrogen reformed from nature gas or other petroleum refining product and atmospheric nitrogen, has risen dramatically in the past two years. Serious proposals have been made in Kansas to use prairie windpower for the production of ammonia. If it makes sense out there it makes 2 to 3 times as much sense (economically) offshore the Atlantic coast! Indeed, the 48 megawatt wind factory ship located as far out over the continental slope as a dragging anchor is feasible, an ammonia factory ship which discharges its product into aqueous ammonia tank barges of the "CATU'G" system[9], could manufacture and deliver liquid ammonia via the port of New Orleans and the river waterways to the agricultural heart of the country at competitive prices. Moving out beyond the 1000 Mile Line of Figure 1, such wind factory ships deployed over shoal high seas regions like The Flemish Cap could turn a handsome profit.

F. Providing Dispersal of Stack Effluents from Ocean Sited Dirty Coal Burning Central Stations

The offshore westerly winds could be used effectively by this country in the energy industry simply to blow away (disperse) stack gas effluents from large semi-submersible coal burning central stations located at least 35 miles to the eastward of the coast line, moored in less than 600 feet of water. High sulfur coal from Appalachia deep mines is now worth about 7 dollars per ton, mine-mouth, and about 10 dollars per ton at the coal pier opposite Newport News. Loading, a 500 mile or less trip to sea, and powered unloading into coal tanks should add no more than 3 dollars per ton, bringing the fuel cost, at the power plant, to about 50 cents per million Btu. With an assured injection temperature of no more than 40F at any time of the year and a minimum of efficiency-robbing stack gas cleanup system installed, a heat rate of 8500 Btu per kWh should be easily achieved in such plants. Fuel cost would then be 4.25 mills per kWh. Capital cost for this kind of plant would be $800 per kW installed, plant in place on the end of a 35 mile cable. At 15.5 percent fixed charge rate and at an average life time plant factor of 80% (customary for ruggedized medium sized coal burning plants) fixed charges would be 18 mills per kWh. Operating and Maintenance charges would be three times their shore-side value or 7 mills per kWh. One thus could have base load electricity at the shoreside end of a 35 mile submarine cable for 30 mills per kWh. The winds would blow the stack gas effluents seaward where their precipitates will be accepted rather graciously by a sea accustomed by nature to acceptance of similar products. There are periodic reversals of that wind toward the shore but the 35 mile distance plus a deliberately low stack would prevent significant gas from reaching the beach, ever. There is no chance that any LWR nuclear base load plant of the future will be able to deliver base load electricity for 32 mills per kWh. Electricity generated from "clean-coal" products will have to pay for fuel close to the liquefied-hydrogen-from-coal prices given in E, above. This use of the Offshore Winds is nowhere as desirable as the other direct windpower processes, but it is certainly an alternative, cleaner and more economic than any of the nuclear or clean-coal processes now receiving preferred treatment by the Energy Establishment.

3. How Large is the Windpower Resource Off the U.S. Atlantic Coast?

Here in the Commonwealth of Massachusetts we have a Corporation president, a surplus physicist bomb-maker from Los Alamos days, who regales the Energy Establishment by ridiculing windpower produced by windmills placed all over the United States on one mile centers. The fact that his company earns over ninety percent of its income from the nuclear power program doesn't enter into his prejudice at all. Out at Oregon State there is another physicist apparently turned sour by the windpower hobby of his department chairman, who also enjoys pointing to a "line of windmills 1300 miles long". A major problem shared by both of those gentlemen is that they don't think big enough. When the United States does something really important to the economy, like building 7 million new automobiles per year, it thinks about a "26 thousand mile long line of automobiles per year". Wind systems of significance are not for the faint hearted or the small-thinkers who get upset at the thought of tens of thousands of windmills. We could use millions of them! We don't want 1300 miles of wind stations offshore: we want perhaps 30,000 miles -- many parallel rows, at one mile intervals, along that 1000 mile line of Figure (1). The reason for many rows is that each row would intercept only a portion of the oncoming wind. By the time the seaward-most row, had been passed, 100 percent of a vertical plane rising from that center row would have seen momentum interchange with a wind wheel.

Practical design studies suggest that that plane could rise to at least 500 feet above sea level with systems that could survive a 200 mph hurricane wind. It is possible that the plane might even rise to 1000 feet; but at this time we'll be content with 500 feet.

It is proposed that 35 foot diameter wind wheels, each allowed a 50 foot diameter working circle to insure that adjacent wakes do not expand into each other, be erected in lattice or billboard type arrays with the lowest row at axis height 100 feet and the upper row at axis height 500 feet. The productivity of those wind wheels has been calculated for a number of sites and sizes of generator. The 40 kW generator at Nantucket Shoals will be used here as a probable "average, desirable installation" just to show one answer to the question. Considerable effort and more data akin to the hourly data tables from TT2,3, & 4, for the rest of the Line would be necessary to give the best possible answer.

TABLE 1

Height of Wind Generator Axis Above Sea Level:	Predicted Annual Productivity, kWh, from a 35'x40 kW Machine
100'	126,000 kWh/year
150'	140,000
200'	151,000
250'	160,000
300'	168,000
350'	174,000
400'	179,000
450'	184,000 kWh/year
500'	187,000

TABLE 1 (continued)

Total Productivity For Vertical Column = 1.469 x 10^6 kWh for a specific power of 4080 kWh per kW per year.

For sake of comparison, though the numbers will not be used, five different sized generators, each driven by a 35 foot diameter wheel, at 100 feet above sea level at Georges Bank, are shown in Table 2.

TABLE 2

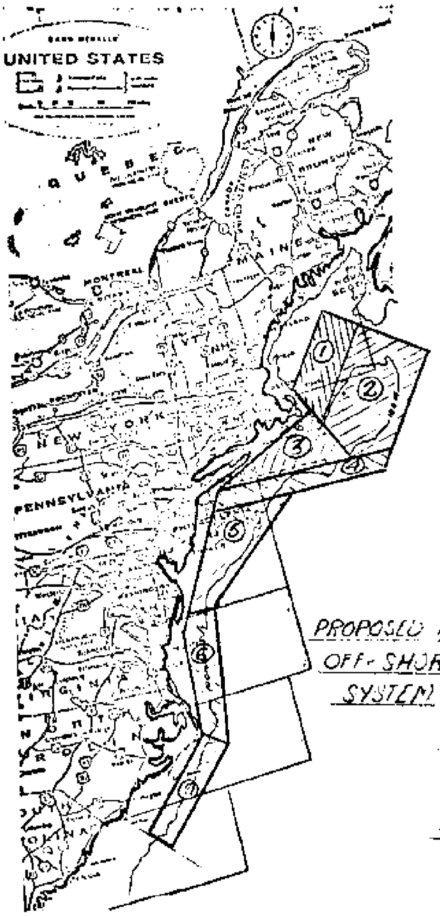
Size of Generator Fitted to 35' Dia. Wheel	Generator Size Relative to 40 kW	Annual Productivity Relative to 40 kW Productivity
40 kW	1.00	1.00
60 kW	1.50	1.29
80 kW	2.00	1.50
100 kW	2.50	1.60
120 kW	3.00	1.70

In 1000 miles of 5,280 feet each there could be 1.056 x 10^5 such vertical columns. The annual productivity across that plane, 100' to 500' above sea level is then 1.55 x 10^{11} kWh.

1.55 x 10^{11} kWh per year is about one-tenth of 1975's total U.S. electricity generation. The 1.55 x 10^{11} kWh generation would replace about 1.5 Quads of thermal energy (one Quad = 10^{15} British thermal units), about two percent of the 73 Quad Energy Budget of the United States, 1975.

There is no reason at all to restrict extraction to that single plane, however. There is a huge amount of energy being frittered away by those winds as they approach that line, and there is excellent opportunity to attempt to drag them down a bit before they move on out to sea. Kung[9] has said that the natural dissipative rate of kinetic energy into thermal energy at the air-surface interface in the path of the Westerlies could be as high as 15 watts annual average per square meter of surface. This rate decreases with decrease in latitude and is a very regional parameter.

There is considerable area inshore of the 100 meter line of Figure 1 and, of course, the huge expanse of ocean outboard of that line whose dissipative energy might be drawn into multiple lines of wind generators arranged and placed with ample clearance to avoid completely any micro interference effects. Figure (12) has been prepared to suggest how the region might be subdivided to make a gross estimate of windpower productivity. Seven regions are blocked out there. It is suggested for a first



PROPOSED ATLANTIC COAST OFF-SHORE WINDPOWER SYSTEM REGION...

FIGURE (12)

move that "extraction levels" be set varying with region and no greater than 10% of values extrapolated very loosely from the guidance of Kung:

TABLE 3

Region	Surface Area, Square Meters	Established Extraction Level	Maximum Installed Power
1	$23x10^9 m^2$	1.0 watts/m^2	$23x10^6$kW
2	$56x10^9$	1.5 watts/m^2	$84x10^6$kW
3	$24x10^9$	"	$36x10^6$kW
4	$22x10^9$	"	$33x10^6$kW
5	$33x10^9$	"	$49x10^6$kW
6	$26x10^9$	1.0 watts/m^2	$26x10^6$kW
7	$16x10^9$	0.5 watts/m^2	$16x10^6$kW

From other work done with the wind data available for Squantum, Mass., Georges Shoals, Nantucket Shoals, Nantucket Island and New York Shoals, it is quite certain that economic systems in each of those regions, using the latticed arrays of 3 bladed wind wheels in the 35 foot diameter region driving generators whose rating lies as small as 20 kW or as large as 120 kW can achieve specific powers as high as: For Regions (1) and (6), 3500 kWh per year per kW; For Regions 2, 3, 4, 5, and 6, 4000 kWh per year per kW; For Region 7, 3000 kWh per year per kW.

It is thus suggested that wind systems could be placed off the East Coast of the United States, in the areas shown in Figure (12), to a total installed power level of 267 x 10 kilowatts; and that their annual delivered raw energy product would be of the order of 1.02×10^{12} kilowatt hours per year. What impact could such an energy level have on a 73 Quad per year Total Energy Budget? Proceed as follows:

(A) Assume that one-fourth of those 10^{12} kilowatt hours per year were used for heating via the Wind Furnace concept to replace heating electricity:

$$(0.25x10^{12}\frac{\text{kWh}}{\text{year}})(\frac{3.413x10^3\text{Btu}}{\text{kWh}})(\frac{\text{3 Btu's of thermal energy}}{\text{1 Btu of delivered heating energy}})$$

= 2.56 Quads equivalent annual substitution

(B) Assume that one-fourth of those 10^{12} kilowatt hours per year were used for heating via the Wind Furnace concept to replace heating oil burned at the national average 0.63 efficiency:

$$(0.25\ x10^{12}\ \frac{\text{kWh}}{\text{year}})(\frac{3.413\ x\ 10^3\text{Btu}}{\text{kWh}})(\frac{1}{0.63})$$

= 1.35 Quads equivalent annual substitution

(C) Assume that the remaining one-half of those 10^{12} kilowatt hours per year were used for direct electricity application, substituting for electricity from unwanted nuclear power plants, whose overall efficiency will not exceed 0.33:

$$(0.50\ x\ 10^{12}\frac{\text{kWh}}{\text{year}})(\frac{5.413\ x\ 10^3\text{Btu}}{\text{kWh}})(\frac{1}{0.33})$$

= 5.17 Quads equivalent annual substitution

Thus a total of 9 Quads of a National Thermal Energy Budget of 73 Quads, 12%, could be obtained from an Atlantic Coast Offshore Windpower System alone.

4. Energy Budget

Preliminary estimates of primary energy investment in all parts of offshore windpower systems suggest pay-back periods between 12 and 16 months for hardware having at least 240 month useful life. The ongoing or operating energy budget is miniscule compared against any fuel consuming energy system. Construction periods for the largest of the floating wind stations envisioned to date are 12 months at the most with a 2 month or shorter period very likely for smaller systems. The laying of seabed cables and/or pipelines will require the longest performance periods.

5. Environmental Impact

The kinetic energy which man would remove from the oceanic winds along the Atlantic Coast is energy intended to be converted out there into low grade heat suitable for reradiation to outer space. The relocation of that energy degredation site a few hundred miles to the westward, in the path of those same westerlies, will probably have negligible effect on the global heat balance. The reduction in aeration of the ocean's surface by virtue of lessened wind-wave action is probably negligible from an eco-balance point of view, and perhaps desirable from many other points of view.

6. Conclusions

The oceanic windpower resource is large. The resource available to the Atlantic Coast of the United States, particularly the northeast coast could make a very significant and economic impact on the U.S. energy demand delivering several rather different products substitutable for those used now or planned in the future. Offshore generated electricity for heating buildings will have at least a 2 to 1 cost advantage over any nuclear generated heating electricity. Offshore windpower generated and liquefied hydrogen could turn New England and the Middle Atlantic states into clean fuel exporters rather than the dirty fuel importers they now are. Winds similar in productivity to those oceanic Atlantic Coast winds abound in many other parts of the world and could be used in even the most remote sites to create clean, economic energy products transportable to population centers. A useable technology baseline exists; development is certainly appropriate. A sense of urgency and appropriate application of capital could bring meaningful windpower systems on line probably faster than any other energy system available today. Undesirable environmental impact is thought to be negligible, certainly minimal in comparison against any combustion, fission or fusion process. Gulf Coast windpower could be meaningful but nowhere near as desirable vis-a-vis Texas-Oklahoma land-based windpower as is the case on the Atlantic Coast. Oceanic windpower along the entire Aleutian chain and the Alaska coastlines could probably be used, economically, to prepare energy products for consumption in the lower 48 states. The windpower process does not compete in magnitude with the ocean thermal difference process, but regionally, it makes more sense than any of the other solar energy processes. With the right kind of leadership, a 100% solar energy based energy economy is achievable for the United States by the year 2000. In one section of this paper it was suggested that thousands of miles of wind stations could be as important to this country as 26,000 miles of bumper-to-bumper new automobiles per year. This nation needs to create genuine energy self-sufficiency as soon as it can, and it should be clever enough to employ and raise the standard of living of its own citizens in the process of so doing. Energy self-sufficiency means complete freedom from domestic privately-held oil, coal and uranium resources just as much as it means freedom from foreign fuels. Windpower is one of the three solar energy processes that can meet all of the requirements for the early creation of an energy self-sufficient society, a comfortable society, a nation of haves with a minimum number of have-nots. Expansion of nuclear power can never achieve any of those vital goals. Expansion of the coal-burning economy could achieve only part of them and that only if coal resources are nationalized. Solar energy is the only winner: windpower is the strong lead horse of the solar energy team.

References

[1] Windpower Climatology of the United States, 1975, Jack W. Reed, Sandra Laboratories Report SAND 74-0348.

[2] Power From the Wind, 1948, Palmer C. Putnam, D. Van Nostrand-Rheinhold, N.Y., N.Y.

[3] "Wind and Solar Thermal Combinations for Space Heating," 1975, J.M. McGowan, W.E. Heronemus and G. Darkazalli, Proceedings, Tenth Intersociety Energy Conversion Engineering Conference @ Newark, Delaware, August 1975.

[4] "A Study of Existing Energy Usage on Long Island and the Impact of Energy Conservation, Solar Energy, Total Energy and Wind Systems on Future Requirements," 1975, by Dubin-Mendell-Bloome Associates, P.C., Consulting Engineers and Planners, for the Department of Environmental Control, County of Suffolk, New York.

[5] Electric Power From the Wind, 1945, Percy H. Thomas, U.S. Federal Power Commission.

[6] A Planning Methodology for the Analysis and Design of Wind-Power Systems, 1974, Ismael Gerardo Dambolena, Dept. of Industrial Engineering and Operations Research, University of Massachusetts (Amherst).

[7] Pollution-Free Energy From Offshore Winds, 1972, Wm. E. Heronemus, in Preprints, 8th Annual Conference and Exposition Marine Technology Society, Sept. 11-13, 1972, Washington, D.C.

[8] Survey Study of the Efficiency and Economics of Hydrogen Liquefaction, by The Linde Division of Union Carbide Corporation, April 8, 1975, Report No. NASA CR-132631, prepared under Contract NAS-1-13395 for the National Aeronautics and Space Administration, Langley Research Center, Hampton, VA 23665.

[9] Marine Engineering/LOG, Vol. LXXX, No. 13, December 1975, N.Y., N.Y.. page 64.

[10] "Large Scale Balance of Kinetic Energy in the Atmosphere," 1966, E.C. Kung, 1966, Monthly Weather Review, Vol. 94, pp. 627-640.

OCEAN THERMAL ENERGY CONVERSION - AN APPRAISAL OF ITS POTENTIAL

By
Frederick E. Naef
Lockheed Missiles & Space Company, Inc.
Sunnyvale, California

Abstract

Ocean Thermal Energy Conversion (OTEC) could have a significant impact on the economy and quality of life of the southeastern United States. The results of a nine month study indicate that the solar energy stored in the surface layers of the ocean can be tapped with state-of-the practice technology, and with design and fabrication improvements, can be made economically competitive with fossil and nuclear fueled plants. The concept presented consists of a spar geometry concrete structure with a telescopic concrete cold-water pipe that extends to a depth of 1,500 feet. Four detachable power modules using aluminum heat exchangers generate a total net power output of 186.5 MW_e. The modular design permits lease-financing arrangements that make the finance requirements of OTEC plants equivalent to those of conventional plants. In the southeastern United States, established shipbuilding and offshore construction industries are located near the ocean thermal resource of the Caribbean Sea and Gulf Stream. The development of this resource offers a unique opportunity for the industrial assets of the southeastern United States.

Ocean Thermal Energy Conversion (OTEC) uses the surface layers of the oceans as a solar collector and converts this energy to electricity with a floating closed cycle heat engine. Nearshore plants are expected to provide electricity directly to land via submarine cables, while more remote plants could produce intermediate chemicals like hydrogen and ammonia. In addition, OTEC plants could supply remote locations where electricity is required to process minerals like bauxite.

OTEC could have a significant impact on the economy and quality of life on the southeastern United States, where the plants could be constructed and operated, and the ocean thermal energy could be utilized as electricity and chemical feedstocks. Because this workshop is dedicated to assessing the potential of ocean energy in the southeastern United States, the purpose of this paper is to present the results of a technical and economic feasibility study of OTEC, and to consider the regional implications of this energy system. In order to relate the special advantages of OTEC to the southeastern region, this paper will review several unique features about the ocean thermal concept before examining the details of a specific systems design.

The Ocean Thermal Resource

The surface layers of the oceans serve as a natural solar energy collector and storage system, which allows the thermal energy to be converted on a continuous basis, 24 hours per day. Unlike other solar and ocean energy schemes, an energy storage system is not required for continuous level power operation. Normally the warm waters move from the tropic regions towards the global poles where the thermal energy is transferred to the atmosphere and radiated back into space. The newly cooled waters, along with the polar run-off waters, sink and move along the ocean bottom until they upwell and repeat the process. Hence, in the tropic areas there is a significant thermal resource that can be tapped continuously.

This natural collection and storage system also serves as a transportation and concentration system. The oceans are characterized by circulating currents which are unstable and meander about while casting off huge swirls and eddys. In areas where the currents are blocked by land masses, a choke point is created, and the thermal resource is concentrated and stabilized. The Florida Straits serve that purpose for the Gulf Stream. At that site, the Carribbean Sea serves as the solar collector and energy storage system, the Gulf Stream provides the transportation, and the Florida Straits provide concentration and stability near the mainland energy market.

Ocean Thermal Energy is renewable and the extraction process is consistent with the natural processes of the earth. The conversion of non-renewable fuels creates a man-made heat addition to the atmosphere and oceans. On a large scale, the heat addition could exceed the ability of the environment to reject the heat into space, and an environmental temperature rise could occur.[4] In comparison, OTEC imposes only a discontinuity in the natural process by extracting a small amount of thermal energy from the ocean at one point and rejecting it to the oceans or atmosphere at another point. There is no net change in the total energy balance of the ecosphere.

Unique Features of OTEC Systems

As a modular marine system, OTEC enjoys positional flexibility which creates unique opportunities in the construction and operation of the plants. The site approval and site preparation procedures will be different and simpler than those of a land based power plant. Of greater significance is the fact that the plant can be built in one location and towed to another location for operation. This provides the opportunity to series manufacture OTEC plants rather than the typical custom construction of single design plants. In addition, this manufacturing can occur in existing shipyards which will increase the utilization of the existing industrial base without significant new facilities investment. Modularization also permits the concurrent production of several major components, as well as site preparation, and this will reduce the construction time and cost. Finally, the marine siting will create a spectrum of market applications and will permit the plants to be relocated as market demand shifts. Overall, it appears that OTEC commercialization could be served best in an area near the ocean thermal resource that has an established shipbuilding and marine construction industry.

To properly evaluate OTEC, the economics should not be oversimplified, but should project costs on a total systems, total lifetime basis. Far too often energy costs are misrepresented when one does not distinguish between peak power and average power in the case of solar systems, or when one presents only the fuel cost component in the case of fossil and nuclear systems. It is also confusing to present energy costs in mills per kilowatt hour at the busbar, or at the consumers meter, without including the political, social and environmental costs associated with the creation, operation and decommissioning of each system and its wastes. Unfortunately, these additional costs are difficult to quantify, but new analytical tools, like net energy assessment and environmental risk analysis are being developed. At some point these may be translated into economic indices to provide a composite performance index for each energy system.

OTEC is capital intensive and consequently the economics are sensitive to the depreciation period and fixed charge rate. There is a direct trade-off between the plant cost ($/kw) and the energy cost (mills/kwh). Because OTEC has no fuel cost, the economics are buffered from inflation and fuel cost escalation. However, this assumes that the economy will not deflate, and the cost of fossil and nuclear fuels will not decrease. While OTEC is capital intensive, the modular marine design may facilitate the problem of raising the necessary capital. The use of lease financing may make it possible for the owner-operator to acquire the services of a plant for a small investment. This assumes that the owner-operator need only own the core structure, and can lease the power modules from other, independent businessmen. In essence, the cash flow normally devoted to fuel for a fossil or nuclear plant would be shifted to the leasing of power modules, and this would make the financing requirements for OTEC similar to those of conventional plants.

The economic performance of OTEC systems is sensitive to the parasitic power ratio and the plant utilization factor. Pumps are required to move the huge quantities of water through the heat exchangers, and this drains off about 30% of the gross power output of the system, leaving the remaining 70% as the net power output. Consequently, the economics of an OTEC plant are more sensitive to small changes in plant operating efficiency. Because the economics are dominated by fixed charges, and there is no variable cost fuel consumption, the net power economics are very sensitive to the plant utilization factor. To insure the best economic results, OTEC should be base loaded and this would be achieved best where there was a large stable industrial process demand.

OTEC can achieve a high utilization factor because it is a low stress sytem that can be designed for high reliability. While the ocean thermal resource is huge, it is characterized by low temperatures and small temperature differences. The highest temperature seen within the plant will be about 80°F. and the Δ T will be approximately 30-40°F. Hence, the thermal efficiency will be low compared to that of conventional plants, but the stresses on materials and components will be low also. Since we are dealing with a renewable, zero cost fuel, the cost of the energy is of greater significance than the thermal efficiency. To be cost competitive, it is necessary to devise an OTEC system where the construction and operating costs are less than the construction, operating and fueling costs of an alternative system. Fortunately, the low stress environment of OTEC facilitates the use of materials and designs that are different from those of conventional plants and consequently permits the construction of a plant that will be economically competitive. This also means that traditional manufacturers will have to change their procedures, and that non-traditional manufacturers, crafts, and geographic regions have an opportunity to enter this new field.

Finally, when comparing the economics of OTEC with those of other energy systems, it should be recognized that OTEC is an immature technology. It takes decades of experimentation and development to economically optimize an energy system. This economic gestation period must be considered, both in planning the demonstration and commercialization program, and in comparing the projected results of OTEC with the achieved results of other systems. One must recognize that OTEC may require some form of subsidization during the early development years, and consequently one should not defer the construction of demonstration plants until economic competitiveness is achieved.

The Challenge and a Solution

The huge renewable ocean thermal resource is available now for development as a new energy source. The challenge is to demonstrate a system that will produce and deliver energy at competitive system economics.

With ERDA/NSF funding, an industrial team consisting of Lockheed Missiles & Space Company, Bechtel Corporation, and T.Y. Lin International studied the technical and economic feasibility of OTEC and developed a conceptual systems design. The study[7] found that OTEC is technically feasible, and with a reasonable development program, could be made economically competitive with fossil and nuclear fueled energy systems. The net energy assessment of OTEC appeared attractive compared to alternative systems, and the environmental impact of large scale utilization was felt to be acceptable, with little chance of uncorrectable catastrophic failure. The study is documented in detail in the technical report and is described in several technical papers. It is not the purpose of this paper to repeat the details of the study, but to describe the results and to focus attention on these aspects that are of special interest to the southeastern United States.

The plant is configured as a number of power-generating modules attached to a semisubmersible spar-type core structure (Fig. 1). Each power module is self-contained, having its own sea-water circulating pumps, heat exchangers, turbine, generator, working fluid pumps, and auxiliary equipment. The modular approach provides the highest probability of successful scale-up as well as advantages in construction, operation, maintenance, and repair. Also, it offers minimum program risk and plant down time and maximum potential for system growth and upgrading. The semisubmersible spar was selected for excellent stability, minimum air-water interface exposure, ability to translate vertically for maintenance, and adaptability to the modular approach.

Power Cycle. A Rankine closed-cycle system (Fig. 2) was incorporated and ammonia was selected as the working fluid because of its superior thermodynamic characteristics, and because it was felt that ammonia could be handled with materials and techniques developed in the refrigeration and fertilizer industries.

In operation, warm water is drawn into the plant from the surface of the ocean and expelled through an evaporator where it delivers some of its heat to boil the ammonia. The ammonia vapor passes through a demister and is delivered to a turbine where it expands to low pressure and exhausts into a condenser. The turbine drives an electric generator. Cold sea water is drawn into the plant from the deep ocean and is expelled through the condenser where it acquires heat as the low-pressure ammonia vapor condenses. The liquid ammonia condensate is pumped back to the evaporator to complete the cycle.

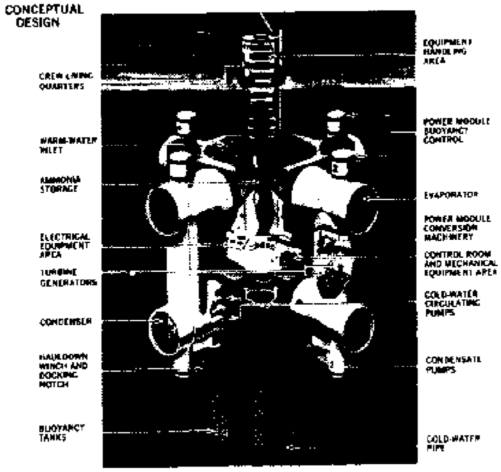


FIGURE 1

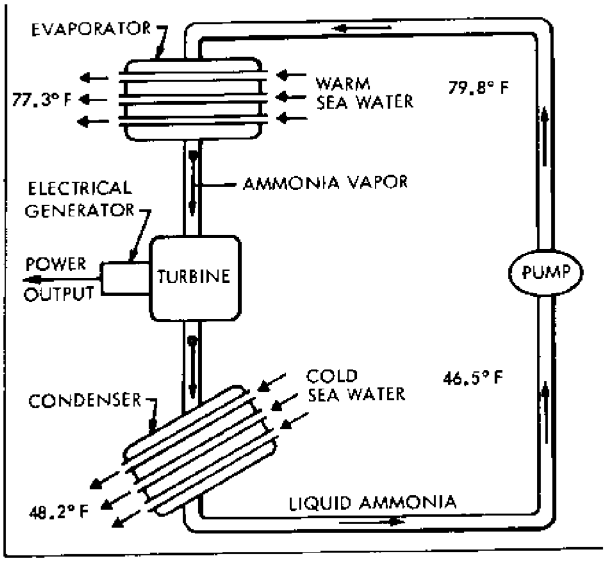


FIGURE 2

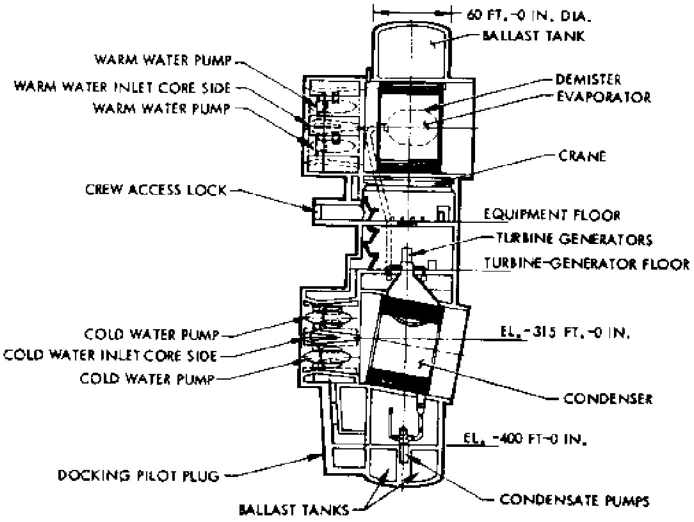


FIGURE 3

Heat Exchangers. The heat exchangers are the dominating cost elements in the OTEC design and consequently received considerable engineering effort. The heat exchanger design was established as a shell and tube configuration with sea water inside the tubes. Each unit consists of 120,000 2-in. tubes mounted in double tube sheets that can be continuously drained in case of a leak. The cylindrical shell is approximately 73 ft in diameter and tube length is approximately 52 ft. Sea-water velocity is between 5 and 6 fps.

Power Module. The 60 MWe power module (Fig. 3) is a positively buoyant steel structure of 9200 long tons. It would be built and launched horizontally in a conventional shipyard and, following outfitting and testing, would be towed horizontally at up to 8 knots to the OTEC site. The module would be ballasted to a vertical position for cable hauldown and mating to indexed interfaces and to hydraulically operated locking arms on the core structure. The module is completely submerged in its normal operating position and can be detached and returned to a shipyard for periodic maintenance and repair.

Located at the upper end of the module is the evaporator, and approximately 138 ft below is the condenser. The machinery compartment, between the heat exchangers, is a cylindrical pressure-resistant structure that contains two integrated turbo-generators producing 60 Hz power. Four axial-flow shrouded sea-water circulation pumps are mounted inside each heat exchanger.

Platform. The platform structure (Fig. 4&5) consists of the core structure and its supporting flotation. The core structure provides support for the power modules, the cold-water pipe, and watertight spaces for the crew, auxiliary equipment, and controls.

The concrete and steel structure will be fabricated by integrating prefabricated buoyancy tanks and using slipform casting techniques similar to those being used for North Sea petroleum-production platforms. The structure will weigh approximately 260,000 long tons. It will be completely submerged in service except for the top 60 ft.

Twelve cylindrical shells are attached to the periphery of the central core structure to provide buoyancy for the system. Each of the cylinders is divided into pressure-proof compartments to permit

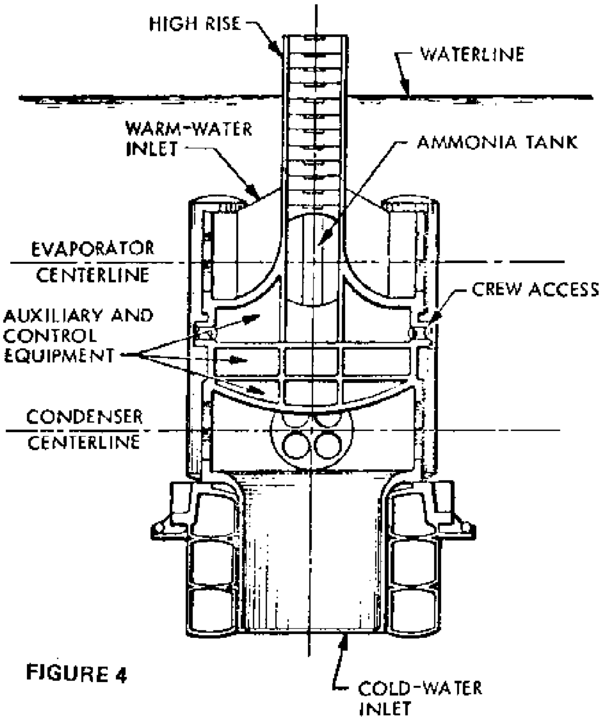


FIGURE 4

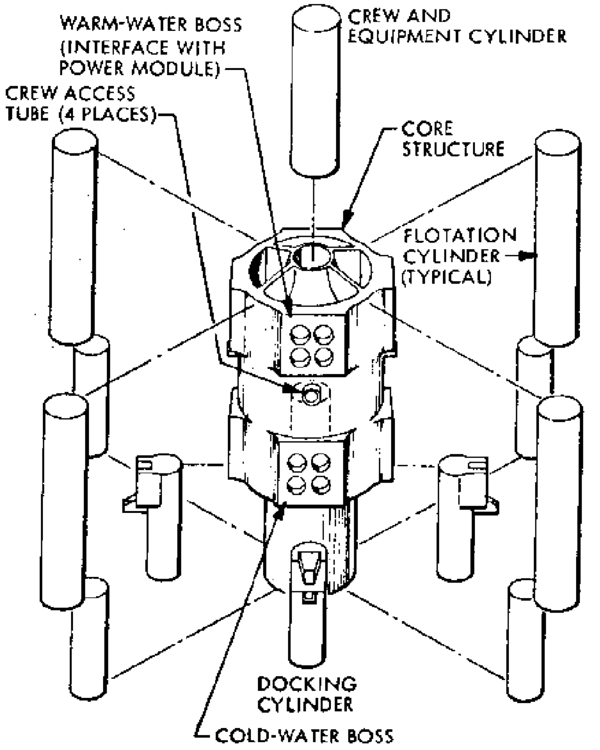


FIGURE 5

proper ballasting and to prevent catastrophic loss of the power plant in case a portion of a cylinder is ruptured. Ballast control in selected compartments of the cylinders sets the depth of immersion in the water during fabrication and maintains a constant plant weight during its lifetime on station. Concrete was selected as the material for construction of the platform because of its ability to survive in the ocean environment. Steel reinforcement, embedded in the concrete, is used throughout for tension and flexural strength.

Cold-Water Pipe. The cold-water pipe (Fig. 6) consists of five telescoping sections of post-tensioned concrete pipe. Each has a nominal length of 200 ft resulting in an overall length of 1,000 ft when extended. The pipe is circular in cross section, each section being of a progressively smaller diameter proceeding from top to bottom. The pipe is 18 in. thick and incorporates 6 in. voids to reduce weight.

Mooring Concept. Single-point mooring systems were studied for water depths of 2,500 to 20,000 ft. Because the mooring line is nearly inelastic, a combination of long scope and platform variable ballast is used to maintain a constant platform waterline.

The major elements of the mooring system are shown in Fig. 7. This arrangement permits the plant to rotate about the swivel as well as the anchor. The mooring line is an assembly of structural links pinned together to make up the line length required. The links are 60-ft long cylindrical pressure shells. The flotation provided by the hollow links partially offsets the weight of the mooring line.

A weight anchor was designed to resist a one-million-pound vertical lift and a 1.27-million-pound horizontal force and with integral flotation to permit it to be towed to the site and lowered into position.

Startup and Operation. After the power module is mated to the core structure and all interconnections are made and tested (Fig. 8), the plant is ready for operation. Since the plant operates with with no fuel cost, it should be baseloaded at all times, feeding maximum power to the electric power grid. Centralized automatic instrumentation and control will permit plant operations by a five-man watch crew, on a three-shift basis. Supervisory, maintenance, and service personnel increase the total

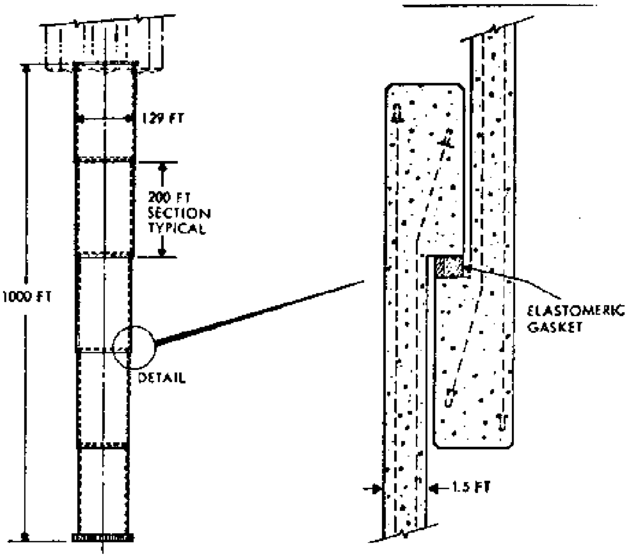


FIGURE 6

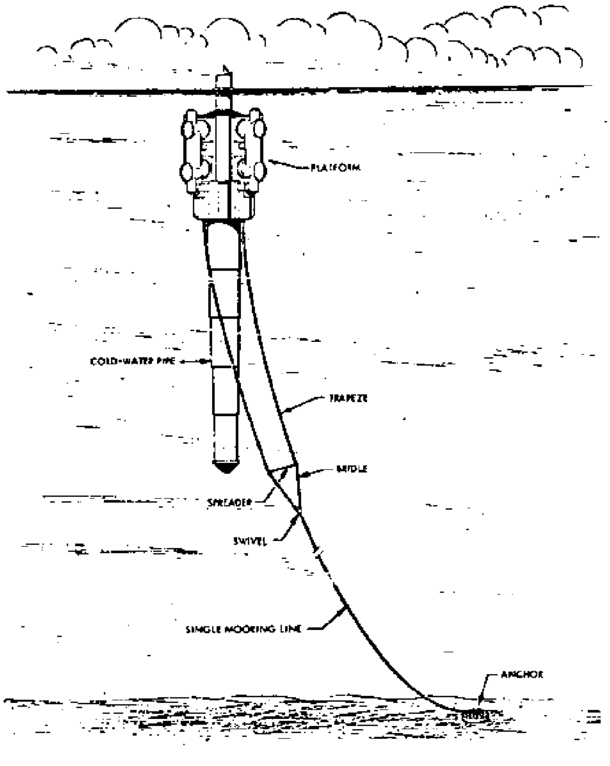


FIGURE 7

crew to 35. Additional personnel may be required for support services if the plant is distant from shore.

Power Transmission. Power transmission was not a part of this effort and for purposes of economic and net energy assessment it was assumed that the OTEC plant would be cable-connected to a shore facility approximately 10 miles away. State-of-the-practice high-voltage undersea cables were assumed.

Economic Assessment. In addition to calculating the cost of construction in dollars per kilowatt (Fig. 9), the design was subjected to life-cycle cost analysis in order to determine the cost of electricity production in mills per kilowatt-hour (both expressed in 1974 dollars) (Fig. 10). Life-cycle cost analysis required an estimate of annual operating cost, projected power output and load factor as well as the expected service life, capital requirement and payback schedule, interest rates, and scrap values.

Net Energy Assessment. All energy supply systems require energy inputs from other segments of the economy in order to deliver their product. One method of evaluating various energy systems is to compare their net energies - the total energy produced from a resource minus the energy invested in facilities and processes to accomplish the discovery, extraction, processing, conversion, transportation, and delivery. A net energy assessment was performed on the baseline design using the methodology developed by the State of Oregon, Office of Energy Research and Planning,[8]. Table 1 compares OTEC to three systems studied in the Oregon Report.

Environmental Considerations. The study began with the premise that there is no pollution-free energy. But there is an opportunity to minimize environmental alteration by using a renewable natural resource. Environmental efforts were concentrated in two areas; materials selection and the maintenance of natural ocean-surface conditions.

Corrosion products from the structure and heat exchanger surfaces were evaluated, and some materials and coatings were eliminated because of potential toxic effects when used in this quantity. The final selection of concrete, steel, aluminum and an impressed-current cathodic protection system was found acceptable.

CANDIDATE SYSTEM	[OUTPUT]	-	PRIMARY RESOURCE	+	EXTERNAL RESOURCE	=	NET ENERGY
OTEC	1000	-	0	+	175	=	+ 855
Nuclear	1000	-	2425	+	451	=	- 6874
Coal-Fired	1000	-	3498	+	566	=	- 3064

TABLE 10

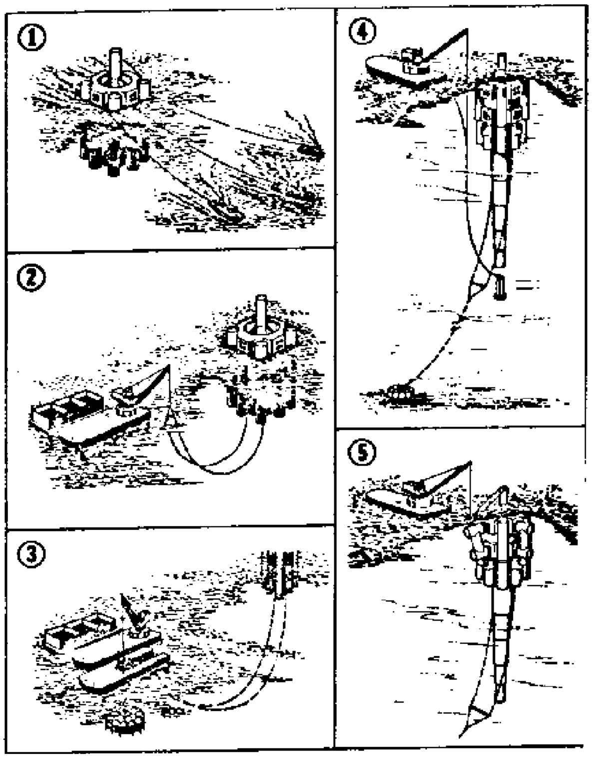


FIGURE 8

OTEC COSTS SUMMARY

	187 MW	
	$M	$/KW
TOTAL	252.0	1350
UNIT COSTS, MILLS/KWH AT 10% COST OF MONEY		17.1
UNIT COSTS, MILLS/KWH AT 15% COST OF MONEY		25.7

FIGURE 9

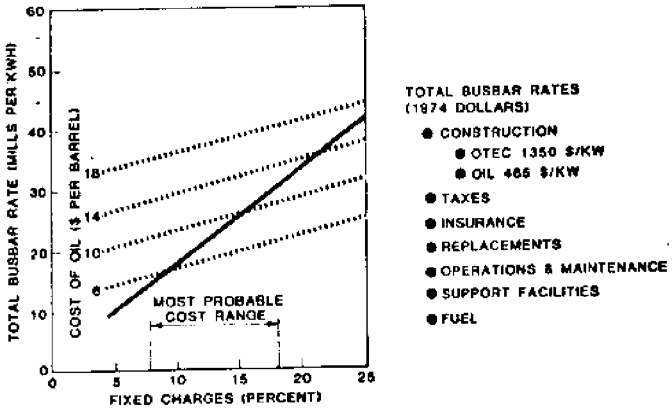


FIGURE 10

The effect of working-fluid leakage prior to detection and repair was found acceptable in the case of ammonia. Evaporator-tube leakage would be into the surface water stream and would reach the photozone where it would be biologically assimiliated. Condenser-tube leakage would be into the working fluid.

The sea-water effluents (Fig. 11) were designed to be discharged at near isothermal depths in order to minimize changes in ambient water temperature.

Engineering Development and Demonstration

An OTEC plant could be built and demonstrated today, but an engineering development program is essential to the achievement of economic competitiveness. The study identified the critical technical problems and proposed several approachs to an engineering development and demonstration program.

The program schedule (Fig. 12) shows a 10-year development span starting in 1976. For the first two years, preliminary design is closely coordinated with component development and site selection. Component development is a two-year span. Major components to be developed include: (1) advanced heat exchangers and the tooling necessary for their construction, (2) ammonia turbines in the range of 60 MW capability, (3) hydrodynamic modeling of the platform, cold-water pipe, and mooring system, (4) sea-water pumps, and (5) cold-water pipe.

Site test and selection will require approximately two years to determine the location in which OTEC is most likely to succeed, to obtain environmental data, and to conduct corrosion and fouling tests that may be site-peculiar.

In review, a system has been devised that could be demonstrated, and with a reasonable amount of engineering development, could achieve economic competitiveness. ERDA has initiated a development and demonstration program, and if all technical milestones are achieved, a demonstration will be conducted and commercialization will be initiated.

Regional Implications

During the next year, ERDA will evaluate and select a site for the initial testing and demonstration of OTEC, and for the next decade, that site will be the focus of the talent and facilities associated with OTEC technology. It is very likely that commercialization will occur first where there is a large

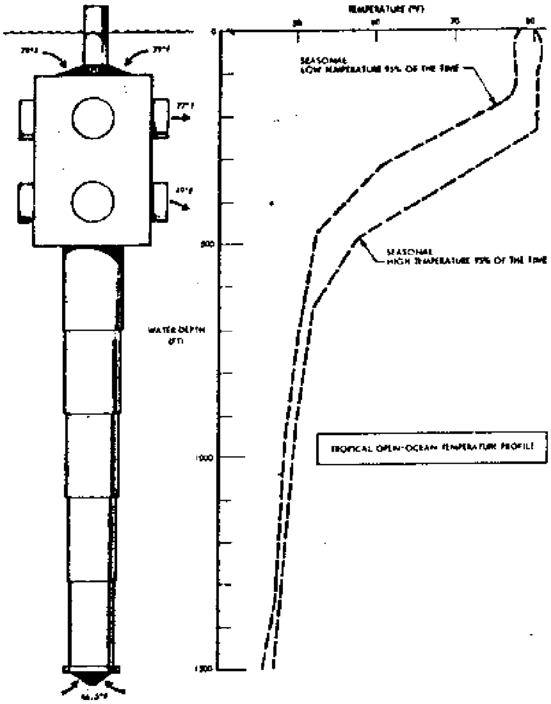


FIGURE 11

RECOMMENDED SCHEDULE

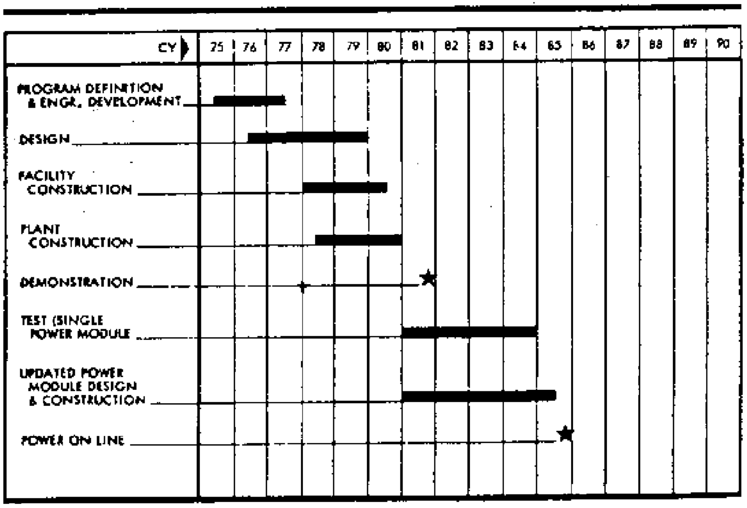


FIGURE 12

demand combined with an established base of expertise and facilities. Hence, the selection of the demonstration site could have long term significance for the regional economy. To maximize the return on the government investment, and to preclude the costly relocation of personnel and facilities, the ERDA test and demonstration site should be located initially where there are sufficient resources and demand available for large scale commercialization. Potential locations can be identified on all coasts of the mainland, as well as Hawaii and Puerto Rico, but since this workshop is regionally oriented, this paper will address only the southeastern States.

The southeastern United States has these resources close to the ocean thermal site in the Carribbean and Gulf Stream. The Gulf Coast and Mississippi River shipbuilding industry and offshore construction companies can build the OTEC structures, while aerospace companies can construct the aluminum heat exchangers. There is a labor force skilled in marine construction and operations. There are universities to address environmental issues and to undertake advanced research tasks. During the demonstration and testing phases, the instrumentation and analysis capabilities of NASA are available from Florida to Texas. In addition, the southeast offers accessibility and visibility to suppliers, potential commercial investors, and the general public. Overall the region appears to have the raw materials, labor force, and other resources necessary to build a large commercial OTEC system.

The commercialization could have a significant effect on the economy and environment of the southeast. In addition to producing electricity, OTEC plants could produce hydrogen based fuels and chemicals for transhipment through seaports to local markets and beyond. The commercialization would expand the economy of the southeast while contributing to natural energy independence, and with minimal degradation or risk to the environment.

In conclusion, it appears that new technology, combined with the natural ocean thermal resource of the Carribbean and Gulf Stream, offers a unique growth opportunity for the industrial assets of the southeastern United States.

References

(1) Claude, Georges, "Power from the tropical seas, "Mechanical Engineering 52, 1039-1044 (1930 December).

(2) d'Arsonval, A., "Utilisation des forces naturelles, Avenir de l'electricite, "La Revue Scientifique, 370-372 (1881 Sept. 17).

(3) Dugger, Gordon L., ed., Proceedings, Third Workshop on Ocean Thermal Energy Conversion (Held in Houston, Texas, May 8-10, 1975). The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, August, 1975.

(4) Greeley, Richard S., "Energy Use and Climate," Report M74-66 Revision 1, The MITRE Corporation (April 1975). (NSF-RA-N-74-184 prepared under National Science Foundation Contract C-938).

(5) Harrenstien, Howard P., ed., Proceedings of Second Ocean Thermal Energy Conversion Workshop (held in Washington, D.C., September 26-28, 1974). University of Miami, Coral Gables, Florida, May 1975.

(6) Lavi, Abrahim, ed., Proceedings, Solar Sea Power Plant Conference and Workshop, held at Carnegie-Mellon University, Pittsburgh, Pa. on 1974 June 27 and 28. Report NSF/RANN/SE/GI-39115/73, Carnegie-Mellon University (1973 September). (Available from National Technical Information Service, catalog PB-228 066).

(7) Lockheed Missiles & Space Co., Inc., "Ocean Thermal Energy Conversion (OTEC) Power Plant Technical and Economic Feasibility," Report NSF/RANN/SE/GI-C937/FR/75/1, 12 April 1975.

(8) Office of Energy Research and Planning, Office of the Governor, State of Oregon, Salem, Oregon, Energy Study Interim Report, 26 July 1974.

OCEAN THERMAL ENERGY CONVERSION: A VIABLE ALTERNATIVE

Abrahim Lavi
CIT Professor of Engineering
Carnegie Institute of Technology
Carnegie Mellon University

Abstract

Contrary to the claims of nuclear power enthusiasts, the United States has an alternative to fission energy. Solar Sea Power Plants based on the conversion of the thermal energy stored in the tropical oceans can begin feeding power into the national grid of the U.S. mainland as early as 1985. The cost of this source of energy is shown to fall below that of nuclear energy. The desired goal of 10,000 MW installed by 1990 can be realized only if work begins soon on a small power plant not larger than 2-5 MW, to become operational before 1980.

Introduction

During the May 1975 OTEC Workshop at Houston, the results of the two major system evaluation studies conducted independently by Lockheed and TRW were presented. A purpose of these two studies was to obtain unbiased and impartial cost estimates of OTEC power plants. The early proponents of OTEC, mostly people at universities, were coming out with rather low cost estimates. In May 1974, our OTEC team at Carnegie Mellon University could foresee a potential low of about \$200/kW[1] for the heat engine. This optimistic estimate was predicated on the possibility of making a staggering improvement in the heat exchanger cost which dominates and drives the total plant capital cost, including the hull, the mooring system, the cold water intake pipe, etc. The University of Massachusetts team was predicting then a different and higher cost, although their design was restricted to a single site; it included the hull, the energy delivery and the cost penalty of siting the plants at a low ΔT location with a strong current.

When Lockheed and TRW arrived at a capital cost of \$2600/ and \$2100/kW, respectively, it took some time for us, as OTEC proponents, to recover from the initial shock. After carefully studying the voluminous reports published and reading the fine print we concluded that, contrary to surface appearances, analyses by industry and the proponents were not really widely disparate[2].

First of all, the industry evaluators dropped their impartiality to OTEC and, as a matter of fact, became avid proponents. The conclusions reached by the industrial firms were:

- OTEC is technically feasible;
- OTEC can be made competitive with conventional energy sources;
- There are a number of ways OTEC plant costs can be reduced;
- OTEC should be given higher national priority;
- Prototype design or large scale testing should proceed henceforth.

Both Lockheed and TRW arrived at what was billed as baseline designs; that is, designs and materials were proposed using state-of-the-practice items. In a way, the cost of the baseline design plants is an upper bound, because both industry teams exhibited a very conservative attitude in arriving at their designs. Unfortunately, the baseline designs and their cost became fixed in the minds of some as "the" OTEC plant designs and "the" cost of the plant.

ERDA deserves the credit for having initiated these studies, because at least now we have "reliable" cost estimates from hard-nosed, impartial "engineers" and not the pie-in-the-sky optimism of "academics". One would have hoped that OTEC priority would rise within ERDA but unfortunately nothing of the sort has happened. OTEC is accorded the lowest priority of all solar energy schemes; this means funding level, manpower, and development schedule.

During the May 1975 Houston Workshop, the CMU team attempted to reconcile the various cost estimates of industry, the University of Massachusetts, Carnegie Mellon and the Applied Physics Labs of Johns Hopkins University. We concluded then that, had all proponents and evaluators used the same initial assumptions and materials, the capital cost estimates would have tallied up more or less the same. Roughly speaking, with today's know-how and engineering practice, OTEC would cost between $2100/ and $2500/kW, depending on the ocean ΔT of the site. These are late 1974 figures, of course.

Some cost reduction may be realized through automation of heat exchanger manufacturing. But such a reduction does not have the multiplicative effect that we seek. To be effective, heat exchanger cost must be reduced, by reducing their size or material or both. The approaches of the Andersons, the University of Massachusetts, the Applied Physics Labs and Carnegie Mellon can accomplish this desired reduction in the effective manner sought. To our knowledge, only the CMU approach has moved into the experimental stage. We are pleased to report that preliminary experiments, conducted by Professor Rothfus as part of Category B ERDA grant, promise that 30% reduction is feasible. That is, by using extruded tubes with flutes on the water side, we need 30% less surface area than by using a smooth tube. This conclusion appears valid for a wide range of water velocities, from 2 ft/sec to 10 ft/sec. We feel that 50% reduction is definitely attainable with little additional effort. We are confident that an overall heat transfer coefficient of 1500 BTU/ft^2 °F sec can be achieved using flutes on both water and ammonia sides. This is in contrast to the ~450 figure used in the baseline designs of Lockheed and TRW. With this reduction, we knock off $600/kW from the heat exchanger cost and an additional $360/kW from the other components. We are thus talking about $1000/ - $1100/kW OTEC plants. At such capital cost, OTEC begins to look like a viable alternative. It is our firm belief that the OTEC effort should be concentrated to achieve this goal in the shortest possible time. The question facing the country and the industrial nations is not whether OTEC will interfere with shipping on the high seas, but rather, whether alternatives to fossil and nuclear energy exist.

We do not imply in this presentation that only the CMU approach can bring this cost reduction about. Nor do we suggest that international ramifications of siting OTEC plants on the high seas are not important. But the issue we face is whether OTEC has any promise. The various studies to date claim it does. We have to demonstrate these claims because once we prove these claims, OTEC will enter a new era and will require a different aura. If the claims are not valid, then the quicker we discard OTEC, the better. Certainly, OTEC should not receive the support of the "Energy Research and Development Administration" if it is merely a scientific curiosity or a mamoth engineering undertaking.

Projected Future of OTEC

An outstanding question remains. Will OTEC be competitive with conventional power plants? Because the cost of electric power from fossil fueled plants is very sensitive to the location of the plants with respect to coal supplies, a comparison of OTEC can most appropriately be made with light water nuclear reactors. The initial cost of the nuclear plant, plus the capitalized cost of the nuclear fuel, should be compared to the cost of an OTEC plant. The nuclear industry has published the anticipated contributions of initial cost and of fuel to the cost of power as 17 mills and 5 mills/kWh respectively for a total of 22 mills/kWh[3]. These figures are no longer valid.

In the September 1975 issue of POWER ENGINEERING, Olds[4] published a very illuminating article which should be read by anyone working on energy systems. While one may disagree with his thesis, the data he presents are extremely revealing. The lead time on nuclear plants today is 10 years. According to Olds, ". . . the industry is looking at 1985 costs of $1500 - $2000/kW for plants it is ordering today at the same time new plants are coming on line for $300 - $400/kW." This increase in cost cannot be attributed to inflation or environmentalists' obstructionism. To complicate matters, the cumulative unit capacity factor is dismally low, averaging between 55-60%. This poor operating experience cannot be blamed on the environmentalists.

It should be recognized that the fuel cost in the nuclear power plants of today is a small fraction of the ammortized cost of the plant. Hence, we should not expect a substantial decrease in mills/kWh from the breeder reactors on account of cheap fuel. Even the most enthusiastic of breeder reactor proponents cannot promise a lower capital cost and better performance from the light water reactor plants.

The figures quoted above illustrate that OTEC has a good chance of beating nuclear energy on economic grounds alone. Even with the added cost of underwater transmission to bring the energy to the Gulf states and Florida, the cost will go up somewhat but as long as the distances involved remain within 50 miles of shore, OTEC will remain competitive.

Potentials for Cost Reduction

In most manufacturing processes, the unit cost drops down as more units are built. The drop in cost we are discussing results from a "learning" phenomenon which takes place. It is reasonable to postulate the learning

$$\text{cost/unit} \sim \frac{1}{N^{\alpha}}$$

where $.2 < \alpha < .4$ and N is the cumulative number of units which have been produced, including the one under construction.

The application of this learning curve to OTEC is illustrated in the following table for the very conservative value $\alpha = 0.2$. Of course, we do not know whether α will remain at .2 throughout. Suppose that $\alpha = 0$ beyond the 5th unit constructed.

Example of Learning Curve for $\alpha = .2$

Unit No.	N	Unit Cost/kW
1	1	$1100
2	2	958
3	3	883
4	4	834
5	5	797
6	6	769
7	7	745
8	8	726
9	9	709
10	10	694

Thus whereas the first OTEC plant may be just marginally competitive, the tenth plant would be highly competitive if learning continues through the tenth unit. Such a reduction in unit cost can be realized only if successive plants are designed and built without major modifications. The Westinghouse Tenneco concept of offshore floating nuclear power plants could have resulted in cost/unit reduction, had the venture gotten started. Land-based nuclear power plants seem to be an anomaly in this respect, because the cost of successive plants seems to increase.

Further reduction in capital cost can be achieved through improved manufacturing, particularly that of heat exchangers. Comparing the raw materials cost of heat exchangers to the final delivered cost, there is roughly a multiplier of 20. We suspect that if the demand for OTEC heat exchangers is established (at 2000 MW/year) there will be sufficient incentive to manufacturers and builders of OTEC to bring about a drop from 20 times to, say, 10 times the materials cost.

Deployment Growth

When we now combine the anticipated developments described earlier which will bring the cost of OTEC to the $1100/kW level with the industrial learning curve, we obtain a wedge with which OTEC plants can begin to supply power to the U.S. mainland.

To obtain a time scale, we must make some assumptions on the rate of build-up of manufacturing capability. Some idea of the rate of manufacturing build-up capability may be gained from the scenario for LMFBR's generated by Chauncey Starr, President of the Electric Power Research Institute. This scenario is presented in Fig. 1. It starts with an annual doubling of manufacturing capability. Because the technology of OTEC is relatively low level, we believe a similar annual doubling is a reasonable goal for OTEC. Taking the first full sized commercial plant to be built by 1983, we now illustrate how the installed capacity of OTEC will increase over the years. We have to remember that an OTEC plant can be assembled in a shipyard and hence will require little on-site construction. Also we are competing with nuclear plants costing between $1500-$2000/kW (including escalation).

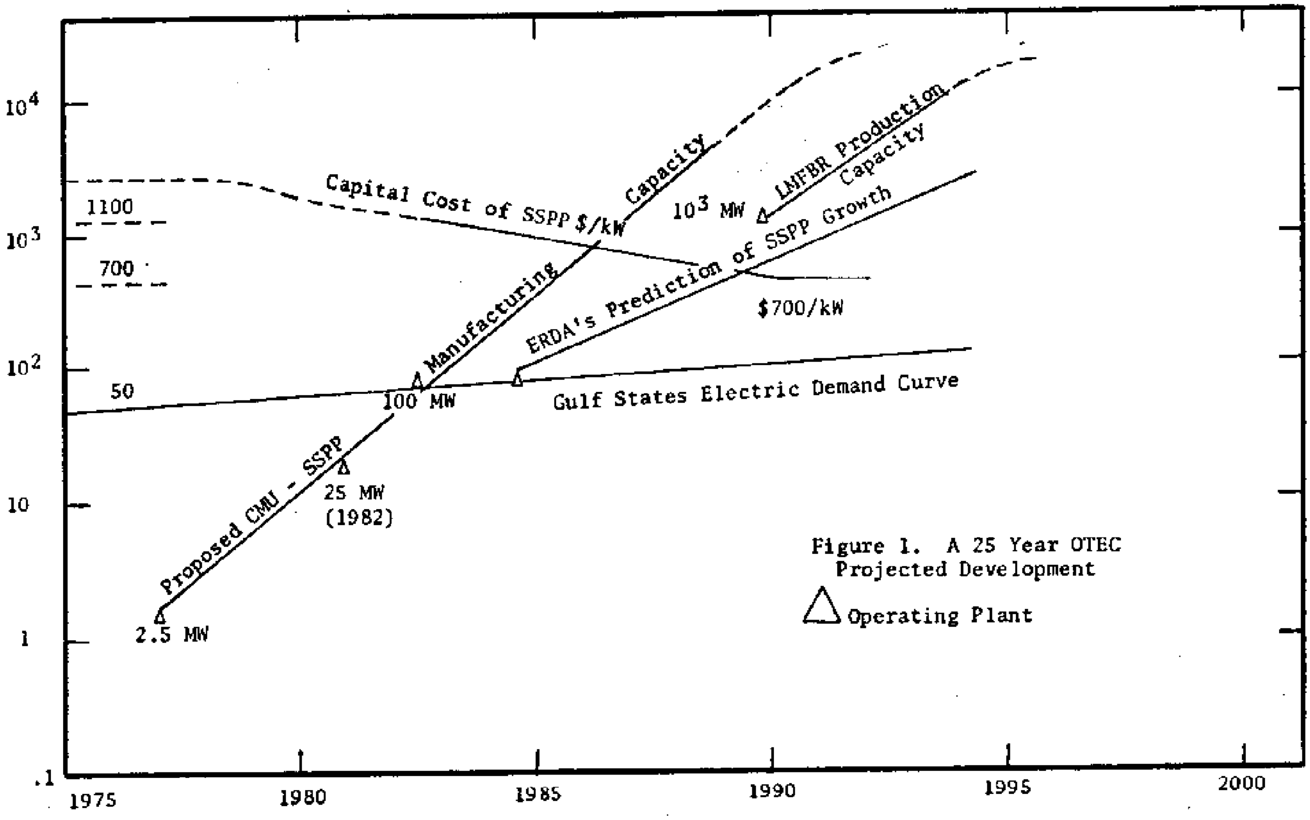


Figure 1. A 25 Year OTEC Projected Development

Early plants will probably be small, of the order 100-200 MW. Because of the planned active participation of the state of Hawaii in OTEC development, the first full sized commercial plant will probably be built for Hawaii. The next nine plants could be used in the Caribbean to power the normal expansion of alumina reduction plants. By the year 1987, this normal expansion will no longer be able to absorb all OTEC plants being built. Because of the learning curve, the plant cost will be reduced from $1100 to $800. The latter cost is now sufficiently low so as to be able to compensate for the added cost of operating with the somewhat cooler surface temperature of the Gulf of Mexico, 76°F in place of 79°F, and for the added cost ($205/kW) of underwater cable transmission of 100 miles to the coast. We estimate the total capital cost of OTEC plant plus cable to be $1050/kW, still competitive with nuclear power. The power so transmitted to the Gulf states would now be used to take care of the normal requirements for annual increments of power, until that time when the increased output of OTEC plants exceeds the normal growth in power demand of the Gulf states plus the aluminum industry. The excess power would then have to be transmitted beyond the Gulf states of Texas, Louisiana Mississippi, Alabama and Florida to the remaining states. Upon observing that the Gulf states consume 16% of the total electric power, and upon assuming a doubling time in power use of 15 years in contrast to a historical 10 year doubling time, we calculate that the normal increase in power capacity of the Gulf states will be saturated with OTEC by the year 1990 if a 2.5 MW plant is deployed by the late 1970's. By 1990, the total power generated by OTEC will be 10,000 MW.

We wish to digress here to reexamine the learning curve. The cost per kW is based on an initial plant capacity of 100 MW. Had we started with a greater first plant capacity, the initial $/kW would decrease with the plant size because the hull and the pipe are not scaled linearly. Thus, to reach a 1000 MW installed capacity by deploying 10 plants, 100 MW each, the cost for the next 1000 MW is anticipated to be about $800/kW. However, if the plant size were 1000 MW, the following plant would still cost $958/kW. Thus it pays us to build small plants in the beginning to bring the unit cost down, rather than to take advantage of the economy of scale. Later, when no further learning is possible and no further cost reduction can be realized, the plant size is raised to take advantage of the economy of size.

The notion that cost can continue to drop with each additional plant is of course fallacious. The curve does saturate beyond a certain N_{max} which we do not yet know. In other words α changes its value and becomes zero. It is more realistic to postulate a learning curve of the form

$$C/kW = C_0 + C_1/N^{\alpha} .$$

Of course the true nature of the curve for a given application can be known only in retrospect. But the notion of a learning curve remains an indispensible thesis in this discussion.

Beginning in 1990, OTEC power will be transmitted beyond the Gulf states. By this time the learning curve and manufacturing improvements will have further reduced the cost of OTEC plus underwater cable below $1050/kW. The figure must become sufficiently low to allow for additional investment in long distance high voltage D.C. transmission lines. The 1970 National Power Survey (I-13-16) of the F.P C. gives a cost of 3.5 mills/kWh for 1,000 miles. Upon assuming today's cost to be twice that value, we conclude that the capitalized cost is ~$350/kW. Barring any further reduction in cost of plant and underwater cable, we thereby arrive at the average total capitalized cost of $1400 /kW for OTEC in the interior of the U.S., 2000 miles from the shore. We anticipate the cost of nuclear fuel in 1990 to increase considerably above the 5 mils /kWh assumed. Likewise, safety requirements, utilization and other factors may drive the cost of nuclear power beyond the 32 mils/kWh calculated from the $1400/kW capital cost.

The straight line representing an annual doubling of OTEC plants finally levels off after 1996. At this time all new additional power capacity will be OTEC, so the growth of these plants will be tied to the growth of the U.S. generative capacity.

Need for Government R & D

Fig. 2 has been constructed solely to show what could happen without further government subsidy if by 1985 government-sponsored R & D has brought the cost of a 100 MW OTEC plant down to $1100/kW. Kun Li of Carnegie Mellon is developing alternate scenarios for

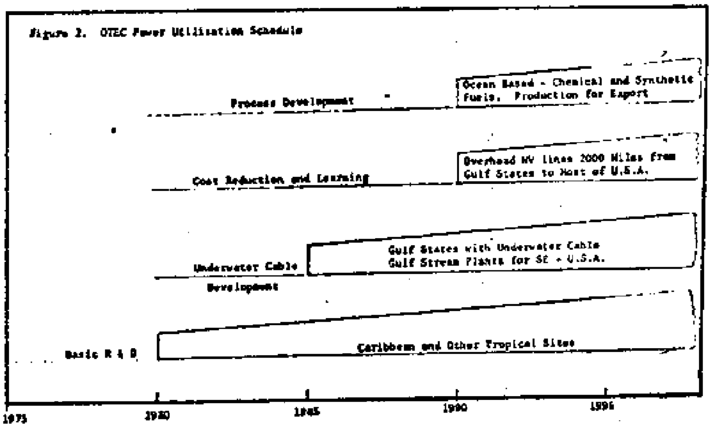


Figure 2. OTEC Power Utilization Schedule

achieving the over-all growth curve represented by the heavy straight line in Fig. 1. The number of viable alternate scenarios multiplies as the prices of natural gas and petroleum increase.

The OTEC growth curve discussed above is predicated upon sufficient R D & D before 1985 to enable OTEC plants to be built at a cost of not more than $1100/kW. When one contemplates what action must be taken to accomplish this objective, the time between now and then is amazingly short.

The scenario just presented requires building a 2.5 MW experimental plant by 1979, a 25 MW full scale pilot module during 1982. Interestingly, these units fall upon a backward extrapolation of the learning curve of Fig. 1. Prior to even the 2.5 MW experimental plant, a tremendous amount of design data must be gathered. As Ronald Smelt of Lockheed has emphatically stated (private communication with C. Zener, July 1975), all necessary engineering input must precede starting on the learning curve. The continued new design changes demanded in the past by the AEC, coupled with their high technology content, has prevented nuclear power plants from even getting started on a learning curve.

Factors Favoring Learning Curve Thesis

Development and construction of OTEC plants do not hinge on scientific breakthroughs or costly and time-consuming materials development. OTEC requires no basic research and no new technology. All the materials required by an OTEC plant are commercially available in the U.S. and are abundant throughout the world: steel, concrete, copper, aluminum and even titanium.

OTEC plants can be built in shipyards similar to those in existence in other countries. The North Sea oil technology is far more advanced and elaborate than that demanded by OTEC plants. In addition, OTEC plants can be replicated, much like building a family of large ships. Thus there is no need for the time-consuming re-engineering associated with conventional and nuclear plants.

Conclusion

The OTEC concept is ready for entry into the experimental phase, and it is ERDA's responsibility to lead development. Additional theoretical studies will be useful in exploring advanced concepts, but concrete data are needed to build confidence in system reliability and economics, and to crystallize a baseline design. Private industry is understandably reluctant to develop OTEC since, due to economic uncertainties in the global energy picture and the absence of a firm U.S. energy policy, industry is hesitant to risk resources, manpower and capital. Thus, it is up to Government to initiate an OTEC testing and development program to yield a working commercial plant which will attract private capital, if economic projections are substantiated as expected. The time to act is at hand; it makes little sense to perform an annual ritual of predicting the future of OTEC by taking last year's predictions and extending the completion dates of future milestones.

REFERENCES

1. C. Zener and A. Lavi, "Solar Sea Thermal Energy," Hearing before Subcommittee on Energy of Committee on Science & Astronautics, 93rd Congress, 2nd Session, 5/23/74 [No. 41], 1-56.
2. A. Lavi, "SSPP Cost and Economics," Proc. Third Workshop on OTEC (Houston, TX: 5/8-10/75, ed. G.L. Dugger, Johns Hopkins University, APL/JHU, SR 75-2 (8/75) 64-71.
3. J.W. Simpson, Position Paper #2, "Nuclear Fission: Its Uses and Economics," Fortune Magazine (2/75) 28.
4. F.C. Olds, "Environmental Cleanup 1975-1985: Huge, new costs, little benefit," Power Engineering (9/75) 38-45.

SALINITY GRADIENTS, TIDES AND WAVES AS ENERGY SOURCES

by

Dr. Michael E. McCormick
Professor of Ocean Engineering
U. S. Naval Academy
Annapolis, Maryland 21402

Abstract

The alternate energy sources of wind-waves, tides and salinity gradients are discussed in terms of their resource potentials, required technologies, and environmental consequences. From the various aspects discussed, it is concluded that salinity gradient energy conversion will yield the most energy and, yet, is the most unfeasible in light of present technology. Tidal power conversion is very regional but requires no technological breakthroughs. Wave energy can be extracted both in deep waters and shoaling waters with existing technologies. Further, the environmental consequences appear to be minimum, thus making wind-wave energy conversion most feasible.

Introduction

Throughout recorded history there are many descriptions of attempts to harness the conspicuous energy forms of the oceans, i.e., waves, tides and ocean currents. More recently, the not-so-obvious energy sources of thermal gradients and salinity gradients have also been considered. The purpose of this paper is to present discussions of three of these alternate energy sources in the oceans: wind-waves, tides and salinity gradients. Each discussion covers the following three aspects of the particular energy source:

(a) Resource potential. Is there enough energy available to merit a national effort into conversion of the energy?

(b) Technology. If the resource is sufficient, is the technology available to convert the energy, or are technological breakthroughs required?

(c) Environmental Consequences. If the alternate energy source is utilized, what beneficial or damaging effects on the environment will result?

Wind Waves

Waves which one normally encounters at the shore are wind-waves, i.e., they have been generated by the wind blowing over a patch of the sea. The length of the patch in the wind direction is called the "fetch" and is denoted in Figure 1 by F. The energy which the wave receives from the wind depends on the fetch, the duration of the storm and the wind velocity. This energy of the wind-wave in deep water (where the depth is greater than half of the wave-length) is characterized by the wave height, H, and period, T. Theoretically, the total wave energy [see McCormick (1973)] is

$$E = \frac{\rho g H^2T^2}{16\pi} \qquad (1)$$

As explained in the U. S. Army (1974) publication, the waves created by a given wind velocity are "fully developed" for a given minimum fetch, F_{min}, and/or minimum duration of the wind. This means that for a wind velocity existing longer than the minimum duration or extending over a distance greater than F_{min} there is no change in the net energy content of the waves so that the height and period (and length) of the wave are fixed.

A. Resource Potential

On a national scale, let us use a value of 1/2 % of the total annual energy consumption in the United States as a minimum energy resource value to justify the investment of Federal funds to tap the energy source. For example, this means that for the case of waves the total annual wave energy available to the country must exceed 1/2 % of the national requirement in order to be a viable resource.

From seasonable wave height and wave period data presented by the U. S. Army (1974) the author calculated the seasonal changes in wave power in the coastal waters of the continental United States. These data are presented in Figure 2. From the curves in Figure 2 one can see that the most advantageous region to convert wave energy is along the Oregon-Washington coast during the Fall and Winter months. A not-so-close second is along the coast of California, although rather strong arguments have been presented to this author by residents of Southern California for wave energy conversion in their region. From Figure 2, using rather crude distance measurements along the coastlines, the maximum wave power striking the Oregon-Washington coastline occurs in March and has a value of 12 x 10^4 megawatts, while the minimum value of 3.8 x 10^4 megawatts occurs in August. Along the U. S. coastline in the Gulf of Mexico, which is more than twice the length of the Washington-Oregon coast, the maximum wave power is 1.1 x 10^4 megawatts and occurs in April while the minimum value (in August) is 0.4 x 10^4 megawatts.

Isaacs, et al (1976), present an interesting idea based on the concept of a "fully developed" sea (which has been previously described). Since the energy of a fully developed sea is constant, energy extracted from the wave beyond the minimum fetch, F_{min} in Figure 1, can be restored by the wind in the region $F_{min} < x < F$. This means that for large fetch values, i.e., $F > n\,F_{min}$ where $n = 1,2,3\text{--}$, maximum quantities of energy can be

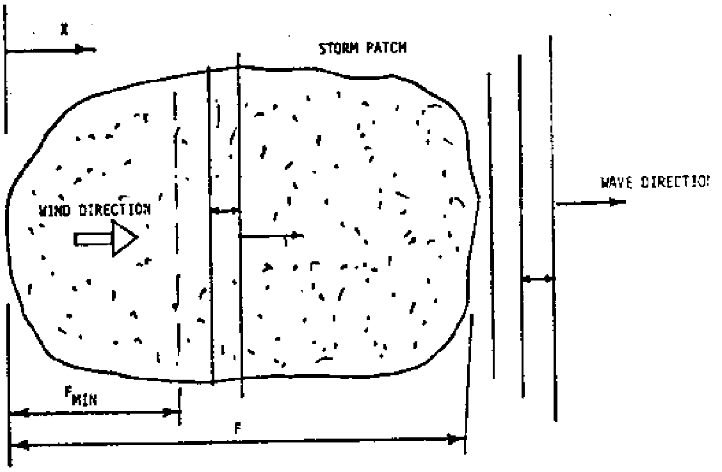


FIGURE 1. Areal Sketch of a Sea Beneath a Storm Patch.

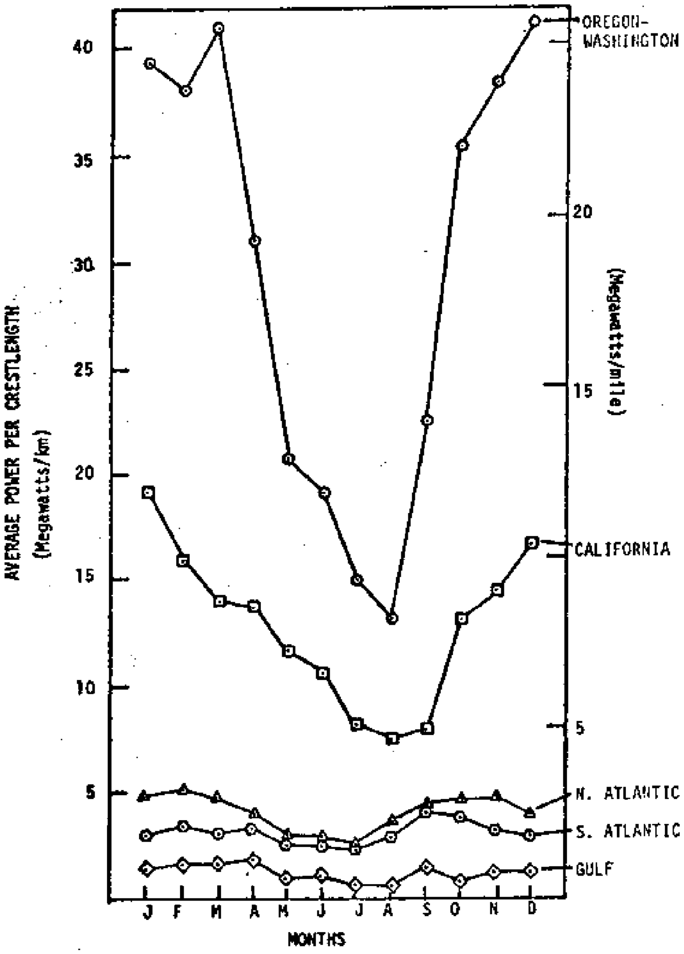


FIGURE 2. Monthly Averaged Wind-Wave Power per Crestlength Striking the Continental United States.

extracted at one or more x-positions depending on the wind velocity, the value of F, and the duration. Thus, if wave energy is converted both at sea and on the coast the total energy converted from wind-generated waves is much greater than that obtained simply from shoreline conversion.

B. Technology

There have been many devices conceived for the purpose of converting wave energy. For example, in the early 1900's a Frenchman by the name of Bouchaux-Praceique designed and constructed a "wavemotion turbine" which supplied all light and power to his seaside home. Arthur Palme (1920) described the device as being unaffected by tides and, because of a unique design, the turbine was free from fouling and corrosion. A schematic diagram of the Bouchaux-Praceique converter is shown in Figure 3.

More recently John Isaacs, et al, (1976) conceived and successfully tested a deep water device which has an excellent potential for practical usage. The device, which is sketched in Figure 4, consists of a float (designed to take advantage of the orbital motions of the water particles within the wind waves) through which a long, vertical, center-pipe passes, The bottom of the center-pipe is in free-communication with the sea. When the float heaves downward, the valve within the centerpipe opens allowing water to flow upward. When heaving upward the valve is closed and the internal water level remains at a constant height relative to the pipe. Over each

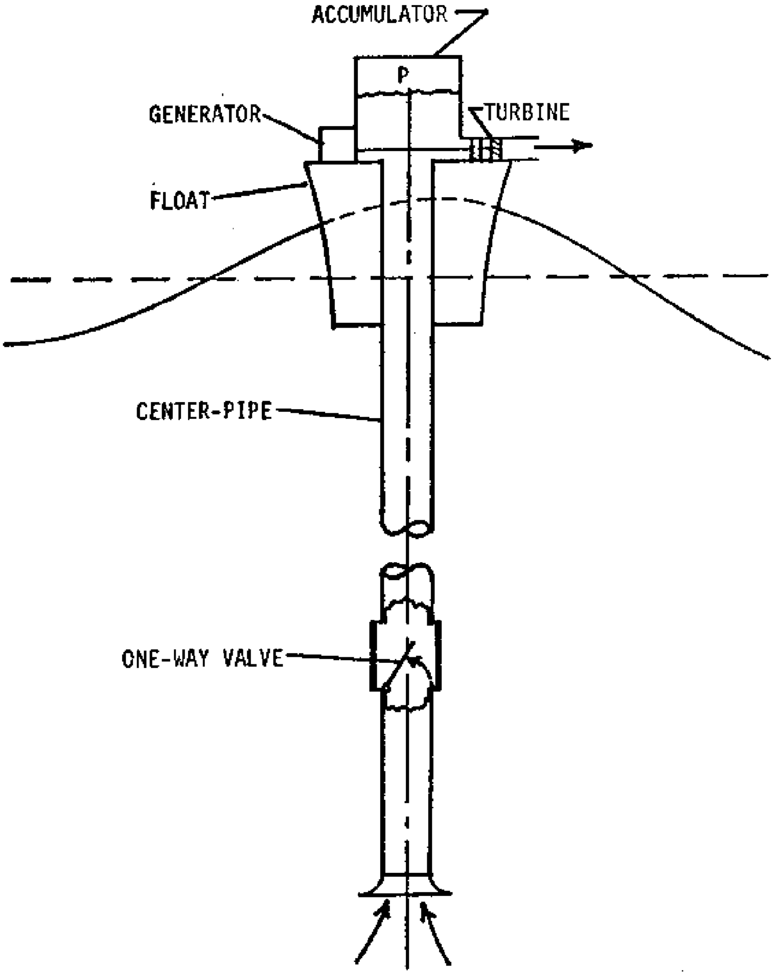


FIGURE 4. Isaacs Wave-Energy Converter.

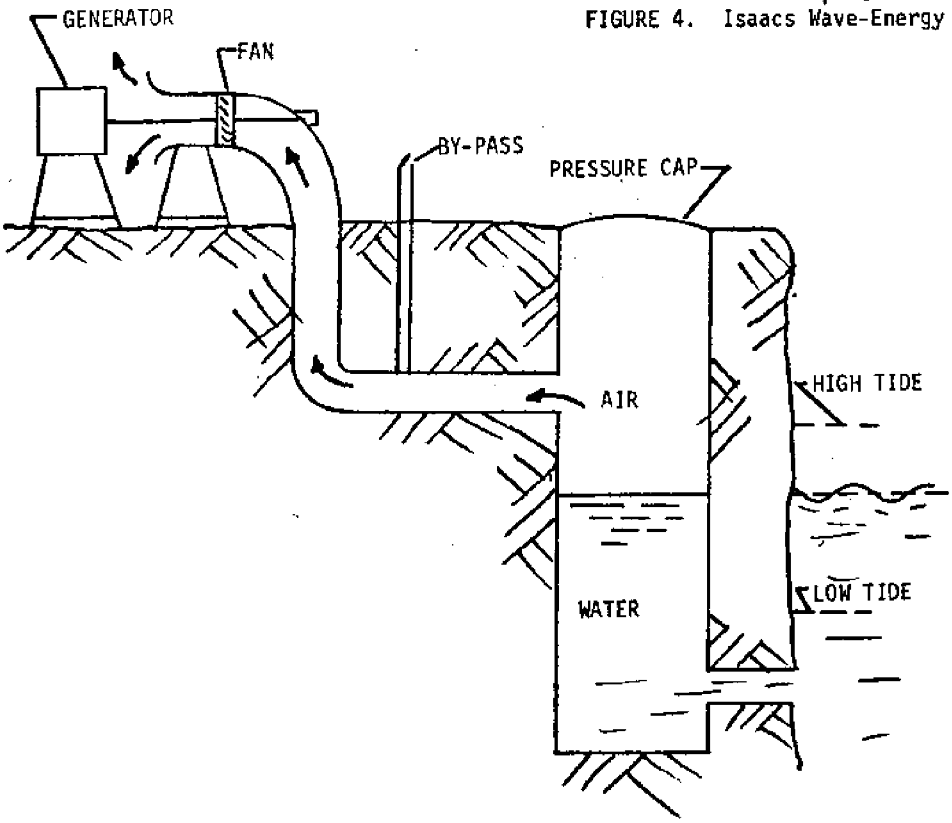


FIGURE 3. Bouchaux-Praceique Wave-Energy Converter.

wave cycle more water accumulates above the valve until air above the water in the accumulator tank is so compressed that no more water is accepted. The air pressure, p, combined with the hydrostatic head of the water forces the water through a turbine. This energy from the turbo-generator system can be used to create hydrogen for export to land in LNG-type carriers, or can be transmitted to shore through cables if the distance is not too great.

A device which can be used either in deep or shoaling waters is the pneumatic type converter devised independently by both Masuda (1971) and R. Rodrequez of the RMR Corporation of Manila. This system depends on the surge-chamber resonance of a center-pipe situated as diagrammed in Figure 5. Since the water-column in the center-pipe is designed to resonate with the wave, one would assume that the device would only be effective in a narrow bandwidth about the natural period; however, in a theoretical analysis of the device McCormick (1975) showed that if the radius of the center pipe is 4.61 m and the draft of the pipe is 1.5 m, then the half-power bandwidth of the device is approximately 7 seconds in a 1 meter sea, and the air driven through an alternating turbine system above the free-surface of the water-column will ideally deliver a maximum power of 24 kilowatts at a period of 4.5 seconds and drop off to 12.5 kilowatts at both 3.5 seconds and 10.5 seconds. Both the Masuda system and the Rodrequez system are commercially available for buoys, and the Masuda system has also been successfully used in Japan to power lighthouses.

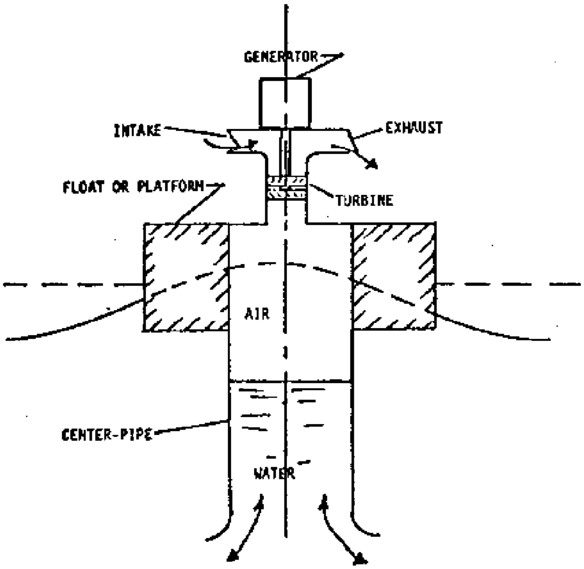


FIGURE 5. Pneumatic Wave-Energy Converter.

J. S. DeMaree of the Suppliers, Inc. of Lexington, Kentucky has invented a system for use in deep and shoaling waters which prematurely causes the waves to break. Inshore of the break the wave naturally begins to surge and then strikes an impulse-type device shown schematically in Figure 6. The advantage of this device is that by prematurely breaking the wave it converts the wave-motion to a surge and, therefore, most of the wave energy is kinetic. A second advantage is that the structure's foundation can be placed below the region of wave action and, therefore, will not encounter the problems caused by scour. Further, by being placed offshore of the surf zone the structure does not interfere with littoral currents.

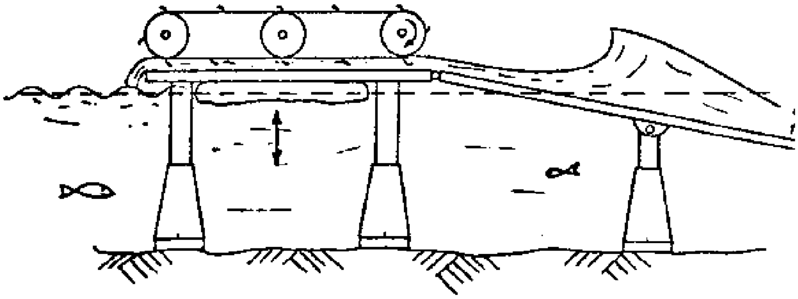


FIGURE 6. DeMaree Wave-Energy Converter.

For use in the surf zone, the Bolding-Alexander Corporation of Rialto, California has proposed a pneumatic device which is sketched in Figure 7. This device takes advantage of the surging motion of the broken wave (hopefully in either a plunging or surging condition). The surge forces air through one-way valves into a storage tank. The compressed air can then be used to drive an air turbine. When the backrush occurs, the tank supply valve is closed while a breathing valve opens which prevents a partial vacuum to occur during the backrush.

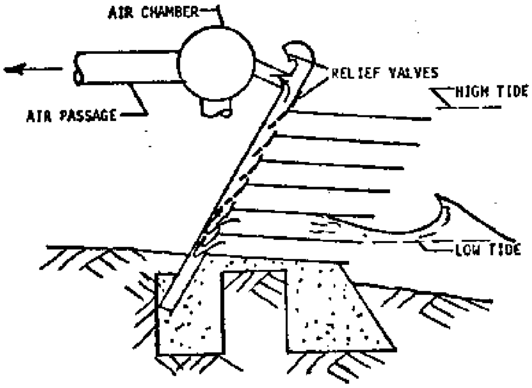


FIGURE 7. Bolding-Alexander Wave-Energy Converter.

A wave-energy conversion device invented by S. H. Salter (1974) should also be mentioned here and is further illustrated and discussed in Part I of the three part article by Arthur Fisher (1975). This is a rotating device which is designed to operate in deep water, i.e., where the wavelength, λ, is less than twice the depth, h., i.e., $\lambda < 2h$. Since Dr. Salter is a contributor to this conference, the author will leave a more knowledgeable and detailed discussion to Dr. Salter.

C. Environmental Consequences

As an introductory statement, it can be stated that all energy-conversion devices have some environmental consequences associated with their use. Some may be trivial and others may be serious. No matter how minor, however, all environmental effects must be thoroughly studied before each device is operational.

Wave-energy extraction may result in an ecological disaster or may result in a minute ecological change, depending on where the energy is extracted. Energy extraction in a shoaling region, i.e., where the wave "feels" the bottom, can drastically alter the littoral processes along the coast. The energy needed for both erosion and accretion of sand comes from the waves. If the energy is removed from the waves at an offshore position where the waves cannot recover (from the wind) then accretion will take place and a "tombolo" may form between the device and the shore, thus, depriving the downdrift side of the tombolo of sand (Figure 8).

If the device is placed offshore of the mouth of an estuary, then a "delta" may form causing a redirection of the currents and, thus, changing both the salinity gradient and temperature gradient in the near region of the estuary. This region is normally the most biologically productive.

Devices which utilize the energy of waves broken along the coastline are actually using energy which would normally be dissipated by turbulence or percolation. The littoral current within the surfzone should experience little change and therefore, the coastal environment is slightly affected by this type of device.

The method of energy extraction from a fully developed sea at a position where the wind can replenish the energy lost by the wave is the most ecologically satisfactory. As previously mentioned beyond the position where the sea is fully developed the wave energy is unchanged by the wind at the air-sea interface. For example, if

(a) Wind velocity, V = 50 km/hr
(b) Wind duration, T = 4 hours

then

(c) Minimum Fetch, F_{min} = 45 km

and,

(d) Significant Wave Height, H_s = 1.68 m
(e) Significant Period is 5.2 Seconds

From these data, which are from the U. S. Army (1973), one sees that the wave energy can be extracted every 45 km or about 27 miles. The waves begin to form just beyond the point of extraction so that the oxygenation of the surface waters by the wave motion is assured.

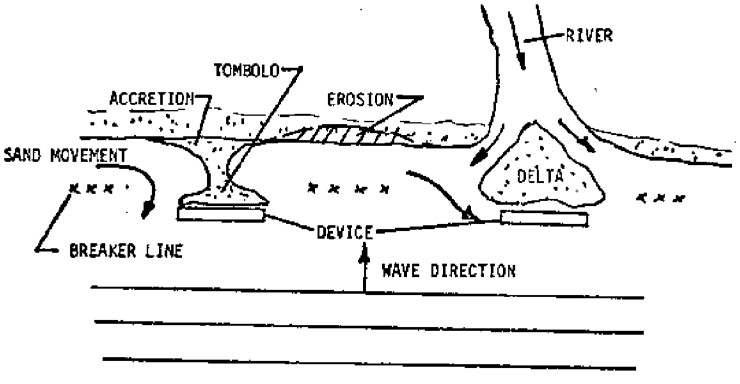
Tides

Tidal-energy conversion, like wave-energy conversion, has stimulated man's imagination for centuries. In 1966 the dream of harnessing the tidal power was realized with the construction and operation of the first commercial tidal power plant in France near St. Milo on the Rance River. An excellent article describing the history and performance of this power plant was recently written by C. H. Lebarbier (1975). There is much literature devoted to tidal-energy conversion, one of the most thorough coverages being in the collection of papers resulting from an international conference which took place in Halifax, Nova Scotia in 1970. The collection was edited by T. J. Gray and O. K. Gashus (1972).

A. Resource Potential

A "rule-of-thumb" which is used in the determination of the feasibility of tidal-energy conversion is that it is not practical to convert the energy of tides with an average tidal range of less than 5 m.

Using this as a criterion, let us examine the average tidal ranges along the coastlines of the



(a) Tombolo Formation (b) Delta Formation

FIGURE 8. Possible Coastline Alterations.

continental United States, as shown in Figure 9. The data in Figure 9 is taken from the 1973 U. S. Army publication. Referring to our minimum tidal range requirement of 5 m, one sees that the region which is most suitable for tidal-energy conversion is along the northeast coast of the state of Maine, particularly in the Passamaquoddy Bay-Cobscook Bay waters. These waters are shared by both the United States and Canada. There was a tidal-power project started during Franklin D. Roosevelt's administration in the 1930's. This project, however, was abandoned because of the high costs involved. An excellent history of the Passamaquoddy project was written by J. G. Crowley (1975) and was reproduced in the Congressional Record on July 8, 1975.

With the recent increases in the price of petroleum and the severe effects of the oil embargo on the New England States, much political pressure has been applied to harness the tidal power of the Passamaquoddy. The Energy Research and Development Administration (ERDA) has been asked by Congress to further study the feasibility of the tidal power conversion.

B. Technology

The harnessing of tidal power requires no technological breakthroughs. The turbines used in the Rance River power station, from Lebarbier(1975), are of the Kaplan type with four adjustable runner blades. The efficiency of the turbines depends on the head and varies from 55% to 85% with a corresponding head variation of from 3m to 11 m. The reader is referred to Lebarbier (1975) and to Gray and Gashus (1972) for a complete coverage of tidal power technology. Further, the three-part paper by R. H. Charlier (1969 and 1970) contains one of the most complete lists of references on tidal power in existence.

C. Environmental Consequences

The natural sites for tidal power plants are unfortunately in rather biologically productive regions. The waters are "relatively shallow coastal estuaries and gulfs," as stated by E. M. Wilson (1973). Any alternation of the flow patterns in these waters will affect some link in the food chain either directly, or indirectly. Some of the environmental effects of proposed tidal power plants are discussed by D. H. Waller in the book edited by Gray and Gashus (1972).

Salinity Gradients

The concentrations of salts in the oceans vary from place to place and, also, with depth since these concentrations are functions of temperature. Thus, the warm surface water (e.g., at 20° C) will have a higher salinity than that at the colder depths (e.g., 5°C at 600m) where the salinity will range from 36.0 ‰ on the surface down to 35.0 ‰ at a depth of 600 m. The most significant change in the salinity occurs at the mouth of an estuary where the fresh river water meets and mixes with the saline ocean waters.

When a semi-permeable membrane is placed between waters of different salinities, a pressure gradient occurs across the membrane which causes water to pass from the lower salt concentration to the higher and, therefore, dilutes the water of higher salinity. This high pressure is known as the "osmotic pressure" and is a function of temperature. Water may also pass through the membrane in the opposite direction if the ambient pressure of the water of higher salinity exceeds the "natural" osmotic pressure just described. Thus, there is a natural and continuing process which can both produce fresh water and, in the case of power generation, create a difference in head between the waters of different salinities.

A. Resource Potential

The osmotic pressure, as previously mentioned, is a function temperature. According to Francis A. Richards in the book edited by J. F. Brahtz (1968) the osmotic pressure (in atmospheres) at a temperature T(°C) is

$$P = P_o \left(\frac{273 + T}{273}\right) \qquad (2)$$

where $P_o = -12.08\ (\Delta T_F)$

and ΔT_F is the lowering of the freezing

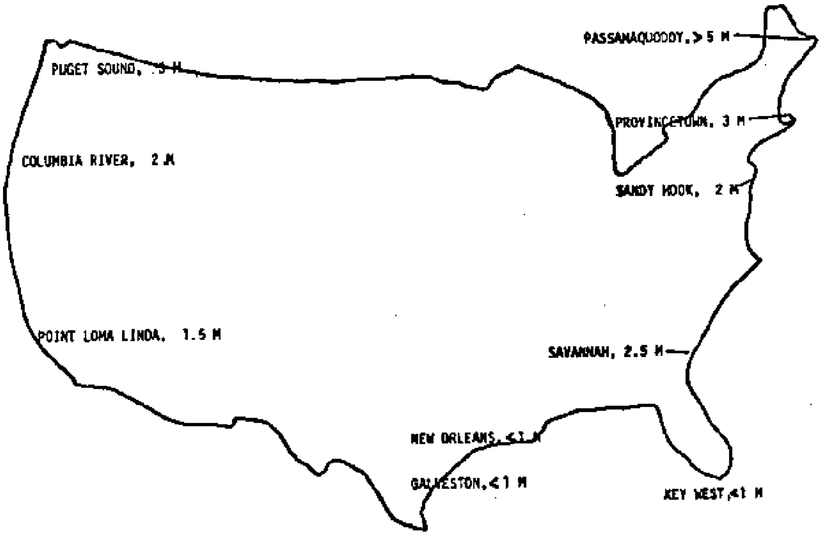


FIGURE 9. Daily Averaged Tidal Ranges for the Continental United States.

temperature due to salinity from the fresh water value of 0°C, i.e.,

$$\Delta T = -9.66 \times 10^{-2}\, cl - 5.2 \times 10^{-6}(cl)^3 \qquad (3)$$

Using these relationships Richards states that for $T = 25°C$ an increase in chlorinity, cl, from 10 $^{o}/oo$ to 22 $^{o}/oo$ will raise the osmotic pressure from 12.87 atm to 29.33 atm. If a semi-permeable membrane could be stretched across the mouth of an estuary to separate fresh water from 35 $^{o}/oo$ sea water then the osmotic pressure would be about 24 atm, i.e., a head of about 238 m of fresh water. One can think of an equivalent dam which is 238 m high supplying water to a turbogenerating system.

As pointed out in the publication by Wick and Isaacs (1975), the hypersaline bodies of water, such as the Great Salt Lake or the Dead Sea, and salt flats present even greater potential energy source. It is pointed out for each 1 $^{o}/oo$ of salinity there is about 0.7 atm of osmotic pressure. Thus, for the Dead Sea, where the salinity is 270 $^{o}/oo$, $P = 189$ atm which is equivalent to a head of 1,890 m of fresh water, i.e., somewhat over one mile in height.

B. Technology

To this author's knowledge there have been three methods of converting salinity gradient energy. The first method was discussed by Levenspiel and deNevers (1974). Their idea is to take a large vertical tube with a semipermeable membrane on the lower end and drive it into salt water. Referring to figure 10, the tube would remain empty, (Fig 10a) until the osmotic pressure is reached. If the salinity of the water is 35 $^{o}/oo$ then this pressure would be reached at a depth of 238 m (Fig. 10b). Beyond this depth fresh water would pass into the tube leaving the salts behind. Since fresh water is lighter than salt water, the level of fresh water would rise above the 238 m depth (Fig. 10c). If now, as sketched in Figure 10d, the fresh water is allowed to pass through a turbogenerator and empty into a tube which draws less than 238 m then the fresh water will generate electrical energy and pass out through the semipermeable membrane of the "shallow" tube. If the draft of the original (deep) tube is sufficient, then the fresh water will rise above the free-surface of the salt water. In this case the "shallow" tube is not needed since the exhaust from the turbogenerator will empty into the free-surface. As an example of this concept, given by Levenspiel and deNevers (1974), consider the original pipe drawing 10^4 m in 35 $^{o}/oo$ salt water. The fresh water in the pipe will rise to a height of

$$\begin{aligned} Z_f &= -238 \text{ m} + \left(\frac{\rho_s}{\rho_f} - 1\right) 10^4 \text{ m} \\ &= -238 \text{ m} + \left(\frac{1.050}{1.023} - 1\right) 10^4 \text{ m} \\ &= 26 \text{ m} \end{aligned} \qquad (4)$$

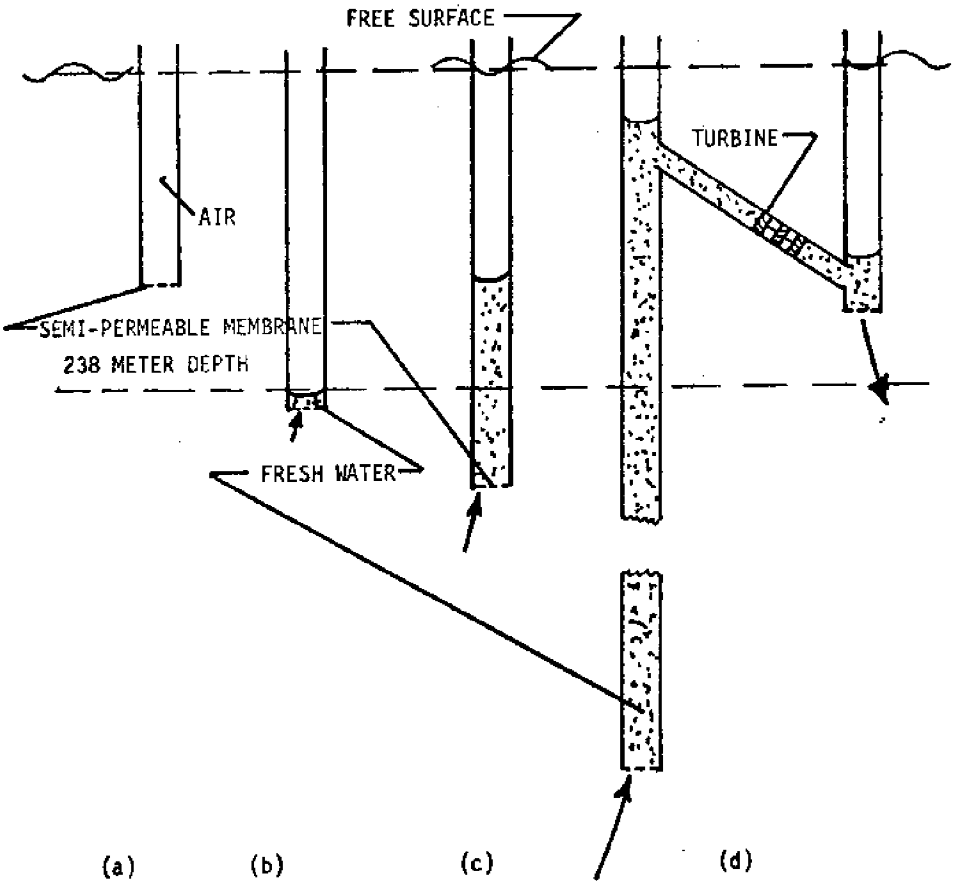


FIGURE 10. Deep Water Salinity-Gradient Energy Converter.

Thus, a head of 26 m of fresh water can be converted to electrical energy and, in addition, the fresh water can be used for other purposes.

The second energy conversion technique described by Wick and Isaacs (1975) involves damming-up the mouth of an estuary as shown schematically in Figure 11, allowing the fresh water to pass through a turbogenerator and into a buffer lake the free-surface of which is less than 238 m below that of both the river and the ocean. Due to osmotic pressure the fresh water would then pass through a series of tubes which would be capped with semi-permeable membranes.

In both of these methods the main technological problem is associated with the semi-permeable membrane. Membrane technology has not advanced to a point where very large self-cleaning membranes can be manufactured.

Further, the cost of constructing the twin-dams needed for the second technique is enormous. The costs of other fuels, however, may eventually justify the construction of such devices, provided that the membrane problem can be solved and the environmental consequences minimized.

The third device suggested for the conversion of salinity gradient energy is the dialytic battery. This is a rather low-yield device and cannot be relied on to significantly help satisfy our energy needs. For this reason and because of a lack of space this device is not discussed here. The reader is referred to the Wick and Isaac (1975)paper for further details.

C. Environmental Consequences

The Levenspiel and deNevers (1974) device has practically no environmental consequences since the device is placed in the deep ocean where the diffusion of the fresh water is rather local. Further, the fresh water will be on the surface where evaporation will take place.

The estaurine device has many environmental consequences. Obviously, the salinity at the mouth of the estuary is drastically changed. A second, and possibly much more serious change, is the alteration of the temperature gradient. Since the estuaries are primary sources of marine life, these two environmental changes would be disasterous. Finally, by constructing twin dams at the mouth of the estuary, migration of certain species into and from the estuary is prevented.

Discussion and Conclusions

Three ocean energy sources are discussed from the viewpoints of resource potential, technology, and environmental consequences. From the discussion it appears that salinity gradients have the greatest resource potential whereas tides have the least. The present technology available, however, makes tidal energy most feasible and salinity gradients unfeasible. Both salinity gradient conversion at the mouth of an estuary and tidal energy conversion have the same environmental problems.

Thus, wave energy conversion in both the deep ocean and coastal waters appears to be most feasible from all aspects. The resource potential in deep water is there because of the wind-wave's ability to regain lost energy. The technology is available and has been demonstrated on a small scale. Finally, except for possible alteration of the littoral currents, the environmental consequences appear to be minimum.

These three energy sources should all be studied and further developed in the future to help satisfy our energy needs.

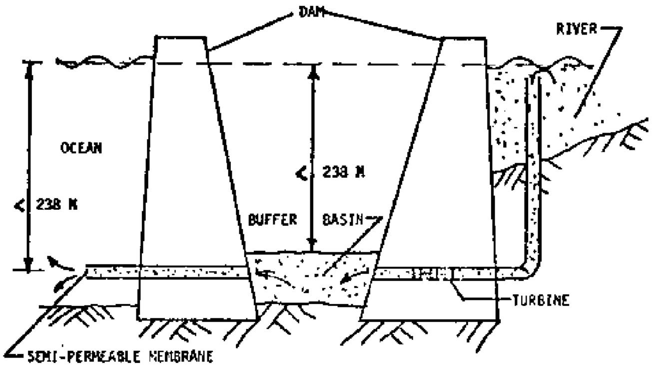


FIGURE 11. Estuarine Salinity-Gradient Energy Converter.

References

Brahtz, J. H. (1968), OCEAN ENGINEERING, John Wiley & Sons, New York.

Charlier, R. H. (1969, 1970), "Harnessing the Energies of the Ocean," Marine Technology Society Journal, Vol. 3, Nos. 3 and 4, Vol. 4, No. 2.

Crowley, J. G. (1975), Article in Boston Globe Magazine, July 8.

Fisher, A. (1975), "Energy from the Sea," Popular Science, May, June, July.

Gray, T. and Gashus, O. (1972), TIDAL POWER, Plenum Press, New York.

Isaacs, J., Castel, D., Wick, G. (1976), "Utilization of the Energy in Ocean Waves," Ocean Engineering (A Pergamon Journal), in press.

Lebarbier, C. H. (1975), "Power from Tides - The Rance Tidal Power Station," Naval Engineers Journal (ASNE), April, pp 57-71.

Levenspiel, O. and deNevers, N., "The Osmotic Pump," Science, Vol. 183, No. 4121, January 18, pp. 157-160.

References (continued)

Masuda, Y. (1971), "Wave Activated Generator," International Colloquium on the Exposition of the Oceans, Bordeau, France, March.

McCormick, M. E. (1973) OCEAN ENGINEERING WAVE MECHANICS, Wiley-Interscience, New York.

McCormick, M. E. 1975), "An Analysis of a Stationary Pneumatic Wave-Energy Converter," JL. for Industry (ASME), August, pp 1015-1019.

Palme, A., "Wave-Motion Turbine," Power, Vol. 52, Vol. 52, No. 18, November, pp 700-701.

Salter, S. H. (1974),"Wave Power," Nature, Vol. 249, No. 5459, June, pp. 720-724.

U. S. Army (1973), SHORE PROTECTION MANUAL, U. S. Government Printing Office No. 0822-00077, Volume 1.

Wick, G. and Isaacs, J. (1975),"Salinity Power," Scripps Inst. of Oceanography, IMR No. 75-9, September.

Wilson, E. N. (1973), "Energy from the Sea-Tidal Power," Underwater Journal, August, pp. 174-186.

LEGAL, POLITICAL, AND ENVIRONMENTAL ASPECTS OF OCEAN THERMAL ENERGY CONVERSION: A REPORT ON AN ASIL/ERDA STUDY

H. Gary Knight*

Abstract

The deployment of ocean thermal energy conversion (OTEC) devices in the world ocean raises a number of domestic and international legal, political, and environmental problems. International aspects include jurisdiction to deploy and operate OTEC devices, political implications of such deployment, regulation of operations, and protection of the marine environment. Domestic aspects include multiple use of ocean space, state and Federal regulation, responsibility and liability for damage to and by OTEC devices, protection of the marine environment, financing, and general economic issues. The American Society of International Law, pursuant to an NSF-ERDA grant, commissioned studies on these and related problems during 1975, the results having been disseminated at a workshop held in Washington, D. C., on January 15-16, 1976. The study provided an overview of legal/political problems contemporaneously with technical research work on OTEC devices. Since legal/political issues have usually been raised after the perfection of a new technology, this approach affords an opportunity for current feedback to forestall impediments to implementation of OTEC projects.

Introduction; Methodology of Study

In 1974 the American Society of International Law ("ASIL") obtained a grant from the National Science Foundation ("NSF") to investigate the legal, political, and environmental implications of ocean thermal energy conversion ("OTEC") devices. The grant later came under the administration of the Energy Research and Development Administration ("ERDA"). The study requested was unique because it sought to identify and analyze legal and related non-technical issues at the same time that fundamental work was being undertaken on the technical feasibility of OTEC devices.

In the past, legal and policy questions have often been deferred or not raised at all until a new technology reached the stage of practical application. The adverse effects of late blooming jurisdictional and environmental impediments to implementation of new technologies has a well known history, some examples being the SST, the Alaskan pipeline, and outer continental shelf oil and gas development.

The study commissioned by NSF/ERDA sought, in part, to avoid this error of the past by considering legal, political, environmental, and related issues from the outset, simultaneously with the development of OTEC technology. If the study results in appropriate action to ameliorate probable legal and political impediments, and if OTEC proves feasible and the deployment stage is reached, then hopefully no significant time loss would be incurred as a result of newly discovered non-technical problems. The study would presumably have alerted decision makers to the issues, and proper legislative, regulatory, or other action would have been taken to coincide with the target deployment date.

Another benefit of this approach was the interaction between the study group members and representatives of the compa-

---

* Campanile Charities Professor of Marine Resources Law, Louisiana State University Law Center; Co-Manager, Ocean Thermal Energy Conversion Panel, American Society of International Law (1975-1976).

nies (TRW and Lockheed) performing the basic feasibility studies. If legal or political problems discovered by the study group can be ameliorated at a pre-deployment stage by technological modifications, legal problems which might otherwise prove to be serious impediments to OTEC deployment could be eliminated entirely. Likewise, sufficient knowledge of the technology at hand on the part of study group members enabled them to identify problems which might otherwise have escaped their attention. Accordingly, the interaction of technology and law in this study may prove to have beneficial effects both for the developers of the technology and for the public interest.

The ASIL's approach to the study, which had been utilized in prior ASIL projects, was to form a panel of experts in various fields such as law of the sea, environmental law, political science, and economics. Issues were then identified by the principal investigator and the two project co-managers, and research papers were commissioned to members of the Panel (a list of the OTEC Panel members is set forth at the conclusion of this paper). The Panel met five times during 1975 at ASIL headquarters in Washington, D. C. to critique the papers in first, second, and final draft form. This inter-disciplinary exchange process resulted in improvements in each draft of each paper, and also provided a wider range of inputs to the respective authors than could have been achieved by any author working alone.

Because the study's purpose was not to reach any definite conclusions but rather to identify and analyze legal, political and other issues which could have an effect on OTEC deployment, the papers were ultimately presented, without specific conclusions or recommendations, at a workshop held in Washington, D. C., on January 15-16, 1976.

Some Major Issues Raised

Because the papers are for the most part quite long and detailed, this portion of the paper will simply identify each major issue area discovered, identify the paper commissioned and its author, and give a brief synopsis of the paper's contents. Those interested in pursuing particular issues further can obtain copies of the full texts through one of the methods indicated in the conclusion. The legal, political, environmental, economic, and other issues raised cover both international and domestic problems, the first four issues described below being concerned basically with international matters.

1. International Issues.

a. Jurisdictional Problems.

A nation's or an individual's right to make a particular use of the ocean depends on the jurisdictional legal regime applicable to the site in question. The right to deploy and operate OTEC devices depends on the particular zone of ocean space involved (e.g., territorial sea, economic resource zone, high seas). The legal content of such zones is in flux, with the final legal regime dependent on the outcome of the current law of the sea negotiations and the Third U.N. Law of the Sea Conference. It seems relatively certain, however, that coastal states will possess authority sufficient to warrant the deployment of OTEC devices off their coasts to a distance of 200 miles. Beyond 200 miles the outcome is less clear. A problem also exists with respect to "ownership" of ocean thermal energy. For the present it seems likely that it will be considered a "free" resource, with "ownership" vesting in the nation or person who first makes use of it. However, recent international economic developments, particularly involving underdeveloped nations (the so-called "new international economic order") indicate that international control over many ocean resources, perhaps including thermal energy, may not lie in the too distant future.

There are other, less compelling, problems raised by international law. For example, the protection of OTEC devices from accidental or deliberate interference may necessitate the promulgation of safety zones surrounding such installations. OTEC's may be subject to international terrorism. Issues will also arise concerning inspection, flags of convenience, and cables transmitting power to shore.

All of these questions are addressed in the paper by Prof. H. Gary Knight entitled "International Jurisdictional Issues Involving OTEC Installations," in which the author discusses the present state of the international law of the sea, the trends in development of that body of rules, and such concepts as the economic resource zone, the "common heritage of mankind," and the regulation of scientific research in the ocean. He also focuses on the "reasonable use" theory as a legal basis for deployment of OTEC installations.

b. Political Problems.

The international political ramifications of OTEC are discussed by Dr. Ann Hollick in "The International Political Implications of Ocean Thermal Energy Conversion Systems." Though such impacts are difficult to ascertain because of the time frame and the many variables involved, an examination of current international developments does indicate some possible future developments which could interact with OTEC. The paper discusses such issues as the political geography of OTEC operations, international political factors affecting OTEC, and operational issues affecting OTEC. Of particular interest is the possible effect on energy relations between developed and underdeveloped nations stemming from the fact that, with the exception of the United States, the nations situated within the equatorial band conducive to OTEC deployment are not major consumers of energy at the present time. Depending on the quantity of OTEC energy produced, this could provide a new basis for "north-south" energy relations.

c. Regulatory Problems.

In "International Regulatory Authority Concerning Ocean Thermal Energy Conversion Devices," Capt. C. R. Hallberg observes that although there are no international organizations which can be said to be clearly seized with authority or competence to deal with OTEC devices at present, it is certain that some agencies will assert jurisdiction at or prior to the time of deployment. There are obviously national and international public interests of some importance to be protected -- environmental protection, labor standards, general economics of operation, safety of life and property at sea, to mention the more important -- and there is a multiplicity of international organizations apparently competent to deal with each such interest. The most likely body to become involved, however, is the International Maritime Organization (formerly IMCO) which is concerned with such matters as pollution of the sea by oil and safety of life at sea. Work already underway on the subject of ocean data acquisition systems (ODAS) by the International Oceanographic Commission (IOC) could also have an impact on OTEC deployment. These problems will not be ameliorated by the establishment of 200 mile economic resource zones under national (coastal state) control, for activities in such zones will still be subject to agreed international standards concerning pollution, safety, and so forth.

d. Environmental Protection.

One of the most important international issues analyzed is that of protection of the marine environment, addressed in Robert E. Stein's paper entitled "Ocean Thermal Energy Conversion: International Environmental Aspects." OTEC's may cause changes in ocean temperature and perhaps in the atmosphere which could have impacts far from the site; water intake and exhaust could affect biologic conditions and fish life in broad areas of the water column; and the use of fluids and chemicals of a potentially hazardous nature could produce adverse effects if spilled. Although some legal precedents exist to deal with international pollution, new initiatives stemming from the Stockholm Conference on the Human Environment and the United Nations Environment Program (UNEP) are more likely to have significant effects on OTEC deployment. There are also a number of international agreements which may impact OTEC, such as the 1972 Ocean Dumping Convention and the 1973 IMCO Convention for the Prevention of Pollution from Ships. The paper dealing with this subject concludes that there will inevitably be environmental effects from OTEC deployment and that there will as a result be a growth in multilateral regulation of OTEC devices.

2. Domestic Problems.

a. Multiple Use.

As the diversity and intensity of the use of ocean space has increased over the past three decades, several conflicts have arisen over proper allocation of resources or space in the marine environment. The list of old and new uses is long -- continental shelf oil and gas, merchant shipping, fishing, artificial islands, military operations, oceanographic research, dumping of wastes, deep seabed mineral mining -- and the introduction of still another use is certain to create at least minor conflicts with existing users of the area. In addressing this problem in his paper "Spatial and Emerging Use Conflicts of the Ocean Space," Dr. Byron Washom first identifies all of the significant present and emerging uses of the ocean, demonstrating that the intensity and diversity of ocean space use is already causing problems of accommodating conflicts for the same space or resources. The paper then identifies a range of probable conflicts of OTEC with such ocean space uses and concludes with a section on possible methods for the adjustment or resolution of such conflicts.

b. Regulatory Problems.

A common current complaint of the populace is overregulation by an increasingly large and pervasive state and Federal bureaucracy. Nowhere is this more evident than when one seeks to make a particular use of a portion of ocean space under the jurisdiction of the United States. Permits or approvals must be obtained from a plethora of departments, agencies, and bureaus. Often there is little or no effort toward consolidation or coordination of these requirements. James C. Higgins, Jr.'s paper, entitled "Ocean Thermal Energy Conversion Plants: Federal and State Regulatory Aspects," identifies a long list of state and Federal agencies which will undoubtedly assert jurisdiction with respect to OTEC devices. Over a dozen such agencies are identified and the bases for their jurisdiction analyzed -- including the Army Corps of Engineers, the Coast Guard, ERDA, the Federal Energy Administration, the Federal Powwer Commission, and the Departments of Defense, Commerce, Interior, and Labor. The major problem foreseen is the multiplicity of permits and approvals which would have to be obtained before deployment.

c. Responsibility and Liability.

J. Daniel Nyhart's paper, "Problems of Legal Responsibility and Liability to be Anticipated in OTEC Operations," deals with the thorny questions of who bears the burden of responsibility for damage to or by OTEC devices, and who is ultimately liable for any such damage. Even though procedures for conflict avoidance may be developed, as pointed out in Dr. Washom's paper, it is inevitable that some other user of ocean space (perhaps a vessel) will cause damage to an OTEC, or that an OTEC will (perhaps through pollution or inadvertant collision) cause damage to some other object or area of land. This paper examines the applicability of traditional maritime law concepts to OTEC (including the issue whether OTEC devices will be considered as "vessels" for purposes of admiralty law), as well as complicated questions of liability resulting from various financing arrangements such as ship mortgaging and leveraged leasing. Because of the problems involved in applying "old" law to "new" technologies, it may be necessary to secure legislation specifically directed at OTEC devices.

d. Environmental Problems.

In his paper "Ocean Thermal Energy Conversion: Domestic Environmental Aspects," Thomas B. Steol addresses the effect of the National Environmental Protection Act (NEPA), subsequent litigation, and environmental impact statements. This paper differentiates between the research and development stage, the demonstration stage, and commercial development in discussing the likely applicable domestic environmental laws and regulations.

e. Financing.

"Legal Aspects of Financing Ocean Thermal Energy Conversion Plants," by John H. Riggs, Jr., analyzes a wide range of possible financing devices for OTEC. Included in the discussion are the financing of privately owned OTEC plants through such devices as unsecured debt or equity financing by the corporate owner, ship mortgage financing, and lease financing; financing of government owned OTEC plants; and mixed forms of financing. Riggs concludes that capital should be available for OTEC financing, despite the looming competition for capital funds over the next 10-15 years, but that much will depend on the willingness of the Congress and the Executive branch to make available federal loan guarantees and tax advantages for such financing.

f. General Economic Analysis.

Finally, Prof. Carlos Stern, in "Economic Issues Related to Ocean Thermal Energy Conversion Plants" has addressed a wide range of general economic questions. Among the issues with which he is concerned are electric power in a utility system (power demand and market), the potential market for OTEC energy, cost comparisons between OTEC and other energy sources, cost estimates for OTEC, and direct on-site processing of OTEC electricity.

Conclusion

Although the study was not designed to produce definite conclusions or make specific recommendations, it seems clear from the papers prepared that a variety of legal, political, and economic problems face OTEC, both at the domestic and at the international level. Consideration needs to be given, therefore, by appropriate legislative and executive personnel, to methods for coping with these impediments prior to the time that OTEC deployment -- even in the demonstration stage -- is upon us. One possible approach is to continue the work of the OTEC Panel, this time focusing on specific jurisdictional, legislative, and regulatory methods for coping with the problems already identified.

All of the papers described in this summary will be available shortly in a hard-cover book published under the auspices of the ASIL. Prior to that time a limited number of copies of the typescript versions remaining from the January 15-16, 1976, workshop will be available from the ASIL. Resort to individual authors is also appropriate for single issues. A list of the authors and OTEC Panel members, and their affiliations, is contained in the annex.

Annex

OTEC Panel members and paper authors: Robert E. Stein (International Institute for Environment and Development), Prof. H. Gary Knight (Louisiana State University Law Center), Prof. J. D. Nyhart (Massachusetts Institute of Technology), Bennett Boskey (Volpe, Boskey & Lyons; Washington, D. C.), Dr. Robert Cohen (ERDA), Capt. C. R. Hallberg (U.S. Coast Guard), James C. Higgins, Jr. (Offshore Power Systems, Jacksonville, Fla.), Dr. Ann Hollick (Woodrow Wilson International Center for Scholars, Washington, D. C.), Dr. Arthur Konopka (NSF), John H. Riggs, Jr. (White & Case; Brussels, Belgium), Prof. Warren M. Rohsenow (Massachusetts Institute of Technology), Dr. Herman E. Sheets (Univ. of Rhode Island), Prof. Carlos Stern (Univ. of Connecticut), Thomas B. Stoel, Jr. (National Resources Defense Council; Washington, D. C.), Dr. Byron J. Washom (Massachusetts Institute of Technology), Norman A. Wulf (NSF).

POTENTIAL MARICULTURE YIELD OF FLOATING SEA THERMAL POWER PLANTS. PART 1--GENERAL STATEMENT

O. A. Roels*, S. Laurence, L. Van Hemelrijck and A. F. Amos

Lamont-Doherty Geological Observatory
of Columbia University
Palisades, New York 10964

*and The City University Institute of Marine and
Atmospheric Sciences
Wave Hill, 675 W. 252 Street
Bronx, New York 10471

Abstract

Mariculture is not only compatible with electrical power production in sea-thermal power plants, but it is a highly desirable and economically sensible approach to the energy and food situation currently facing the world. The technical feasibility of maintaining the proper mixing of deep and surface water, and keeping this mixed layer at an optimum depth within the euphotic zone, remains to be demonstrated, as does a simple and inexpensive means of growing and harvesting shellfish in the open sea. Increasing cooperation between the power engineers, economists and mariculturists interested in OTEC plants is obviously needed. No sea-thermal power plant design which excludes the possibility of mariculture should be adopted until the relative contribution of the energy-production and biological potential of OTEC plants is examined carefully and in detail.

Introduction

During recent years, we have been made aware of the enormous problems facing the world in obtaining sufficient quantities of inexpensive, renewable, and non-polluting sources of energy. This shortage of energy, in addition to great increases in world population and the insistent demands of developing countries for energy-intensive industrial and agricultural progress, is swiftly leading to a possibly calamitous food crisis. Energy and food production represent a complex and interdependent whole which must be analyzed and implemented together (Pimentel et al., 1975).

As Beck (1975) and others have pointed out, the direct utilization of sunlight, through a variety of means, is probably the only resource by which energy and food problems to be faced by future generations can be overcome. A number of the talks given at recent conferences indicate an understanding of this point, and it is clear that sea-thermal power plants could be a significant step forward in attempting to harness the energy given off by the sun and absorbed by the upper layers of the ocean.

In addition to this enormous reservoir of energy which can be tapped by utilizing the temperature gradient known to exist between surface and deep (over 400 m) water, however, the deep water contains significant quantities of nutrients necessary for phytoplankton growth. Thus, the water discharged from a sea-thermal power plant can be used to start marine food chains, after its energy has been tapped. In this way, the sea-thermal power plant represents a unique and unified approach to the solution of the dual problems of energy and food production.

This paper presents, briefly and generally, a description of the potential biological yield of water discharged from sea-thermal power plants. The results are highly encouraging and make it clear that cooperation among those interested in the engineering, economical and mariculture aspects of such plants can all profit from closer collaboration and mutual support.

---

*This paper was presented at the 1975 Fall Meeting of the American Geophysical Union, San Francisco, Ca., Dec. 8-12, and at Conference on "Energy From the Oceans--Fact or Fantasy?", Raleigh, North Carolina, Jan. 27-28, 1976. The work presented in this paper was supported by the U. S. Energy Research & Development Administration under Contract E(11-1) 2581.

Mariculture As A By-Product of Sea Thermal Power Plants

The technical feasibility of producing energy from the temperature differential existing between deep and surface water was demonstrated by Claude in 1930, using an open-cycle plant on the North shore of Cuba. Since 1969, the mariculture potential of deep-sea water has been demonstrated by our group at the St. Croix Artificial Upwelling project.

The Artificial Upwelling project is located on St. Croix, in the U. S. Virgin Islands, about sixty miles southeast of Puerto Rico and 1200 miles southeast of Miami, Florida.

As can be seen from Figure 1, the sea floor drops precipitously off the North Shore of St. Croix, reaching a depth of 1000 m approximately 1.6 km offshore. This topography and its tropical light and temperature made the island ideal for the installation of the Artificial Upwelling project.

Table 1 lists some physical and chemical properties of the deep and surface waters off St. Croix.

Phytoplankton growth in deep water is limited by the availability of dissolved inorganic nitrogen. The amount of dissolved inorganic nitrogen (Table 1) present as nitrate (NO_3-N), nitrite (NO_2-N), and ammonia (NH_3-N) is much greater in the deep water than in either the offshore or reef surface water.

In combining the total nitrate, nitrite and ammonia in surface water, we find that the total dissolved nitrogen in these chemical species is approximately 1 µg-at l^{-1}, while the deep water contains approximately 32 µg-at l^{-1}. Phosphate (PO_4-P) and silicate (SiO_4-Si) are also much more abundant in the deep water. The respective salinities and temperature for surface and deep water are very different, of course, and this is of great importance for the mariculture potential of floating sea-thermal power plants, since they govern the density of the deep and surface waters, and, therefore, the fate of the deep water after its discharge from the sea-thermal power plant.

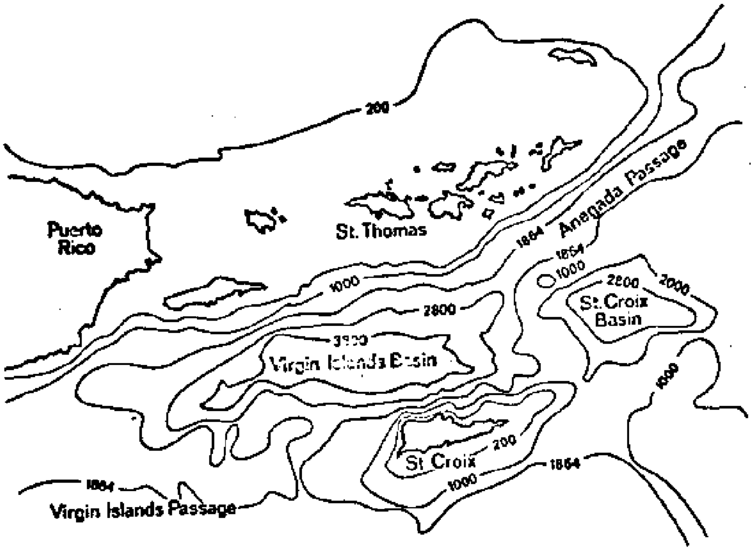


Figure 1. Isobaths (m) in the U.S. Virgin Islands. The ocean floor drops precipitously off the North Shore of St. Croix.

The Mariculture System in St. Croix

Nutrient-rich deep water is pumped to the surface through three polyethylene pipelines, the intakes of which are located 1900 m offshore in 870 m of water. Each pipeline has an internal diameter of 7.5 cm and a wall thickness of approximately 1 cm. The water flow through these lines is about .3 m sec^{-1}, and conduction warms the water

TABLE 1. ST. CROIX WATER PROPERTIES

	NUTRIENTS					SALINITY (°/oo)	TEMPERATURE (°C)
	NO_3+NO_2-N	NO_2-N	NH_3-N	PO_4-P	SiO_4-Si		
OFFSHORE SURFACE WATER	.2	.2	.9	.2	4.9	35.539	26-29
NEARSHORE REEF SURFACE WATER	.2	.2	.8	.3	2.1	35.596	26-29
870-M DEEP WATER	31.3	.2	.7	2.1	20.6	34.852	7

to between 21.5 and 23.0°C at the land discharge. The total flow through these three pipelines is 170 liters per minute.

A schematic layout of the mariculture system is given in Figure 2. The deep water is pumped into two 45,000-liter concrete pools in which unialgal cultures of planktonic diatoms are grown in continuous culture. These pool cultures are started by cultures grown in cyclindrical 757-liter polyethylene tanks which have been inoculated from axenic cultures grown in a constantly illuminated and temperature-controlled laboratory.

Through the processes of photosynthesis, nutrient uptake and cell division, the algae in the pools utilize sunlight to convert the dissolved nutrients in deep water into new cells. The growth rate of the algae is regulated by the rate at which nutrients are supplied by the incoming deep water, thus assuring nearly complete utilization of the nutrients in the deep water. One species being tested, the diatom Chaetoceros curvisetus Cleve (clone STX-167), grows extremely well on unsupplemented deep water, while the other species currently being used (Thalassiosira pseudonana Hasle & Heim. (clone 3H) and Bellerochea polymorpha Harg. & Guill. (clone STX-114) require supplemental additions of vitamins and iron. Our goal, of course, is to grow a variety of organisms which provide the shellfish with optimum nutrition and yet grow well in unsupplemented deep water.

The algal cultures in the pools, containing from 1.0×10^4 to 7×10^6 cells per milliliter, are pumped continuously into the shellfish tanks at metered rates, based on the feeding activity of the shellfish. The total flow pumped into the shellfish tanks matches the flow of deep water into the algal pools, so that the pool volume remains constant. At present, turnover rates in the pools of from 1.1 to 1.5 volumes per day are used; we produce 117,000 liters of phytoplankton culture per day.

Flow into the shellfish tanks is adjusted to ensure that the animals remove up to 90% of the algae from the pool-culture suspension. In this system, with a yearly temperature range of from 22 to 29°C in the tanks, we have successfully raised to market size ten species of shellfish, listed in Table 2. The most successful of these are the Japanese littleneck clam (Tapes semidecussata) and the Kumamoto variety of the Pacific oyster (Crassostrea gigas).

Not shown on Figure 2 are tanks holding spiny lobsters, Panulirus argus, which are being fed bivalves culled from our growing

TABLE 2

SHELLFISH GROWN TO MARKET SIZE IN THE ST. CROIX ARTIFICIAL UPWELLING MARICULTURE SYSTEM

SPECIES	
Crassostrea gigas Thunberg	Pacific oyster
Crassostrea gigas (Kumamoto variety)	"Gigas"-type oyster for half-shell trade
Ostrea edulis Linnaeus	European oyster
Argopecten irradians Lamarck	Bay scallop
F_1 clam (M. mercenaria ♂ x M. campechiensis ♀)	Cross of northern and southern clam or quahog
Mercenaria campechiensis Gmelin	Southern clam or quahog
Tapes semidecussata Reeve	Japanese littleneck clam
Pinctada martensii Tanita & Kikuch	Japanese pearl oyster

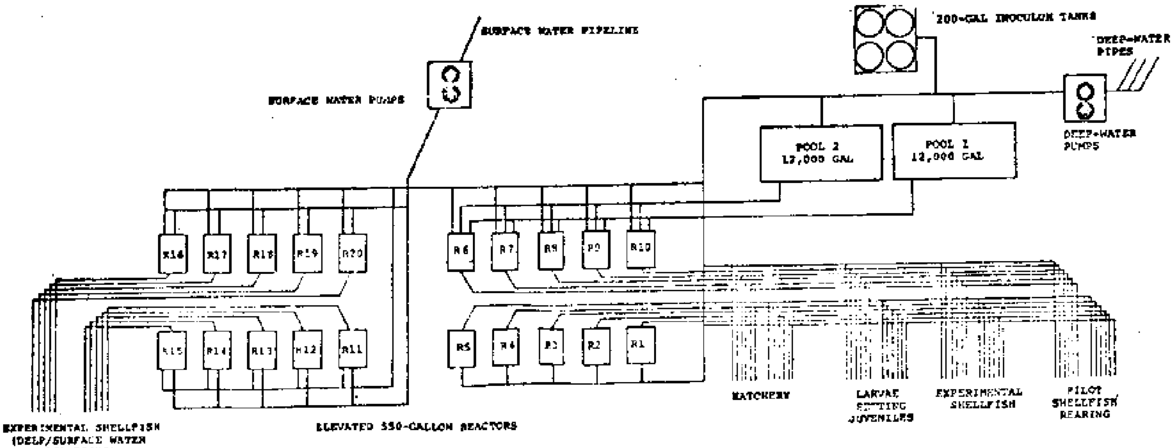


Figure 2. Schematic diagram of the St. Croix Artificial Upwelling mariculture system.

stock. We have also reared the Queen conch, *Strombus gigas*, on algae growing on the sides and bottoms of small ponds which receive effluent from the shellfish tanks.

The effluent from the animal tanks, which contains approximately 10 μg-at liter^{-1} of ammonia-nitrogen excreted by the shellfish, is fed into seaweed tanks. *Hypnea musciformis*, a carrageenan-producing seaweed, can double its weight every three days by utilizing this ammonia. Aside from adding to the economic yield of a deep-water mariculture system, the seaweed helps to eliminate contaminants in the discharge.

The St. Croix site also contains a hatchery and an experimental shellfish area, the latter is used for the optimization of plankton protein to shellfish protein conversion. Twenty 2000-liter concrete culturing vessels are used for shellfish diet studies and for the testing of new species of planktonic algae. These vessels were used to test phytoplankton production in mixtures of surface water and deep water described in this study.

The results of these tests demonstrate that it is technically feasible to operate a mariculture system utilizing the nutrients in the deep water. In addition to the high biological productivity offered by such a system, the use of deep water has other important advantages, for it is free of parasites, predators, pollutants and disease and disease-bearing organisms.

High Economic Potential

During recent, highly controlled studies, we have been able to convert over 43% of the dissolved inorganic nitrate-nitrogen present in the deep water into shellfish meat protein-nitrogen. This high conversion efficiency (which, it must be emphasized, is occurring through two trophic levels) means that the system appears very attractive from an economic point of view. If duplicated on a large scale, shellfish yields of over $300,000 per hectare per year could be achieved.

The Need For A Shore-Based Pilot Facility

Based upon these results, we recommend that a commercial feasibility test which would pump 100 cubic meters per minute be coupled with a shore-based sea-thermal power pilot plant. If these mariculture results are confirmed, a significant part of the costs of technical development tests of desalination, airconditioning and power generation would be offset by the sales of the mariculture products.

Open-Sea Mariculture

Based on this work, we have recently initiated a series of studies to determine if mariculture operations could utilize the condenser effluent of large floating sea-thermal power plants. The major factors affecting phytoplankton productivity utilizing the deep water nutrients from such a system are: (1) the fate of the deep water, after its discharge from the power plant condenser, (2) the dilution of the deep water with surface water, (3) the depth of the mixed layer, (4) the size and species composition of the phytoplankton population in surface and deep water.

It is important to determine first whether the nutrient-rich deep water, after being warmed in the condenser, can be discharged in such a way that it remains near the surface of the ocean in concentration great enough to allow for sufficient primary production to occur, or whether mechanical containment of some kind is necessary. Table 3 lists the characteristics of St. Croix deep and surface water which influence its density and hence the vertical movement of the discharged deep water. Table 3 also lists the amount of heating of deep water required for density equilibrium with surface water and the density equilibrium for a 70:30 deep-/surface-water mixture.

The deep water, with a temperature of 6.7°C and a salinity of 34.852 $^{0}/_{00}$ has a σ_t of 27.364, while surface water, with a temperature of 27.5°C and a salinity of 35.339 $^{0}/_{00}$, has a lower density (σ_t = 22.983). The greater density of the deep water is due to its lower temperature alone. For density equilibrium with surface water to be reached, the deep water must be raised by 19.1°C, and therefore discharged at a temperature of 25.8°C. In batch experiments, it was ascertained that a mixture of 70% deep and 30% surface water would result in optimal blooms of phytoplankton, and such a mixture would have to be at 26.4°C for density equilibrium with the surface water at 27.5°C.

TABLE 3. CHARACTERISTICS OF ST. CROIX SURFACE AND DEEP WATER

	TEMP. (°C)	SALINITY ($^{0}/oo$)	σ_t	ΔT NECESSARY FOR DENSITY EQUILIBRIUM WITH SURFACE WATER	TEMPERATURE FOR EQUILIBRIUM WITH SURFACE WATER
SURFACE WATER (S)	27.5	35.539	22.983	--	--
DEEP WATER (D)	6.7	34.852	27.364	+19.1	25.8
30:70 MIXTURE (S:D)	--	35.058	--	--	26.4

Batch Studies

To assess the mariculture potential of floating sea thermal power plants, a series of batch experiments were done in which a range of surface water/deep water mixtures were used to assess primary production and lag time of the plankton blooms. Since the surface water is nutrient-poor but contains the phytoplankton necessary to initiate a bloom, it is clear that the greater the percentage of surface water used, the shorter the lag time will be before exponential growth is initiated, and the lower the final level of productivity will be since this depends upon the concentration of nutrients. Conversely, high proportions of deep water would result in extended lag times, but greater levels of productivity.

These expectations were confirmed experimentally; generally, mixtures containing more than 40% surface water resulted in unacceptable levels of productivity, while mixtures with more than 80% deep water resulted in such long lag times that some cultures failed to bloom at all. In general, we found that batch mixtures of 70% deep and 30% surface water resulted in an optimal combination of lag time and productivity. In such mixtures, we found that 1 µg-at NO_3^-N yielded .26 µg Chl*a*, and that the half-saturation constant, K_s, was 1.55 µg-at NO_3^-N per liter. The maximum doublings of the phytoplankton per day which we obtained with such mixtures was 3.55.

Continuous Flow Studies of Primary Production

Continuous flow phytoplankton studies and shellfish feeding studies were then started, using these optimal mixtures of surface and deep water. This work is still in progress. Preliminary analysis indicates that the phytoplankton blooms obtained in mixtures of deep and surface water--if properly managed--result in very efficient conversion of dissolved inorganic nutrients to phytoplankton protein and, in turn, to a very efficient conversion of phytoplankton nutrients to shellfish meat protein.

For these studies, 2000-liter, epoxy-coated concrete culturing vessels ("reactors") measuring 113 cm wide x 223 cm long x 93 cm deep were used for growing the phytoplankton, and these cultures were fed by gravity into small trays holding juvenile *Tapes semidecussata*. The blooms are managed by first filling the "reactors" with 400 liters of surface water, which is pumped from 30 m offshore through a 3.75 cm diameter polyethylene pipeline and 500 liters of deep water pumped from 870 m depth, 1800-m offshore. This combination results in a minimum lag time to growth, and once peak productivity is attained, deep water is added so that the final mixture contains 80% deep and 20% surface water. Once this mixture reaches peak productivity (ascertained through daily measures of phytoplankton protein and dissolved inorganic nutrients), the reactor is "activated", or placed on continuous flow, with the 80:20 proportion of deep:surface water maintained. During current studies, the phytoplankton blooms which result can be maintained on continuous flow for about 40 days, at a turnover rate of 2000 liters per 24 hr (1.0 turnovers per day). Under these conditions, over 99% of the available dissolved inorganic nitrate, nitrite and ammonia nitrogen is assimilated by the phytoplankton.

Theoretically, once a bloom has been started, maximum productivity should be reached with a continuous flow of 100% deep water, as we use the pool cultures described earlier. However, under open-sea conditions, it is highly unlikely that a mixture containing more than 80% deep water could be maintained. The optimal mixtures which could be maintained under such conditions remain unknown. A carefully considered compromise between the maximum productivity which can be realized and the costs and technical problems associated with control over the discharged water will be necessary.

Shellfish Feeding Studies

The growth of juvenile *Tapes semidecussata* fed from these cultures has been spectacular. In a "constant weight" experiment, 100 grams (total wet live weight) of *Tapes* in a square tray of four-liter volume very efficiently converts phytoplankton nutrients when fed at a rate of 1.0 ml per sec. (The weight is maintained "constant" by periodically culling the animals, and therefore keeping the total weight in the tray near 100 g.) Under these conditions, 100 g of *Tapes* will produce 50 g of culled animals over a 30-day period, and the conversion efficiency of deep and surface water inorganic nitrate, nitrite and ammonia nitrogen to shellfish meat protein nitrogen is 45%.

Economic Potential of Open-Sea Mariculture

Table 4 illustrates the potential gross sales value of the power and of the shellfish produced by a 100 megawatt sea-thermal power plant utilizing 4.5 x 10^7 liters deep-sea water per minute.

If such productivity could be maintained under open-sea conditions, the economic potential of the mariculture operation would be very large: 17 times greater than the value of the electrical power produced. There are a number of ways to look at such figures: shellfish meat could be sold for as little as 10¢ per pound, and the economic benefits of the mariculture operation would still exceed that of the power generation alone. Of even greater interest is the fact that the plant could be one-tenth of the proposed size (100 MW Lockheed design), and still produce enough shellfish to make the economic return greater than that obtainable from the electricity sold by a 100 MW plant. This means that an economically viable plant, perhaps of pilot-scale size, could be constructed for a relatively small investment compared to currently proposed plants. In addition, we estimate that perhaps 59,000 tons (dry weight), or 590,000 tons (wet weight) of *Hypnea musciformis* or carrageenan containing seaweed could be produced from a 100 MW OTEC plant. The seaweed would utilize the shellfish excretory products.

It must be stressed that animal protein will become an increasingly important economic resource in the foreseeable future, and the design of an integrated power and protein producing plant makes not only sound economic sense, but will help to alleviate the protein shortage currently experienced by much of the world's population.

Conclusion

Mariculture is not only compatible with electrical power production in sea-thermal power plants, but it is a highly desirable and economically sensible approach to the energy and food situation currently facing the world. The technical feasibility of maintaining the proper mixing of deep and surface water, and keeping this mixed layer at an optimum depth within the euphotic zone, remains to be demonstrated, as does a simple and inexpensive means of growing and harvesting shellfish in the open sea. Increasing cooperation between the power engineers, economists and mariculturists interested in OTEC plants is obviously needed. No sea-thermal power plant design which excludes the possibility of mariculture should be adopted until the relative contribution of the energy-production and biological potential of OTEC plants is examined carefully and in detail.

Acknowledgements

We wish to extend our appreciation to the following people: Jim Petersen, who performed the batch studies, Rich Lyons, Dr. Tom Dorsey and Paul McDonald, who were responsible for chemical analyses, and Leo Aust, St. Croix station manager and resident engineer for the Artificial Upwelling project, who helped through all phases of these investigations.

TABLE 4. POTENTIAL ANNUAL GROSS SALES OF A 100 MEGAWATT SEA-THERMAL POWER PLANT UTILIZING 4.5 x 10^7 LITERS DEEP-SEA WATER PER MINUTE

	POWER	CLAM MEAT
UNIT PRICE	$0.04/KWH	$1.00/LB
GROSS OUTPUT/YEAR	$8.76x10^8$ KWH	6x10^8 LBS
VALUE	$3.5x$10^7$	$60x$10^7$

REFERENCES

1. Beck, E.J., 1975. Ocean thermal gradient hydraulic power plant. Science, 189:293-294

2. Roels, O.A., K.C. Haines and J.B. Sunderlin, 1975. The potential yield of artificial upwelling mariculture. Tenth European Symposium on Marine Biology, Ostend, Belgium, September 17-23.

3. Pimentel, D., W. Dritschilo, J. Krummel and J. Kutzman, 1975. Energy and land constraints in food protein production. Science, 190:724-760

MARITIME ASPECTS OF PRODUCING PRODUCTS AT OTEC PLANTS AT SEA AND DELIVERING THEM TO THE UNITED STATES

G. L. Dugger and E. J. Francis
Applied Physics Laboratory, The Johns Hopkins University
Laurel, Maryland

Abstract

The conceptual design of a 100-MW$_e$, 313-ton/day, Ocean Thermal Energy Conversion (OTEC)/ammonia plant-ship has been developed in sufficient detail to assure that it can be built in and launched from existing U.S. shipyard facilities for deployment to tropical ocean sites. This design provided the basis for a first-of-a-kind cost estimate from which extrapolations were made for nth plant cost of a 500-MW$_e$, 1697-ton/day commercial-size OTEC/ammonia plant-ship. With a reasonable level of government cost sharing in the early years of operation of such a commercial-size vessel, it is estimated that ammonia can be produced and delivered to U.S. ports at a cost of \$90/ton (1975 dollars) compared to recent sales prices near \$180/ton, yielding a 50% return on sales and a cash flow that would equal the plant investment in approximately 5½ years. Ammonia, produced via water electrolysis for the H_2 and air liquefaction or combustion for the N_2, appears most attractive as the product for early (1982-1985) plant-ships, because it is needed for fertilizers and other chemicals, it is presently made from natural gas (in short supply), no raw materials are required for its manufacture by OTEC at sea, and the economics appear to be attractive in the near term. Alternative uses of OTEC for the energy-intensive process of reducing alumina to aluminum (7-8 kWh/lb Al) and for making liquid hydrogen (LH_2) are also sufficiently attractive to warrant further study in depth. It appears possible to achieve a commercially competitive position for electrolytically produced LH_2 in large quantities in the 1990s. This LH_2 could serve as a fuel for heating and transportation, a chemical for industrial uses, and a source of electricity via fuel cells on shore. Other possible OTEC plant-ship products are magnesium and a variety of fuels and chemicals (e.g., methanol).

Introduction

In the period April-December 1975 the Applied Physics Laboratory (APL) conducted an analysis[1] of the maritime aspects of Ocean Thermal Energy Conversion (OTEC) plant-ships for deployment in tropical oceans to produce ammonia or other energy-intensive products. This analysis was supported by the U.S. Maritime Administration (MARAD), Department of Commerce. Working with APL were the Sun Shipbuilding & Drydock Company (SS&DD), who provided substantial company-funded design and consulting efforts; Hydronautics, Inc., who conducted analyses on platform motions and other marine aspects; the Woods Hole Oceanographic Institution for site selection and design criteria; Avondale Shipyards and Kaiser Aluminum and Chemical Corporation who contributed consulting efforts; the law firm of LeBoeuf, Lamb, Leiby, and MacRae, who addressed the international legal considerations; and many industrial organizations and consultants who provided information on the OTEC and product equipment.

The baseline design for a 100-MW$_e$ OTEC/ammonia plant-ship features the integration of a novel concept for low-cost OTEC heat exchangers with a simple, relatively low draft, rectangular concrete hull. The concept for the heat exchangers, which employ large-diameter, multipass aluminum tubes with the ammonia working fluid inside the tubes, was developed under APL inhouse support and support from the U.S. Energy Research and Development Administration (ERDA).[2]

The present U.S. interest in Ocean Thermal energy was stimulated by the Andersons, who developed a closed-Rankine-cycle, OTEC plant concept in the early 1960s.[3] There is still interest in the open-cycle process (vacuum-flash-vaporization of the warm water to drive a low-pressure steam turbine) that was initially demonstrated by Claude in 1930[4] and has been analyzed recently by Brown and Wechsler.[5] Beck[6] and Zener and Fetkovich[7] have conceived improvements on the open cycle that would use a "steam lift water pump" or a foam lift concept, respectively, to raise the warm water, which would then fall to drive hydroelectric turbine-generators. However, most of the recent OTEC work in the U.S., which was supported primarily by the National Science Foundation prior to January 1975 and has been supported primarily by the Solar Energy Division of ERDA since its formation at that time, is addressed to closed-Rankine-cycle systems. In these systems, a working fluid (e.g., ammonia) is vaporized by heat exchange with warm sea water, drives a turbine, and then is condensed by heat exchange with cold sea water pumped from 1100-4000-ft (340-1220 m) depth. Notable have been the plant concepts developed by the University of Massachusetts,[8] Carnegie-Mellon University,[9] and industrial teams headed by the Lockheed Missiles and Space Co., Inc.[10] and TRW Systems Group.[11] The first three of these are described in other papers at this Conference.

There are two primary concepts for using OTEC power. One is to moor a plant near shore, e.g., in the Gulf Stream off the lower U.S. East Coast, and deliver to shore either electricity via cables[8] or high pressure gaseous hydrogen. Development of a demonstration plant using this approach would offer greater visibility to the U.S. public than one in tropical oceans, and the potential exists to deliver a significant amount of energy to the southeastern states. However, plants in the Gulf Stream would have to be much more rugged to withstand hurricanes and large currents, and would have to operate with a much lower ocean temperature difference (ΔT, 30-34°F) than is available in oceans nearer the equator. These factors make such plants more expensive per unit of electric power developed on board.

The other concept, addressed in this paper, is to base OTEC plants in selected tropical ocean sites where design winds and currents are much smaller and available ΔTs are much higher (40-43°F) and are less subject to seasonal variation. The available ΔT is a powerful factor; plant cost varies inversely with ΔT to a power of 2 to 2.5. The total energy potential from large siting areas in tropical oceans is much greater, too.

The power generated by OTEC plants at such sites in tropical oceans must be used to make energy-intensive products (e.g., ammonia, aluminum, liquid hydrogen) which can be shipped to U.S. or foreign markets. This paper presents primarily the concept and economic estimates for building OTEC/ammonia plant-ships and producing and delivering the liquid ammonia. Briefer descriptions of the plants and costs for producing aluminum and liquid hydrogen are included. At present ERDA is supporting other studies of production of ammonia and hydrogen on OTEC plants[12] and of ocean industrial complexes based on OTEC plants.[13] The writers have not received any results from those studies at this writing.

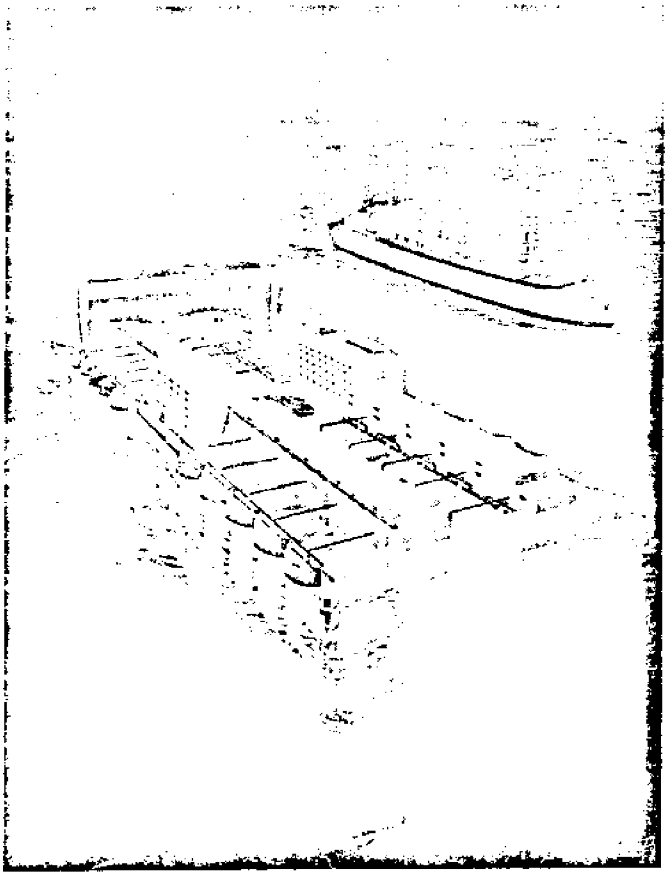


Fig. 1 Ocean Thermal Energy Conversion (OTEC)/Ammonia Plant-Ships

The Baseline, 100-MW$_e$ Plant Concept

At the outset of the platform design study by APL, SS&DD, and Hydronautics, consideration was given to circular, square and rectangular surface vessels. Each was evaluated in terms of potential for seakeeping qualities, structure arrangement, complexity of piping and cold and warm water ponds, and ability to fabricate. The resulting baseline configuration for the 100-MW$_e$ (net), OTEC/Ammonia Demonstration Plant Ship is shown in Fig. 1. The following primary design considerations essentially fix the configuration:

1) Heat exchanger enclosure and access;
2) Deck area for machinery, maintenance, and crew;
3) Volume for product storage and trimming ballast;
4) Simplicity of hull fabrication using mass-produced subassemblies;
5) Hull shape to permit construction in existing shipyards (beam width is 196 ft);
6) Reasonable weight, low draft for launching in 40-ft waterways, and sufficient reserve buoyancy to meet all conditions at sea;
7) Hull stability and strength; and
8) Minimum maintenance.

The platform arrangement is basically symmetric about a centrally located cold water pipe (CWP). The cold water is pumped from 2500-ft depth through this 60-ft-diam CWP to head ponds over the condensers, flows down through the condensers by gravity, and is discharged from them below the platform at 80-ft depth. There are two condenser head ponds, one each fore and aft. Each has a sloped feed channel on each outboard side, deepest near the CWP, from which the water overflows transversely inward toward the pond centerline, thus providing a distributed flow over the ponds. The ponds probably will have removable covers (not shown) to mitigate free-surface dynamic effects and minimize growth of marine slimes (biofouling) on the tubes. The warm water is pumped from the surface with 20 pumps supplying 20 separate evaporator head ponds; the water from the evaporators also is discharged beneath the ship at a depth of 80 ft.

Smooth-sided, prestressed concrete panels are used for the heat-exchanger compartment walls (the only heat exchanger "shells" required in this gravity-flow design). These walls also serve as ship structure and are tied together in the longitudinal and transverse directions. All equipment is housed on decks above the water line. Twin deck houses containing crew quarters and control rooms are located amidship to minimize walking distances to the machinery. A total staff of 48 is required (31 on board and 17 ashore on leave). The accommodations on the SS&DD demonstration plant design include 24 spare cabins for scientists, inspectors and Government officials participating in the demonstration tests and programs.

The arrangement allows clear vertical access over all the heat exchanger units and location of the turbines and associated equipment on decks above them with a minimum of piping. Areas at the ends of the platform are available for product manufacture, for repair and maintenance of heat exchangers, and for the conduct of several tests and programs simultaneously. A 200-ton gantry crane spans the beam and travels the length of the platform. The hull is made of concrete to minimize maintenance, provide long life, and reduce cost. The superstructure is made of steel to retain flexibility to make changes in the machinery houses, labs, etc., and to reduce the weight and buoyancy requirements of the total structure. The total "dry" operating weight is 63,800 long tons (LT). Provision is made for 10,000 LT of product and 42,000 LT of ballast. Total operating displacement is 141,600 LT (Table 1). The heat exchanger tubes provide a significant fraction of the buoyancy. Closed areas between the heat-exchanger compartments ("hull tanks") provide all of the volume needed for ballast as well as for the product.

TABLE 1
WEIGHT AND BUOYANCY SUMMARY (LONG TONS)

HULL	39000 LT
SUPERSTRUCTURE, HULL OUTFIT, PROPULSION	3000
HEAT EXCHANGERS	9300
HEAT CYCLE MACHINERY	3500
PRODUCT MACHINERY	2500
DELIVERY TOTAL (WITH 34 5 FT. DRAFT*)	57300
COLD WATER PIPE (CWP)	6500
"DRY" OPERATING TOTAL	63800
10% MARGIN (6400), NH_3 STORAGE (10000)	16400
POND WATER (15000), WORKING NH_3 (4400)	19400
TOTAL WT. LESS BALLAST	99600
DISPLACEMENT (BUOYANCY)	
HULL WALLS & TANKS, CWP	103100
HEAT EXCHANGERS	38500
TOTAL DISPLACEMENT (AT 84 FT DRAFT) (141600–99600)	141600
BALLAST REQUIRED (141600–99600)	42000

*THIS DRAFT FOR LAUNCHING EXCLUDES THE DRAFT REQUIREMENT FOR THE CONDENSER SUMPS AND AMMONIA PUMPS, WHICH WOULD BE INSTALLED ON SITE

A propulsion capability for "grazing" at 0.5-0.95 knot relative to the local current and for steering is provided by four 1200-SHP electric drive thrusters, one at each ship corner. The power requirement for normal station-keeping against a 0.5-knot current is only 750 SHP total (0.6 MW_e input).

The Two-Phase-Flow Heat Exchangers

The fundamental design decision for this OTEC plant-ship concept was the selection of submerged, modular heat exchangers with 3-in. to 6-in. diameter, multipass, aluminum tubes with the ammonia working fluid inside the tubes and the sea water outside. This approach has been selected for the following reasons:

(a) Use of a relatively large tube diameter reduces the number of tube joints, thus reducing fabrication and assembly costs and facilitating cleaning, maintenance, and repairs.

(b) No heat exchanger "shells" *per se* are required.

(c) A strong potential for economical, *in situ* cleaning of the heat exchangers using the Hydronautics Cavijet™ system[14] results. This advantage of a simple heat exchanger design could outweigh the initial efficiency of a more complex design.

(d) The use of 80 heat exchanger modules assembled into 20 power modules in a total plant will permit regularly scheduled cleaning and maintenance operations, one module at a time, without a large reduction in the total power output.

The objective is to achieve the lowest cost overall plant-ship design, which will not necessarily result from optimizing the heat exchanger arrangement *per se*. A vertical arrangement of the multipass tubes, in which the ammonia would flow up and down in alternate passes connected by return bends, was considered first, but was found to have excessive internal pressures losses due to gravitational effects, which were confirmed by an APL experiment. Therefore, a horizontal orientation was chosen which also reduces the probability of flow instabilities among manifolded tubes in heat exchanger modules and offers lower weight and structural/installation advantages. The computer program developed for the analysis of these two-phase-flow, convective heat exchangers[2] uses a Chisholm approach for estimating frictional pressure drops,[15] the Chaddock and Brunneman correlation for evaporator heat transfer,[16] an ASHRE-recommended correlation for condenser heat transfer,[17] and estimates for the effects of gravity, acceleration, and tube bends on pressure drop.[18]

Many conflicting factors are involved in the selection of the tube diameter, pass length, and tube spacing. In general, the best tradeoff among the following effects is sought:

1. For a given total power output requirement and a given enthalpy drop (or pressure ratio) across the turbine, the total ammonia flow rate is fixed. If ammonia velocities entering the heat exchanger tubes

also remain the same, the total number of tubes N_T required is inversely proportional to tube diameter squared, D^2. However, the required total length L of a multipass tube increases approximately as $D^{1.2}$. Two effects cause this exponent on D to exceed 1.0: heat transfer efficiency decreases slightly as D is increased, and, for a given heat exchanger compartment width (available tube pass length l), the number of return bends per tube n_r increases with D, so that internal loss increases (see item 3). Letting A_T = total heat exchanger surface area, N_R = total number of return bends, V_T = total internal volume of the tubes, and V_m = volume of ammonia being circulated, the following approximate relations apply ($\propto$ = proportionality sign):

$$N_T \propto D^{-2}; \quad L \propto D^{1.2}; \quad n_r \propto L/l \propto D^{1.2} \tag{1}$$

$$N_R = N_T n_r \propto D^{-2} D^{1.2} = D^{-0.8} \tag{2}$$

$$V_T \propto V_m = N_T \, L \, \frac{\pi}{4} D^2 \propto D^{-2} D^{1.2} D^2 = D^{1.2} \tag{3}$$

$$A_T = N_T \, L\pi D \propto D^{-2} D^{1.2} D = D^{0.2} \tag{4}$$

2. Although volume V_T decreases as D is decreased, N_R and N_T increase, making the plumbing more complex, and required ship planform area may not be appreciably reduced (see item 4), although ship depth can decrease. The contribution of the heat exchangers to platform buoyancy also decreases.

3. The internal pressure losses affect both the ammonia pumping power requirement and local water-to-ammonia temperature differences (ΔT's) for heat transfer. The latter effect arises because the saturation temperature at which the ammonia boils increases as the pressure is increased. As D is increased, a higher initial pressure in the evaporator is required to overcome losses due to more bends (higher n_r) and to a larger gravity head (depth reached by the multipass tube), resulting in a lower ΔT and lower heat flux.

4. Tube spacings must be sufficient for practical tube-bundle fabrication, and a uniform lateral spacing between rows is important because it controls water flow distribution. Since variations in straightness of low-cost-production tubing may run near 1/4 in. per 25 ft, this is not a trivial problem. Engineering judgement indicates that design spacings should be at least 3/4 in., so a 3/4-in. spacing in the vertical plane is used in all cases. This desire for large spacings reduces the volumetric advantage achieved by reducing D.

5. Sea water velocity v_w is inversely related to lateral tube spacing. A v_w of 5 ft/sec or more is desired (a) to keep the water-side heat transfer coefficient h_w up and (b) to minimize the rate of biofouling, especially in the evaporators. However, the proposed method for cleaning the tubes employs a cleaning head of approximately 1-in. to 1.5-in. diameter which would be translated vertically through the lateral spaces.

6. The water-side pressure drop is proportional to v_w^2 and to the number of tube passes in a bank. Since the water pumps are among the major OTEC cost items, and the required water-pond height above the heat exchangers adds to ship buoyancy requirements, the system cost optimization leads to v_w's below 5 ft/sec, which tends to increase the lateral spacing as desired.

7. To take advantage of a reasonable platform depth, striking a balance between required planform area and depth, it is desirable either to "tier" or to "nest" two or more tubes in the vertical plane (Fig. 2). Either approach leads to a multiple of the lateral tube spacing for a given water velocity, since approximately the same quantity of water per tube must flow, for a given water temperature change through the total depth, to accomplish the heat transfer. Thus, either approach would alleviate the lateral spacing problem (items 6-8).

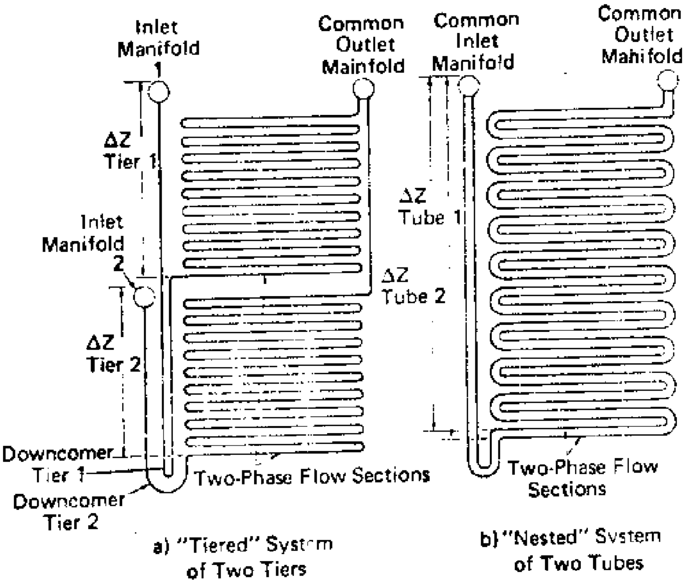


Fig. 2 Illustration of Tiered and Nested Evaporator Systems. The Tiered System Requires Separate Inlet Mainfolds to Deliver Equal Ammonia Heads; The Nested Tube System Can Use a Common Inlet Manifold with Very Small Head Difference

8. The tiering approach, Fig. 2a, raises problems, however, in equalizing the input ammonia heads to the various tiers in the evaporators (see item 4). A more complex and expensive plumbing system would be required to provide a separate inlet manifold system for each tier. Moreover, the bottom tier will see the lowest-temperature water, which has already given up heat to the upper tier(s), so that the remaining available water-to-ammonia ΔT will be smaller, and it will be more difficult to fix the point for the beginning of nucleate boiling. This means, in turn, a greater danger of encountering flow instabilities among tiered tubes if common exit manifolds are used, so a separate exit plumbing system for each tier might also be required.

9. The "nesting" approach, Fig. 2b, therefore, is preferred. Two or more multipass tubes run in adjacent, parallel passes, so that all experience

essentially the same full sea-water ΔT and essentially the same internal ammonia head conditions throughout.

The computer program was used to explore all of these factors and to compute the case for triply nested, 6-in.-O.D. tubes (Fig. 3) which was selected in October 1975 for the development of the baseline plant-ship concept. The results computed for the evaporator and condenser were arithmetically averaged to obtain common spacings, pass lengths, and numbers of passes and tubes, on the assumption that a small change in the distribution of the overall available ocean ΔT among the evaporator, condenser, and turbine can produce this desired commonality of parts and fabrication and packaging requirements (aside from inlet and outlet manifold differences) between the evaporator and condenser modules. These results are summarized in Table 2.

(Subsequent to the selection of this configuration for the plant-ship design work, additional heat exchanger configurations were evaluated. It presently appears that use of five nested 4-in.-O.D. tubes per element and 26 elements per module would lead to heat exchangers with reduced volume requirements and some cost reduction,[1] and the commercial-size plant-ship costs are based on the latter.)

Heat Exchanger Operation and Power Summary

In an evaporator element (Fig. 3) each of the nested tubes is fed liquid ammonia via a downcomer pipe in which part of the liquid heat-up is accomplished. A short (about 5 ft) riser, in which the liquid flows upward, is then provided to enhance the onset of nucleate boiling while avoiding the possibility of gas bubbles forming too soon and flowing up the feed pipe. As the ensuing two-phase mixture flows upward through the multipass tube, 60% of the liquid is vaporized, i.e., a mixture of 60% quality goes from the top of the evaporator to a demister. The demister returns the liquid to the evaporator inlet, and the vapor drives the turbine and then goes to the condenser.

In a condenser element, ammonia vapor enters each tube at the top, is condensed completely as it flows down, and is delivered through a manifold to the sump, from which it is pumped with the total pressure required for delivery to the top of the evaporator. The condenser element is identical to the evaporator element except for replacement of the downcomer section by the sump pump section. This approach simplifies construction and inventory problems. Figure 3 shows square corners to make the return bends, but several alternatives that may offer lower cost are being evaluated.

The heat exchangers are fabricated from an aluminum alloy (possibly Alclad) to minimize weight and cost. Much experience with aluminum in marine environments[19] and in heat exchangers in water desalting plants[20] indicates that satisfactory life can be achieved; our design life is 20 years. Since the tubes are cleaned in place, it is only necessary to remove a module when repairs are required. The overall baseline 100-MW_e (net) demonstration-size plant contains 40 condenser and 40 evaporator modules. Two each of the evaporator and condenser modules are used to drive one 6-MW_e out-

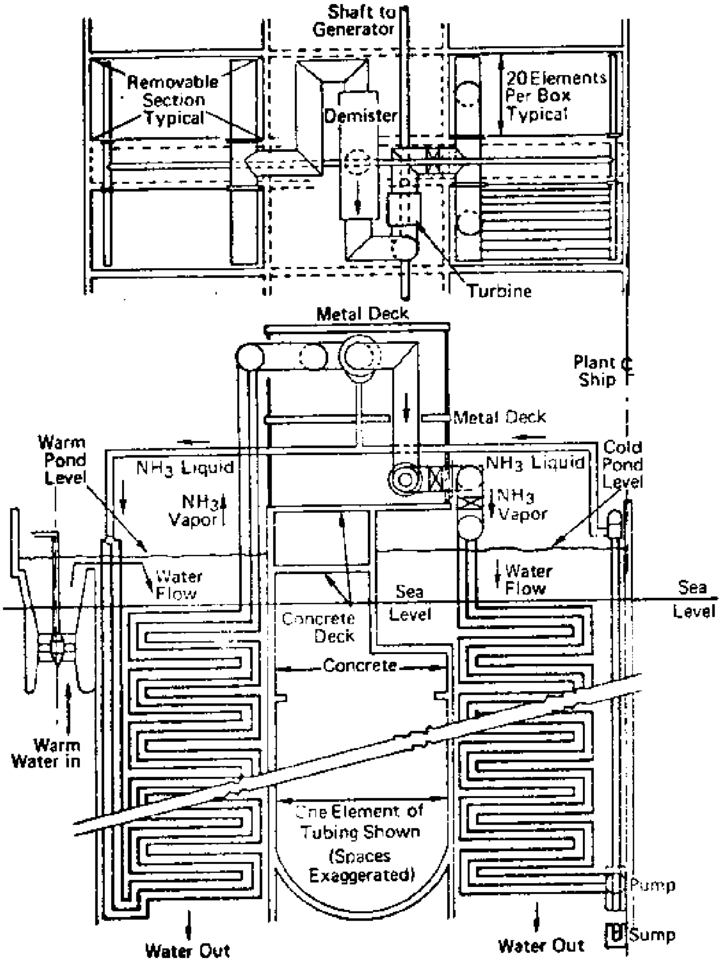


Fig. 3 Basic Power Unit

TABLE 2

SUMMARY OF CHARACTERISTICS OF THE THREE-NESTED, 6-in.-O.D.-TUBE HEAT EXCHANGERS USED FOR THE BASELINE 100-MW_e-NET-OUTPUT PLANT DESIGN

TOTAL LENGTH OF EACH 6-IN.-O.D., MULTIPASS TUBE	1154 FT
PASSES/TUBE (TOTAL OF 135 PASSES/3-TUBE ELEMENT)	45
LENGTH/PASS (OCCUPYING 23.9 FT LENGTH TO ENDS OF BENDS AND AVG. 1.7 FT LENGTH DUE TO RISE)	25.6 FT
TRANSVERSE TUBE SPACING (FOR 3.5 FT/SEC WATER VELOCITY)	1.8 IN.
VERTICAL TUBE SPACING	0.75 IN.
TOTAL TUBES (2400 EACH IN EVAPORATORS AND CONDENSERS)	4800
NO. OF MODULES (40 EACH, EVAPORATORS AND CONDENSERS)	80
NO. OF 3-TUBE ELEMENTS/MODULE (13 FT COMPARTMENT LENGTH)	20
TOTAL HEAT EXCHANGER SURFACE AREA	8.2×10^6 FT^2
EVAPORATOR WATER FLOW	4.62×10^6 gpm
CONDENSER WATER FLOW	4.45×10^6 gpm
AMMONIA FLOW	6750 LB/SEC

put turbine. Five turbines are connected on a shaft to drive each of four 29-MW_e-output, a.c. generator/transformer/rectifier sets. With 16 MW_e of power output required for the pumps and propulsion, the total net output is 100 MW_e (Table 3).

TABLE 3

POWER SUPPLY FOR 100-MW_e BASELINE DEMONSTRATION PLANT

TURBINE OUTPUT EQUIVALENT (20 TURBINES)		121 MW_e
ELECTRICAL OUTPUT (4 GENERATOR/TRANSFORMER/RECTIFIER SETS)		116
AMMONIA PUMP INPUT (40 PUMPS)	2.3	
WARM WATER PUMP INPUT (20 PUMPS)	5.0	
COLD WATER PUMP INPUT (19 PUMPS)	8.1	
SUBTOTAL, AUXILIARY POWER REQUIRED		15.4
PROPULSION POWER (1/2 KNOT)		0.6
NET POWER OUTPUT		100 MW_e

The Cleaning Concept

The aforementioned Cavijet™ cleaning head[14] comprises a 4-ft-long pipe with radially disposed 1/8-in.-diam nozzles. Tests have indicated a cleaning rate of about 3000 ft^2/hr for slime removal with a single 1/4-in. Cavijet at 2000 psi. Other tests at 2000 psi have removed heavy encrustations of barnacles from painted steel plates without damaging the paint. Furthermore, plates of 6061 T6 aluminum with paint stripes have been subjected to 2000-psi jets; the paint remained, and there was no detectable damage to the aluminum. Hydronautics, Inc. predicts that a multijet cleaning head designed for use on the aluminum heat exchangers will remove slimes at a rate near 5 ft^2/sec. If so, one heat exchanger module can be cleaned by one automated cleaning head in 6 hr, and a routine heat-exchanger cleaning cycle for a 100-MW_e plant can be accomplished in 20 days with 1 head or in 5 days with 4 heads. The cost should be far less than with systems designed for other OTEC plant concepts based on cleaning the insides of tubes with abrasive rubber balls.

Oceanography and Platform Motions

The six shaded areas in the Atlantic and Pacific Oceans in Fig. 4 were found by A. R. Miller of the Woods Hole Oceanographic Institution to have the following suitable characteristics:

1) Surface currents of approximately 1/2 knot or less, and no substantial subsurface currents; deep currents of 0.2 knots or less.
2) Deep bathymetry which insures that there is no possibility of encountering an under-ocean peak extending up to 1/2 mile below the surface.
3) Available water ΔT between the surface and 2500-ft depth exceeding 20°C (36°F); surface temperature $\geq$ 25°C (77°F).
4) Normal winds of Beaufort force 3 to 4 (7-16 knots).
5) Normal sea states $\leq$ 5 (wave height $\leq$ 12 ft or 4 m).

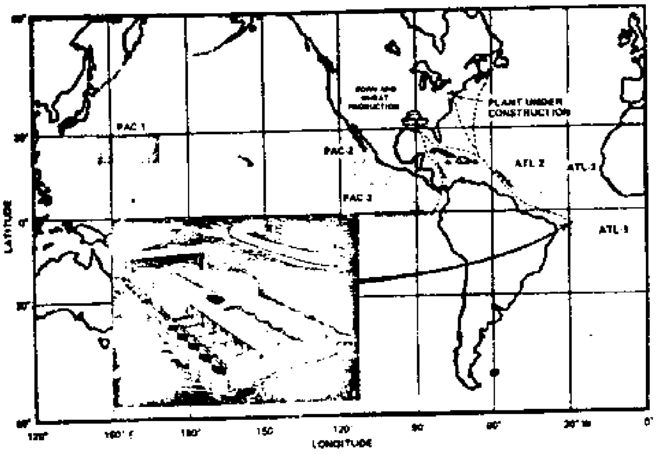


Fig. 4 The Six Tropical Ocean Sites Selected for Deployment of OTEC Plant-Ships

For the preferred initial site, Atlantic 1, data are available based on observations back to 1888 and the nearby "Gate" experiment of 1974 (conducted by an international assemblage on site for 60 days with instruments continuously in the water). This 360,000 sq. nmi. area is located 300-900 miles off Brazil from 5° to 15° south latitude. Water depth exceeds 5000 ft (1500 m). There are no islands or other national land. Therefore, the preliminary opinion of the law firm LeBoeuf, Lamb, Leiby and MacRae is that an OTEC plant in this location will be a protected activity under the law of the high seas, similar to fishing.

The on-site temperature, wind and wave conditions have been characterized[1] by oceanographic data for four Marsden Squares covering and near site Atlantic 1, which comprises the lower half of Square 302 and the upper half of Square 338. Histograms show that the predominant temperatures are 81-83°F (27-28°C) at the surface and 39-40°F (4-4.5°C) at 2500-ft depth, yielding a representative ΔT of 43°F (23.9°C), our design value. No Beaufort wind force greater than 6 was recorded. A 20-ft significant wave height is, therefore, the extreme on-site design condition. The corresponding sea-state histograms (Fig. 5) show that the most probable sea state is 3, but sea state 4 occurs with appreciable probability and therefore is the nominal on-site design sea state. The significant wave height is 8 ft, with maximum energy occurring at a frequency of 0.80 rad/sec.

When the OTEC plant-ship is operating on site, pumps maintain the water levels in the ponds. The large cold-water head ponds could be subdivided transversely and longitudinally to reduce the free surface and the resulting loss of stability, and either a high-reliability, pond-level control system or removable pond covers will be employed, as well as some pumping power margin above the nominal requirement. However, the estimated water plane inertia for the stability calculations did not include the water in the heat exchangers or subdivision in the cold water pond. The heat exchangers are buoyant and provide stability to the vessel, but they may be removed for repairs.

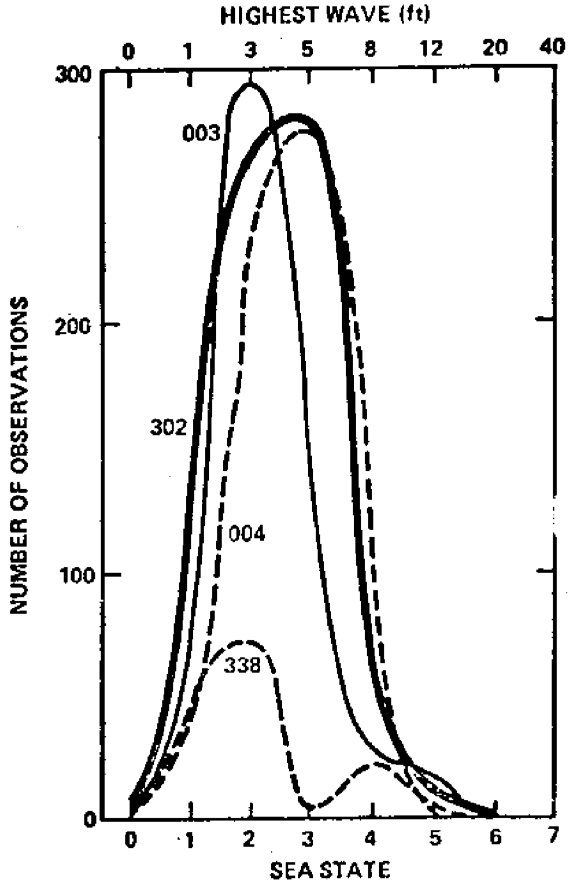


Fig. 5 Sea State Histogram for Selected Marsden Squares

Platform stability was estimated for six cases. The worst-case, very improbable, emergency condition with the lowest stability was one with the heat exchanger head ponds filled but with the heat exchangers withdrawn and the cold water pipe (CWP) missing. This condition still has a positive transverse stability satisfactory for a sea-going merchant ship. Thus, the stability of this vessel appears to be entirely satisfactory.

The on-station seakeeping or dynamic behavior with CWP deployed was calculated using a 5-degree-of-freedom seakeeping program. For this analysis, the platform was idealized as a hull having a displacement of 80,000 long tons and a transverse GM of 110 ft. Based on calculations of the dynamics of the water in the CWP, this water was assumed not to respond to CWP heave and yaw motions but to follow CWP pitch, roll and sway motions exactly. The CWP was assumed to have no amplitudes of motion relative to pipe diameter.

The foregoing design conditions and estimated worst-case ship motions for normal-operating, extreme operating, and in-transit-to-site conditions are summarized in Table 4. Of particular interest are the normal operating conditions, for which the platform is very stable indeed. It should be very useful for a variety of research activities in addition to its primary mission of ammonia production.

For deployment of the plant to this site, the hurricane months would be avoided. Available data indicate that the worst condition in "non-hurricane" months (November through July) is the top of sea state 7 having a "significant" (or one-third highest) wave height of 40 ft. Thus, the maximum loads and motions experienced in transit should result from encounter with a wave at or near the peak energy frequency, which is 0.36 rad/sec corresponding to a wave length of 1560 ft. (The maximum instantaneous forces acting on the platform would correspond to the "1 in 10,000" value, which can be expected to occur at least once in a storm, and is 2.22 times the above-defined significant value.) The American Bureau of Ships requires survivability in a 100-knot wind and use of a 70-knot wind for design operating conditions for offshore platforms in open ocean locations. For sheltered locations they permit an operating design wind of 50 knots. Since the hurricane season is to be avoided for plant deployment, a 70-knot wind has been used for the survival condition during transit, and a 50-knot wind for a survival condition on station. The resulting motions (Table 4), which are based on the platform alone (no CWP) experiencing the worst expected sea conditions and the worst heading angle, do not appear to be hazardous; the significant acceleration is about 0.15 g.

TABLE 4

ESTIMATED SHIP MOTIONS FOR 100-MW_e, DEMONSTRATION-SIZE PLANT SHIP

PARAMETER	ON SITE NORMAL	ON SITE EXTREME	IN TRANSIT
DESIGN BEAUFORT WIND FORCE	4	7	–
DESIGN WIND (SURVIVAL CONDITION), KNOTS	6	33 (50)	(70)[a]
DESIGN SEA STATE (TOP END)	4	6	7
SIGNIFICANT (1 IN 3) WAVE HEIGHT, FT	8	20[b]	40[b]
PITCH, deg	0.02	< 0.1	6
ROLL, deg	0.02	0.1	13
YAW, deg	0.2	0.7	2
HEAVE, FT	2	12[c]	23
SWAY, FT	0.5	2.3	14
SIGNIFICANT ACCELERATION, g	–	~ 0.1	~ 0.15

[a] DEPLOYMENT ONLY IN NON-HURRICANE MONTHS, NOV. - JULY.

[b] HIGHEST (1 IN 10,000) WAVE IS 2.2 TIMES THIS; DETERMINES MAX. INSTANTANEOUS FORCES.

[c] EXCEEDS SIGNIFICANT WAVE AMPLITUDE OF 10 FT, SO PLATFORM TENDS TO "CONTOUR" OR FOLLOW WATER SURFACE (GOOD FOR HXERS).

The estimates of CWP bending moments made to date have limited accuracy because elastic effects could not be considered. The pipe wall thickness required to resist such bending moments is estimated to be less than the 1.88 in. determined by buckling considerations over much of the pipe length, but a 2.5-in. thickness is estimated to be required in the upper part of the pipe. (A thickness of approximately 1.25 in. at the pipe-platform junction would be sufficient to resist the bending moment induced by steady motion of the plant at a speed of one knot relative to the water.)

Ammonia Production

Hydrogen Production by Electrolysis

The background and basic tradeoffs in the electrolytic production of hydrogen were reviewed by Konopka and Gregory.[21] A few points are of interest here as background for the information from Teledyne Energy Systems, Timonium, Md., and the General Electric Company, Wilmington, Mass., upon which the present investigation is based.

The isothermal generation of hydrogen and oxygen by water electrolysis at 25°C (77°F) ideally requires that a quantity of energy be supplied equal to the heat of formation of liquid water, which is the same as the higher heating value (HHV) of hydrogen, 61,030 Btu/lb. This energy could all be provided as electrical energy at a cell potential of 1.47 V, in which case the quantity can also be expressed as 17.9 kWh/lb of H_2, or 94 kWh per 1000 SCF.* In this isothermal case, no heat would be added from or wasted to the surroundings. However, a voltage as low as 1.23 V could still generate hydrogen (Fig. 6) at a very slow rate; this would correspond to an electrical energy input of 79 kWh/1000 SCF, or 83.7% of the HHV of hydrogen: the other 16.3% would have to be supplied as heat. Since the "thermal efficiency" of electrolysis is defined as the thermoneutral voltage of 1.47 V divided by the actual voltage used, this means that an ultimate efficiency of 119.5% is theoretically possible if that heat is supplied by the surroundings.

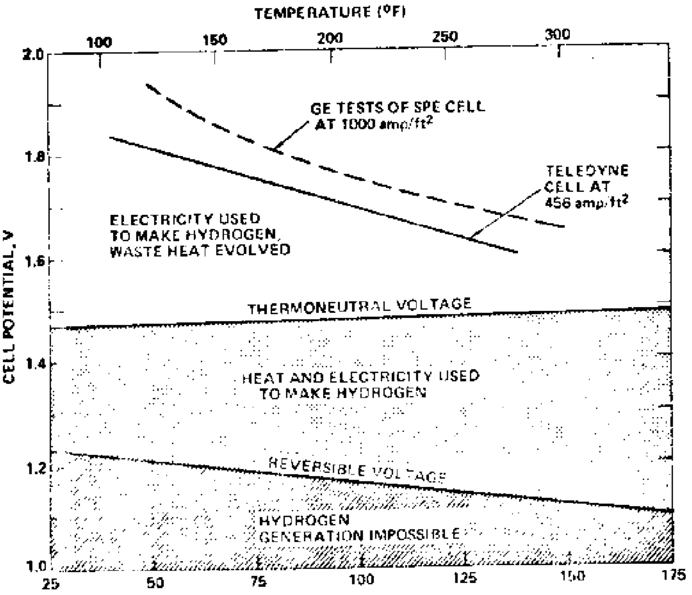


Fig. 6 Idealized Operating Conditions for Electrolysis and Temperature Effect

Present industrial electrolyzers do provide all of the energy as electrical energy and, in fact, operate at a voltage above the thermoneutral value due to inefficiencies inherent in a given design and to a desire to increase the rate of production of hydrogen. The rate of production increases as the applied current and hence the current density I/A (current per unit area of electrode) increases. However, the cell operates as a non-linear resistor, so there are tradeoffs among E, I/A, and capital cost. Thus, many industrial units today operate at $E \simeq 2.0$ V, or 23.8 kWh/lb, or 74% thermal efficiency. However, near-term advances promised by recent and planned developments mentioned hereinafter appear to assure improvements to the 1.5-1.8 V range, corresponding to 18-22 kWh/lb, or efficiencies in the 82-98% range.

Increasing the temperature will decrease the cell's internal resistance and overvoltage because the diffusional and activation processes are accelerated. The solid curve in Fig. 6 was provided by Teledyne[22] for a cell operating at 456 amp/ft². For the GE solid polymer electrolyte (SPE) cell,[23] the dashed curve was obtained in tests of a single cell at a current density of 1000 amp/ft²; the efficiency increased from 76% at 120°F to 90% at 300°F. The advantage of operating at high temperatures is, in some designs, offset by decreased life of the cell materials. If an attempt is made to achieve efficiencies very near (or ultimately in excess of) 100%, heat will have to be supplied from the surroundings, because the total enthalpy change of the reaction, as indicated by the thermoneutral line in Fig. 6, increases slightly with temperature.

The Teledyne Electrolysis System--The Teledyne Energy Systems Company is currently manufacturing and marketing commercial systems ranging in sizes up to 430 SCFH of hydrogen and expects to have a breadboard model of a large-scale cell operating early in 1976. In their proposed system for the OTEC application[22] a 25% KOH solution is used in a filter-press-type electrolysis module. The hydrogen is generated at 100 psig, separated from the electrolyte and piped to the heat exchangers and compressor of the ammonia synthesis loop. The installation for a 100-MW_e demonstration plant would be made up of 16-MW_e input unit plants, each containing five electrolysis modules run by auxiliaries. The hydrogen and oxygen gases generated are removed from the exiting KOH solution in separators, and the KOH solution is cooled from 180°F to 165°F in heat exchangers and filtered before re-entering the five electrolysis modules from a main header. Teledyne has proposed that for the OTEC/ammonia plant application, the aforementioned heat exchangers would be in the ammonia synthesis plant, used to preheat the reactant gases.

Control equipment will monitor electrolysis module inlet temperature and flow rates; if a high temperature or low flow is encountered, an alarm will be sounded, and if the condition persists, the plant will be shut down automatically and purged with nitrogen. The H_2 and O_2 product gas streams will be saturated with water vapor at 180°F; the heating values of these streams can be utilized in the ammonia plant. A deionized water system capable of producing pure water for all six plants required will be supplied. Input to

---

*SCF = standard cubic feet measured at 68°F and 1 atm.

this system will be potable water supplied from a fresh-water plant on the platform. The deionized make-up feed water is delivered to the hydrogen separators on demand from level switches in the separators.

Each electrolysis module may be run from 25% to 100% capacity by varying the voltage between 840 V and 860 V (1.68 to 1.72 V/cell) and the current between 950 and 3800 amps. The cathode members of the cell are modified by a proprietary technique to achieve the current density required without an unacceptably high cell voltage. To date, this technique has been verified only by preliminary laboratory tests. Table 5 lists the performance characteristics per unit that would apply for a demonstration plant.

TABLE 5

TELEDYNE ELECTROLYSIS PLANT PERFORMANCE AND REQUIREMENTS
(16.14-MW PLANT UNIT COMPRISING 5 MODULES & AUXILIARIES)

ITEM	MAX. CAPACITY OR REQUIREMENT
HYDROGEN OUTPUT	149,500 SCFH OR 776 LB/HR
CELL VOLTAGE	1.72 V
POWER DENSITY	791 W/FT²
VOLTAGE EFFICIENCY	85.6%
CURRENT EFFICIENCY	98.0%
OVERALL SYSTEM EFFICIENCY	83.8%
MAXIMUM OPERATING PRESSURE	100 psig
GAS PURITY AFTER WATER REMOVAL	98+%
DEW POINT (REDUCED TO NH_3 PLANT REQ'T. IN NH_3 PLANT)	180 F
SPACE REQUIREMENT	25 FT x 25 FT x 15 FT HIGH
TOTAL WEIGHT	149,000 LB
PLANT LIFE	20 YEARS
PLANT MANNING OPERATIONS: COMPLETELY AUTOMATIC WITH MANUAL OVERRIDE - ONE MAN CAN START UP, RUN, AND SHUT DOWN IN MANUAL MODE PREVENTIVE MAINTENANCE: 183 MAN-HR, FIRST YEAR, 124 MAN-HR, 2nd THROUGH 20th YEARS	
SERVICES REQUIRED	
DEIONIZED WATER: 500,000 OHM/CM RESISTANCE (MINIMUM)	
COOLING: WATER MUST BE AVAILABLE IN NH_3 SYNTHESIS LOOP TO COOL KOH ELECTROLYTE TO 165 F	
POWER: 3.2 MWe PER MODULE 440 V 3φ FOR PUMPS, REMAINDER 220 V 3φ	
AIR: OIL-FREE, 80 PSIG MINIMUM	
NITROGEN: 700 SCF PER STARTUP, 20,000 SCF FOR EMERGENCY PURGE USE	
INITIAL KOH CHARGE: 13,764 GAL OF 25% WT. SOLUTION	

<ins>The General Electric SPE Electrolysis System</ins>--GE is developing a large-scale electrolysis plant and is receiving some funding from ERDA for this work. In their Solid Polymer Electrode (SPE) system,[22] the 5-MW_e-output (in hydrogen thermal equivalent) system depicted in Fig. 7 is their basic unit. The electrolysis module is 3 ft in diameter by 6 ft high, contains 580 cells of 2.9 ft^2 and 220°F, weighs 5000 lb, and generates approximately 53,800 SCFH of hydrogen. Distilled water is circulated through the cell anode cavities at a sufficient rate to remove internal waste heat as well as the amount needed for the electrolysis reaction. Part of this water is carried over to the cathode side in the proton transport process, so that some liquid water is discharged with both the hydrogen and oxygen gases. The O_2-water mixture is passed through a heat exchanger to remove the waste heat from the system, and then to a water separator from which the water is recirculated to the pump inlet. The H_2-water mixture goes directly to a water separator. If required, gas driers can be added to the system downstream of the water separators. The system will be completely automated for unattended operation.

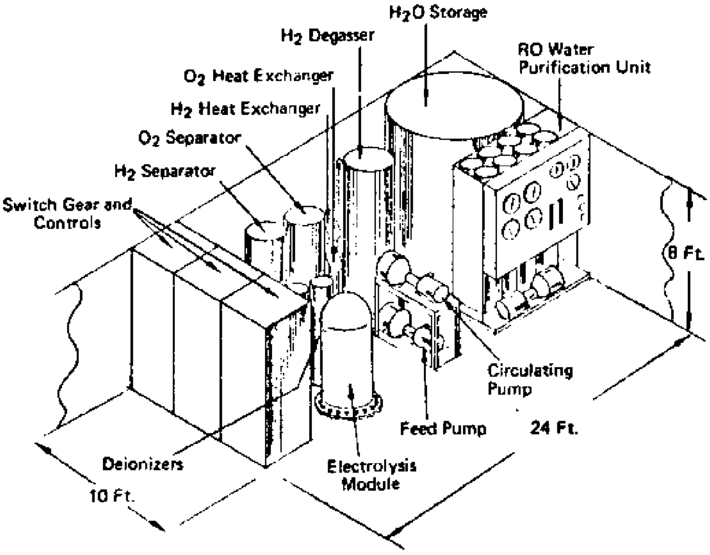


Fig. 7 Conceptual Layout of General Electric's 5-MW_t-Output SPE Water Electrolysis System

Although the 580-cell stack used in the electrolysis module had not yet been produced at this writing, continuing improvements in anode electrocatalysis are being demonstrated in the laboratory from which GE has projected that the cell voltage at 2000 amps/ft^2 will be reduced to approximately 1.75 and 1.6 V by 1980 and 1985, respectively. Two other areas of development are demonstrating significant potential for achievement of these goals: an increase in operating temperature (Fig. 6), which reduces both the catalytic activation losses and the internal resistance of the electrolyte, and permits a voltage reduction of 0.25 V; and a reduction of the SPE thickness from 10 mils to 5 mils, permitting another 0.25 V reduction. With the latter two improvements alone, the voltage would be reduced to within 0.05 V of their 1985 projected performance. Life testing up to 4 years on single units without maintenance showed no degradation of performance, and during the past 7 years (10^6 cell hours of operation), there have been only two failures in SPE cells, both due to gasket failures.[23] With improved sealing techniques now available, GE confidently projects a reliable, maintenance-free life potential of 10 to 20 years for the SPE electrolysis stack in commercial service.

Cell efficiency is primarily a function of the cell voltage, since the coulombic losses at ambient pressure are almost negligible. The projected[24] electrolysis efficiencies are 86% for the demonstration plant (1980), and 90% for commercial plants (1982-85), assuming that adequate government funding for development is provided. That rate of development would correspond to the schedule advanced by APL for the development and production of OTEC ammonia-producing plant ships.

Summary of Hydrogen Output and Cost Data--The hydrogen output and cost information provided by Teledyne[32] and GE[34] is summarized in Table 6. Teledyne's projected costs cover the electrolysis modules, auxiliary equipment, and installation; DC power is supplied directly at a suitable voltage from the OTEC generators. (Teledyne has advised that H_2 output can be increased by modifying the cathode members of the cell by a proprietary technique, by increasing cell operating temperature to 250°F and other developments. With R&D funding, Teledyne states the output for the 500-MW_e plant could rise as much as 8-14% with no attendant capital cost increase.)

The GE plant cost is quoted for delivery to a U.S. shipyard, tested and installed. It does not include the power for the air driers which would be supplied from an integrated total OTEC/ammonia plant. A funded pilot plant development program is presupposed. Hydrogen is generated at 14.7 psia. At 500 psia, the hydrogen output for the 500-MW_e plant would be reduced to 4,605,000 SCFH, allowing a tradeoff between ammonia output and compressor investment.

For the production of ammonia in a plant which uses the air liquefaction process to obtain the nitrogen, our preliminary estimate was that the nominal 100-MW_e plant would deliver 97 MW_e to the electrolysis cells and 3 MW_e to the ammonia plant and air liquefaction equipment. (Another 3 MW_e needed for the latter equipment would be obtained from the waste-heat recovery in the plant.) Thus, the hydrogen output figures shown in Table 6 were reduced by 3% in the subsequent economic analyses for ammonia plants, which are based on use of the Teledyne system for the 100-MW_e demonstration plant in 1980, and on the more favorable projections by GE for the longer term for 500-MW_e, commercial-size plants.

The Need for Alternatives for Ammonia Production

Ammonia is considered the prime near-term candidate product for tropical OTEC plants for the following reasons. It is a vital commodity for use in fertilizers (75% of the U.S. ammonia consumption at present) and other chemicals. Furthermore, over 95% of U.S. ammonia production uses natural gas as the feedstock (H_2 source). In 1975, 16 million tons were produced, which required 640 billion SCF of natural gas--nearly 3% of the total U.S. consumption. Projections suggest that by 1980 ammonia production may require over 5% of the U.S. total, and by 1990, over 11%. These figures are approximately doubled when the projected petrochemical use of natural gas is added. The forthcoming additional pressure on prices and availability of gas to home-owners and other consumers is readily apparent. Furthermore, ammonia itself as a sale commodity no longer contributes to the U.S. trade balance. In the August 1974-May 1975 period, the U.S. exported only 335,000 tons of ammonia while importing 495,000 tons.[35] The total U.S. demand for ammonia is expected to increase by 10 million tons per year by 1985.

Thus, it is clear that the U.S. will need an alternative to ammonia production from natural gas. Ammonia can be made from petroleum (naptha) or coal, and for the longer term, coal would be the better of these two fossil fuel routes for the U.S. However, there will be many competing demands for coal, and many social and environmental problems will attend a substantial increase in coal mining and transportation capabilities, in addition to the environmental problems of using coal to make ammonia on shore. The attainable schedule which we have projected for building OTEC ammonia plant-ships would have 15 commercial size plants in operation by the end of 1985, saving 536 billion SCF of natural gas per year; the projected cumulative saving through the year 2000 is 12 trillion

TABLE 6

SUMMARY OF PROJECTED LEAD-TIME REQUIREMENTS, HYDROGEN OUTPUTS, AND ELECTROLYSIS SYSTEM COSTS FROM TELEDYNE AND GENERAL ELECTRIC

	100 MW_e (1980)			500 MW_e (1982-85)		
	LEAD TIME, YR.	1000 SCFH OUTPUT	$/k$W_e$ INPUT	LEAD TIME, YR.	1000 SCFH OUTPUT	$/k$W_e$ INPUT
TELEDYNE	2.5	926	142	3	4634[a]	128
GENERAL ELECTRIC[b]	2.5	932	198	3	4876	78-89

[a] COULD EXCEED 5,000,000 SCF WITH R&D FUNDING

[b] GE PROJECTIONS REQUIRE ADEQUATE R&D FUNDING

SCF. Table 7 shows that our estimates for the cost of producing ammonia via hydrogen generated by OTEC plants and delivering it to the U.S. would be competitive with costs of making it on shore from coal, or even from naptha or natural gas. Successful development of OTEC/ammonia plant-ships could also lead to sale of that technology or the plant-ships themselves to other nations who do not have large supplies of fossil fuel.

TABLE 7

COMPARISON OF ESTIMATED U.S. PRODUCTION COSTS FOR AMMONIA FROM VARIOUS SOURCES

SOURCE	FUEL COST	NH_3 COST $/SHORT TON[a]	ENVIRONMENTAL IMPACT
NATURAL GAS	$0.80 – 1.90/$10^3$ SCF	64 – 106[a]	MODERATE
NAPTHA	$80 – 95/TON	108 – 122[a]	MODERATE
CRUDE OIL	$11 – 14/bbl	111 – 128[a]	MODERATE
COAL	$22 – 42/TON	108 – 150[a]	GREATEST
OTEC	NONE	68 – 90[b]	LEAST (SOME ASPECTS FAVORABLE)

[a] ESTIMATES FOR PRODUCTION FROM FOSSIL FUELS ARE BASED ON A REPORT BY HARRE ET AL. OF THE TVA NATIONAL FERTILIZER DEVELOPMENT CENTER.[36]

[b] THE $68/TON ESTIMATES FOR OCEAN THERMAL ENERGY CONVERSION (OTEC) IS FOR THE POSSIBLE COST AFTER AN AGRESSIVE R & D PROGRAM THE $90/TON FIGURE IS FOR ESSENTIALLY STATE-OF-THE-ART (1982) TECHNOLOGY WITH STRAIGHTFORWARD DEVELOPMENT (SEE TABLES 9 AND 10 AND TEXT).

The Selected OTEC/Ammonia Process

Electrolytic hydrogen generated by equipment previously described could be used to synthesize ammonia by either of two approaches. The first approach studied[1,26] was to use approximately 1/7 of the hydrogen in a burner to remove oxygen from air, condense the resulting water to be used as feed to the electrolysis cells, and combine the remaining gas (mainly nitrogen but containing carbon oxides, argon, and other trace gases) with the other 6/7 of the hydrogen to make the feed gas for the ammonia synthesizer. The other approach is to obtain the nitrogen by using an air liquefaction plant to remove the oxygen, water vapor, CO_2 and argon from the air, using a process similar to that used to produce liquid oxygen on Navy aircraft carriers today. The latter approach, used for our cost estimates herein, requires a slightly higher capital investment but, due to the greater ammonia yield for a given OTEC power plant size, is presently judged to be more attractive. It is illustrated schematically in Fig. 8. We have not yet con-

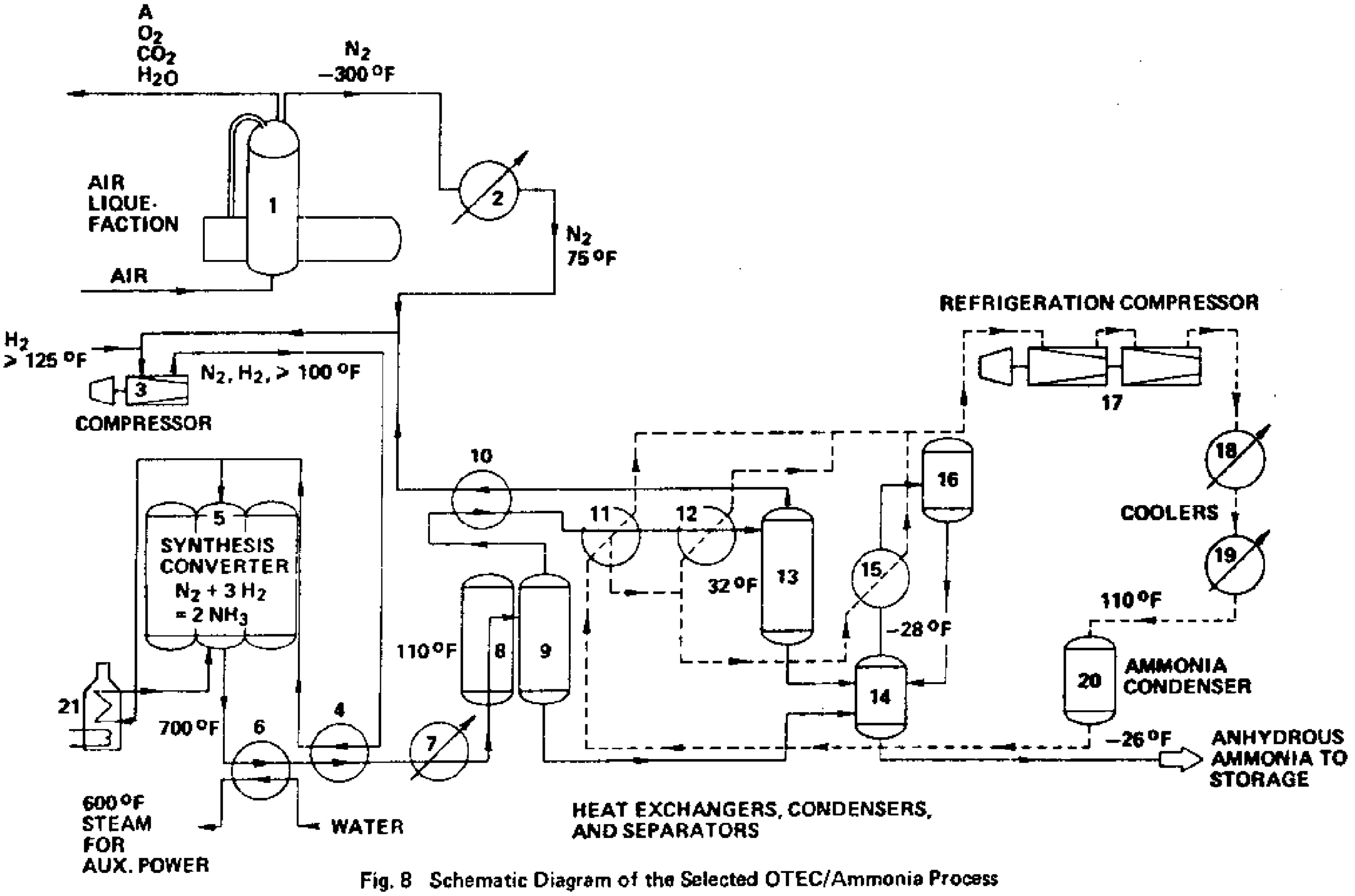


Fig. 8 Schematic Diagram of the Selected OTEC/Ammonia Process Using Air Liquefaction

ducted a specific process engineering study or prepared a heat balance for this application. However, for purposes of our plant sizing and cost estimate we used the values summarized in Table 8. Most of the costs are based on installed costs of equipment in the TVA National Fertilizer Research Center's experimental, 240 short-ton-per-day (STPD) ammonia plant, increased to the 313 STPD level (1.26 ratio) for our 100-MW_e OTEC/ammonia plant ship, and escalated to 1975 dollars (1.57 ratio to 1970 costs per Chemical Engineering Plant Cost Index). The TVA plant is a natural gas reformer plant; the 1970 equipment costs were provided by TVA for the aforementioned plant.[36] The estimate of $2.5 M for the air liquefaction equipment, based on information from Air Products, is in line with a $5 M estimate for a 1000-STPD plant.[37]

TABLE 8

AMMONIA PLANT EQUIPMENT FOR 100-MW_e PLANT

ITEM	DECK AREA, FT.^{2}	WT., LT	COST, $M
AIR LIQUEFACTION	600	19	2.5
GAS COMPRESSOR	150	16	1.2
SYNTH. CONVERTERS (3) AND CATALYST	300	77	0.8
WASTE HEAT BOILERS (2)	250	8	0.1
VARIOUS HXERS, COOLERS	830	106	0.7
REFRIG'N COMPRESSOR	150	16	1.3
CONDENSERS & SEPARATORS	1600	54	0.3
LIQUID STORAGE (10^4 LT)	(HULL)		0.8
TRANSFER PUMPS, HOSE	(HULL)	40	0.4
INSTALLATION & CONTROLS		1	2.3
	3880	337	10.4

The demonstration-size plant-ship described earlier has ample space and a great deal more buoyancy than needed to accommodate the electrolysis and ammonia synthesis plant equipment. The great stability of that platform in the normal, on-site operating conditions has been described. A larger, commercial-size plant ship will be even more stable. The optimum size for a commercial-size OTEC/ammonia plant ship is expected to be in the 1000 to 1700 STPD range, requiring an OTEC power capacity of 300 to 500 MW_e net. An important factor for an ammonia plant is to exceed a 600-STPD level in order to gain the economies of using centrifugal compressors (as sketched in Fig. 8) as opposed to reciprocating compressors. The costs established for the 100-MW_e demonstration-size plant were as follows in 1975 dollars: heat exchangers, $31 M; other OTEC cycle equipment, $30 M; platform, $29 M; cold-water pipe, $14 M; electrolysis and ammonia plant, $25 M.

The 100-MW_e plant-ship costs were then extrapolated to the case for multiple-vessel production of 500-MW_e, 1697-STPD, OTEC/ammonia plant ships in 1982-85 using the GE projection for electrolysis system cost and no advance in ammonia synthesis technology. The major factors taken into account were the relative savings due to a learning curve in multiple production of the platform (10% savings) and re-use of the forms for the concrete hull; optimization of the heat exchanger module size and packaging arrangement (5% on the heat exchangers); approximately 30% reduction in turbine, generator, and water pump costs for sizes 2-3 times larger; economy of scale on the cold-water pipe(s), approximately 20%; and the relative saving on required crew accommodations and outfitting that result for a larger commercial ship. The resulting cost estimate is presented in Table 9.

TABLE 9

COST ESTIMATE FOR 500-MW_e OTEC/AMMONIA PLANTS
(ALL FIGURES MILLIONS, 1975 DOLLARS)

HEAT EXCHANGERS		$124
MULTIPASS ALUMINUM TUBES	60	
ANCHORING, LIFTING, SUPPORTING STRUCTURES	51	
VALVES, MANIFOLDING	15	
CAVIJET CLEANING SYSTEM	0.2	
MACHINERY		104
WATER PUMPS & STARTERS	43	
AMMONIA DEMISTERS, TURBINES & PUMPS	23	
GENERATORS, TRANSFORMERS & RECTIFIERS	27	
CONTROLS & AUXILIARY EQUIPMENT	17	
AMMONIA INVENTORY IN HEAT CYCLE	4	
PLATFORM		113
BASIC CONCRETE HULL	47	
SUPERSTRUCTURE, OUTFITS, PROPULSION	52	
ENGINEERING & SERVICES	14	
COLD WATER PIPE		50
TOTAL BASIC OTEC SHIP COST		$391
ELECTROLYSIS PLANT INCL. FRESH WATER SYSTEM		47
AMMONIA PLANT		39
NET PLANT SHIP COST		$477
CONSTRUCTION INTEREST & ESCALATION		57
GROSS PLANT SHIP COST		$534
GOVERNMENT COST-SHARING*		−153
DEPLOYMENT TO SITE		2
PLANT INVESTMENT		$383M or $766/$kW_e$
PLANT INVESTMENT, BASIC OTEC SHIP ONLY		$573/$kW_e$

*APPLIED ONLY TO BASIC SHIP COST AND CONSTRUCTION INTEREST AND ESCALATION (12%) ON SAME. APPLIED AT A 35% RATE

The bottom line in Table 9 shows the required plant investment for private funding on the assumption that Government support for the construction of OTEC plant ships will be provided at a level of 35% of the basic power-plant ship, not including the electrolysis and ammonia production and transfer equipment. This 35% level is the same as the Construction Differential Subsidy level currently authorized by the U.S. Merchant Marine Act of 1970 for ships built in U.S. yards to fly the U.S. flag in competition with foreign vessels on specified trade routes. It is not clear that OTEC ships will qualify under that Act, but it seems reasonable that a similar level of support should be provided by some means for this new alternative in the energy field.

Using the resulting $384 million (in 1975 dollars) plant investment for a commercial-size plant, the cost for producing ammonia at site Atlantic 1 and delivering it to U.S. ports has been calculated as shown in

Table 10. Straight-line, 20-yr depreciation is used, and other assumptions and bases for the calculation are indicated by footnotes to the table. The calculated ammonia cost, FOB New Orleans, Louisiana, is $90/ton, which would provide a 50 percent return on sales at the 1975 price level of $180/ton.

TABLE 10

ESTIMATED AMMONIA PRODUCTION COST (1975 DOLLARS) FOR A 500-MW$_e$ (NET), 1697 – SHORT-TON/DAY, COMMERCIAL OTEC/AMMONIA PLANT-SHIP

PLANT INVESTMENT: $383 M
WORKING CAPITAL (120 DAYS): $11 M
RATED CAPACITY: 585,600 SHORT TONS/YEAR (345 DAYS)
COSTS PER SHORT TON:

	$/ST
CATALYST AND CHEMICALS[a]	0.60
LABOR AND OVERHEAD[b]	4.53
MAINTENANCE MATERIALS (1% OF PI)	6.53
INSURANCE (2.8% OF PI – ODS)[c]	9.14
DEPRECIATION (20 YEAR, 5% OF PI)	32.66
INTEREST (8% OF 1/2 PI)	26.13
PRODUCTION COST	79.59
INTEREST ON WORKING CAPITAL (8%)	1.50
SHIPMENT TO U.S. PORT[d]	9.00
COST AT U.S. PORT ($/TON)	90.09
RETURN ON INVESTMENT ($180/TON)	89.91
GROSS PROFIT (% OF SALES)	50%

[a] PER HARRE ET AL., TVA NATIONAL FERTILIZER RESEARCH CENTER,[28] PLUS CHEMICALS COST FOR STILL AND ELECTROLYSIS CELLS.

[b] INCLUDES ALL WAGES AND OVERHEAD FOR 39 ON BOARD CREW PLUS 20 STAND-BY CREW (4 WEEKS ON, 2 WEEKS OFF CYCLE) AT AN ESTIMATED $45,000/YEAR AVERAGE COST PER MAN.

[c] INCLUDES HULL INSURANCE, PROTECTION AND INDEMNITY RISKS, AND CONSTRUCTION RISK. CREDIT OF 50% COMPARABLE TO AN OPERATING DIFFERENTIAL SUBSIDY (ODS) UNDER THE MERCHANT MARINE ACT OF 1970.

[d] SHIPPING COST ESTIMATED BY A LONG-RANGE STUDY BY SS & DO USING THEIR COMPUTER ESTIMATOR MODEL; INCLUDES CREDIT FOR ODS AVAILABLE TO US FLAG SHIPS.

The relatively high plant investment required for an OTEC/ammonia plant remains a matter of concern. However, depending upon the income and tax situation for the investing company, the total cash requirement may be recovered in a relatively short time. For example, the 1975 update of the Investment Credit and Accelerated Depreciation Restoration Act of 1967 allows an investment credit of 10% with a limitation that the credit can not exceed 50% of a corporation's federal income tax. For a corporation in a 48% tax bracket with other income sufficient to allow use of the investment credit to at least the amount of the computed tax on ammonia profits, an annual cash flow of $72 million per year would result, and the plant investment of $383 million would be recovered in 5.3 years.

The "gross plant-ship cost" of $534 million (excluding deployment) in Table 9 is considered to represent state-of-the-art for the 1982-85 time period with the assumption that funding is provided for the development required on electrolysis systems to meet the GE projection of cost and performance, as well as the necessary program for development and demonstration of the OTEC equipment from the existing concepts and technology base. An estimate was made of the cost reductions that could be achieved by research and development to advance the heat cycle and platform technology, use of enhanced heat transfer surfaces, a 3°F elevation of local water surface temperature by use of a monomolecular film (currently used to reduce evaporation on agricultural ponds[28]), sharing the cost of the cold-water supply system with a mariculture operation, and receiving a small credit for the oxygen produced by the electrolysis system. These factors could bring the plant-ship cost assigned to ammonia production down to $362 million. With the same percentages of government cost-sharing on construction and operating costs as in Tables 9 and 10 in the early years, the ammonia production cost would be reduced to $68/ton. Without this government cost-sharing, the cost would be $95/ton.

Another interesting possibility is that U.S. plant-ships built to sell ammonia to other nations might receive Export-Import Bank financing with a 6% interest rate.[29] This advantage, coupled with a lower transportation cost to nearby foreign ports ($5/ton) would reduce the production cost in Table 9 from $90/ton to $79/ton.

An economic aspect which will be important to investors is the fact that the competitive position of an OTEC/ammonia plant will be expected to improve as the years pass. Its production cost will be affected less by inflation than will that for a land-based plant using fossil-fuel as a feedstock. The OTEC plant's relatively high fixed costs will remain constant, while the cost of feedstock for the competitor probably will rise continuously.

This OTEC plant-ship, which uses aluminum heat exchangers and is designed to take advantage of high ocean ΔT's at selected tropical sites where all environmental operating conditions are most favorable, is considerably lower in cost than the baseline designs that have been developed by the teams headed by Lockheed[10] and TRW.[11] The latter teams reported that cost would be reduced by replacing their titanium-tubed heat exchangers by aluminum ones and making other design changes. However, they did not present complete cost breakouts for such changes to their baseline OTEC ships (which were of 160- and 100-MW$_e$ size, respectively) or for commercial plants of larger size. We made rough estimates of OTEC/ammonia plant-ship investment costs (on the same basis as in Table 9) for 500-MW$_e$ plants for their cases by reducing their baseline OTEC ship costs per kW$_e$ by 21% for economies of scale, substituting a lower cost for dynamic positioning in tropical oceans for Lockheed's mooring system cost, and adding our $86M estimate for the equipment needed to produce ammonia. The resulting plant investments are approximately 210% and 180% of the $766/kW$_e$ APL value, respectively. The corresponding ammonia production costs are approximately 150% and 130% of the APL value, respectively, with depreciation based on 38-yr and 40-yr plant life for their cases rather than the faster write-off (20 years) we assumed.

Aluminum Production

The Situation for Aluminum

The situation with respect to energy requirements for aluminum production is less critical than for ammonia. Nevertheless, there appear to be economic, environmental, and political incentives for implementation of ocean thermal energy plants to produce power for either nearby on-shore production of aluminum or for onboard refining of alumina to aluminum, as follows:

1) Economics. The aluminum producers have been enjoying the use of low-cost electric power because a) they have provided for company-owned power sources or long-term favorable price contracts, and b) they have been large users when power was abundant and have received price concessions based upon the marginal dollar of business concept. However, the latter concept is being attacked by smaller power users today. In California, a recent decision by the Public Utilities Commission reflects the belief that preferential rates to large users are inappropriate with fuel not in surplus. Recent Maryland decisions also pass electricity rate increases only to larger users. By our estimates, aluminum can be produced in an OTEC plant economically and will be very attractive if the cost of power to aluminum producers ashore rises to the 25-50 mill/kWh range charged to smaller consumers, as shown later.

2) Environmental. The aluminum producer today pays a premium price for a large tract of land to provide an emissions buffer between his plant and his residential neighbors. His investment in pollution control equipment is substantial, and still there are significant emissions. As our air becomes marginally safe, it is wise to look for production alternatives.

3) Political. U.S. aluminum companies, to get cheap power, low-cost labor, and favorable land and environmental costs, have gone abroad. Some of the host governments have cast an increasingly acquisitive eye at these industrial complexes. Some nationalization of U.S. industry abroad has already taken place. An open-seas-based OTEC plant-ship would be exempt from expropriation claims by others as mentioned earlier.

Aluminum Production & Costs

Aluminum is the most abundant metal in the earth's crust (8%). The principal raw material used for aluminum production is bauxite ore, a mixture of aluminum minerals, chiefly aluminum hydroxides. The ore is leached under pressure and heat by a caustic solution to obtain a solution of sodium aluminate, from which hydrated aluminum oxide is precipitated, washed, and calcined to obtain alumina, Al_2O_3, using the Bayer process. This alumina is reduced to the metal by electrolysis of a hot molten solution of alumina and cryolite (Na_3AlF_6), a process requiring 7 to 8 kWh/lb of aluminum.

In the 1964-74 decade, U.S. primary aluminum production climbed about 6.8% per year, reaching 4.9 million short tons per year (STPY) in 1974. Stamper[30] presented high, median, and low projections for future growth. The median projection indicated increases of 4.5 million STPY by 1985 and 18 million STPY by the year 2000. At 7 kWh/lb, the latter figure would require an additional 252 billion kWh/yr. If this electricity is generated by fossil-fuel power plants at 33% thermal efficiency, it will consume 2.5 quadrillion Btu (2.5 Q) per year, equal to 1.2 million bbl/day of oil.

There are two ways OTEC plants could be used for aluminum production: they could supply power by undersea cables to aluminum plants on tropical land sites or the electrolysis of alumina to aluminum could be conducted on board. Since others are studying electrical energy transmission from OTEC plants to shore, this preliminary feasibility study addressed the potential for onboard alumina reduction at site Atlantic 1 off Brazil.

Potential sources of alumina and possible locations for the necessary on-shore support facility are: Brazil (1750 miles) where a billion dollar expansion of alumina and aluminum processing facilities 250 miles upriver on the Amazon is in progress; Jamaica (3750 miles); Surinam (2000 miles); Venezuela (2400 miles); or St. Croix (300 miles). Large bauxite mines are located in Jamaica, Surinam, and Guinea; large new mines in Venezuela are not yet in production. Jamaica has long been a large alumina producer. The U.S. has imported alumina from Surinam for many years, averaging about 400,000 short tons per year from 1970-1975. New alumina facilities are being developed in Venezuela on the Orinoco River. Bauxite produced in Guinea has been shipped to St. Croix where facilities are available to refine it to alumina. These various sources imply trip times of 3-11 days to site Atlantic 1.

An OTEC/alumina-reduction plant-ship might have the configuration sketched in Fig. 9, with the OTEC power plant located in the center and one-half of the alumina reduction facility located on each side. For a 240-cell, 87,600 STPY demonstration plant, there would be 120 cells per side on two decks, i.e., 60 cells per deck.[31] Inboard areas near the power plant are devoted to metal casting, anode assembly and storage, and ingot storage. Liquid metal produced on the upper deck is discharged from the tapping ladles directly into the furnaces on the lower deck. The OTEC generators, transformers, and ac-dc rectifying equipment are located on a deck below the lower aluminum production deck. Alumina and baked anode blocks are delivered by a support ship to the stern of the plant-ship. The alumina is transferred by a pneumatic conveyor (airveyor) to distribution bins on each of the aluminum production decks. The support ship can also be used for crew transfers.

The nominal cell operating condition is 135,000 amps at 4.3 VDC per cell to produce 1 ton/day/cell. The cells are of the center break (i.e., centrally located crust breaker) type shown in Fig. 10. The carbon-lined cathode contains a layer of molten aluminum 8-12 in. deep. Floating on the liquid metal is a 6-8 in.-thick layer of electrolytic bath, primarily cryolite (Na_3AlF_6). The carbon anodes are suspended from the anode bus on both sides of the super-

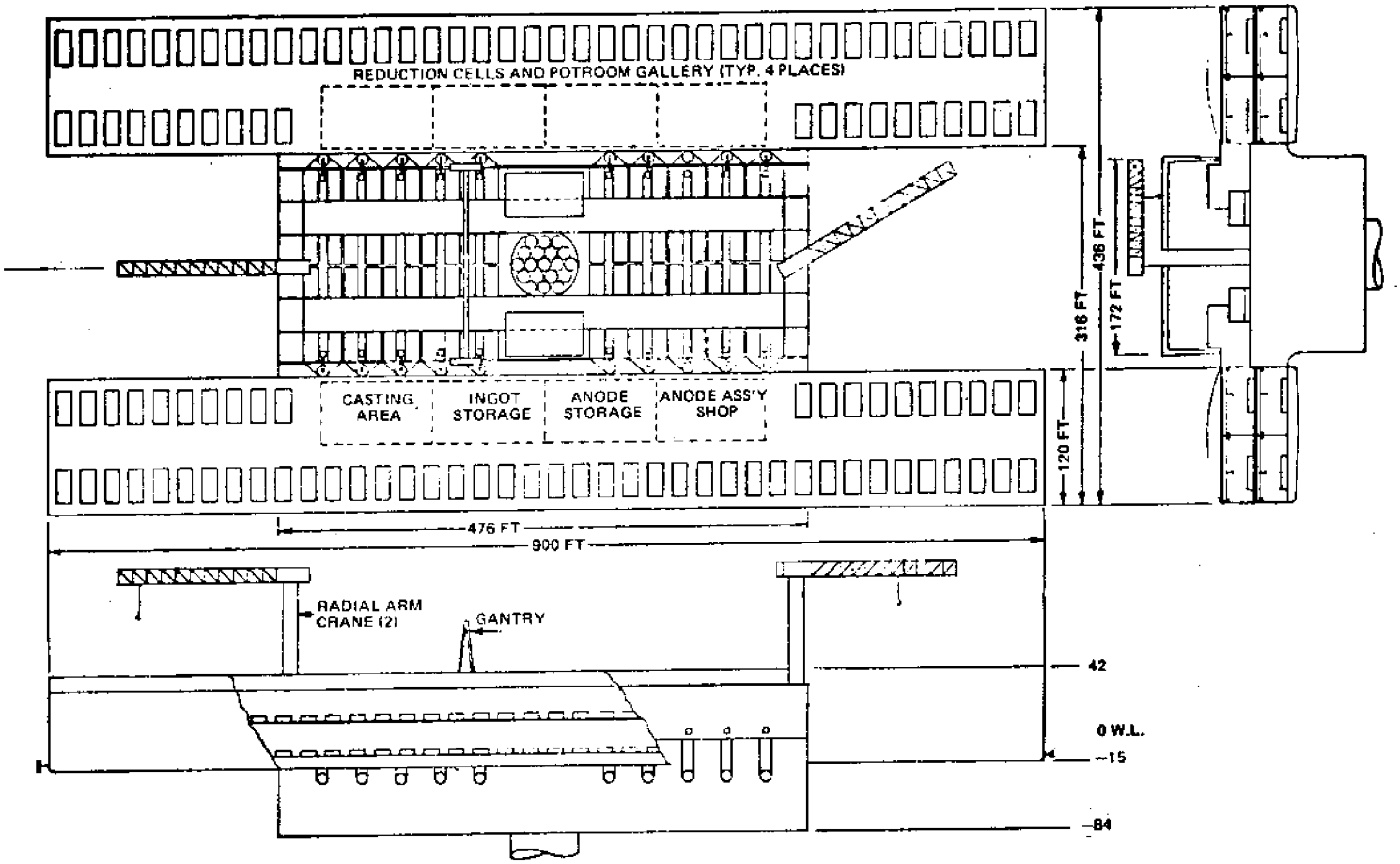


Fig. 9 Possible 140-MW_e, 87,600-STPY, OTEC/Aluminum Reduction Demonstration Plant Layout

structure and are lowered into the bath so that they rest approximately 2 in. above the metal level. As the current passes from the anode to the cathode, oxygen ions released from the ore combine with the anode carbon to form CO and CO_2 while molten aluminum deposits on the cathode.

Periodically, the "crust breaker" breaks the fused crust which has formed between the rows of anode blocks, and alumina is added to the cryolite bath to maintain 2 to 5% in solution. This operation will be controlled by a process computer. Insulated fume hood panels are placed between the top of the steel shell and the ore bin. Each cell contains 18-20 anode blocks. Each block is 30 in. x 60 in. x 20 in. high and is grouted to a bracket/stem. The anodes are gradually consumed over a 25-30 day period and are replaced one at a time (i.e., one every 36 hr or so). The steel shell of the cell (14 ft x 30 ft x 5 ft deep) is lined with carbon, and steel collector bars embedded in the carbon extend out the sides of the shell. Aluminum busbars are bonded to the ends of these steel bars and extend to the adjacent cell anode bus, thus creating a series circuit.

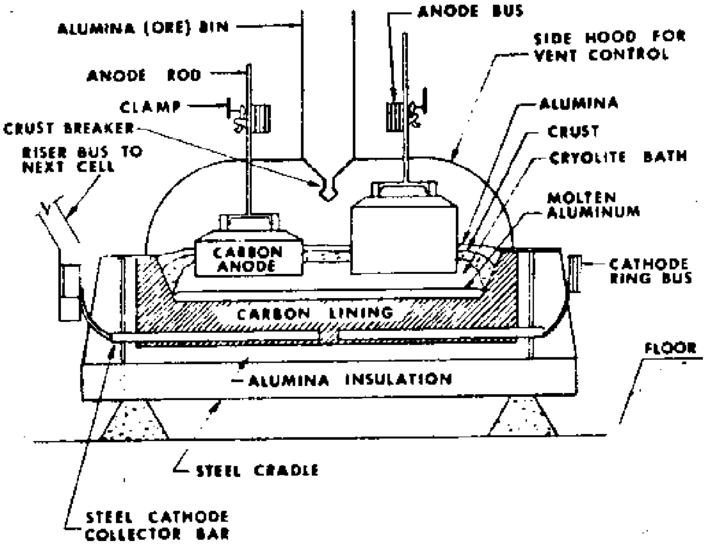


Fig. 10 Center-Break-Type Alumina Reduction Cell

Approximately 1 million Btu/hr/cell of waste heat is generated; approximately 60% of this is in the hood gases, and 40% is emitted from the cell below deck level. If 90% of this heat is salvaged (by use of good insulation and a compact circuit) and used to drive a closed-Rankine-cycle turbine generator, one will obtain a power output of 17 MW_e. We have assumed that this will be done, reducing the OTEC power plant requirement from 140 MW_e net to 123 MW_e net.

Every 36 hours or so a portion of the molten aluminum is tapped (by suction) from the cell at 970°C (1778°F) and transferred to one of two pairs of electrically-heated, 26-short-ton-capacity, holding furnaces. One pair plus a vertical direct chill casting unit will be located on the lower deck on each side of the plant. Each of these casting facilities will produce 170 STPD of 60-in. T-ingots. Casting temperature is approximately 1300°F.

Because of the slight roll of the plant-ship at the extreme on-site conditions, some method of stabilizing the cells may be required. Analysis of this requirement was beyond the scope of this study, but two methods appear to be feasible: active mechanical stabilization and use of hydrodynamic bearings. In the latter approach, groups of ten cells would be floated on pressurized hydrodynamic bearings, which will provide a high degree of inherent isolation from ship motions. A possibility exists that the passive use of such bearings would provide adequate stabilization. If active stabilization proved necessary, a "fail-soft," or gradual degradation design approach with redundant components would be employed, because a failure could lead to significant damage to the reduction plant.

An alternative aluminum production process has been patented by the Aluminum Company of America (ALCOA), U.S. patent 3 725 222. It is still under development (a pilot plant is under construction). It consists of two stages: 1) The Bayer hydrate of alumina, a porous $Al_2O_3 \cdot 3H_2O$ of large specific surface, is processed to obtain aluminum chloride ($AlCl_3$). 2) The $AlCl_3$ is electrolyzed in a vertically-stacked cell of several electrolysis sections in a solidly fixed anode/intermediary electrodes/cathode arrangement. The molten aluminum produced within this horizontal stack is understood to overflow from the edges of the stack at a controlled rate. It appears possible that this process would not require a cell stabilization system. The output per cell also is understood to be higher. However, the process appears to be more complicated than the "classic" one we have described, and the information necessary for a tradeoff study has not been made available.

Although the cell cathode is not consumed like the anodes, it usually fails after 4-5 years. When this occurs, a bypass busbar is placed around the cell, the cell is removed from the electrical circuit, tapped out, and allowed to cool. It is then shipped to the onshore support facility for relining.

Anode block production is the largest operation at the on-shore support facility. The blocks are made from a "paste" produced by crushing, sieving, heating, and mixing petroleum coke and coal tar pitch; they are then baked to cokefy the pitch and improve their resistivity. The shore facility also includes more complete maintenance facilities than those located on the plant-ship.

The onboard equipment for this 240-STPD alumina reduction plant is estimated to cost $52 M and to weigh 52,700 long tons.[5] About 62% of this cost and 96% of this weight would be in the reduction cells. The basic OTEC power-plant ship items would be increased by 23% from the 100-MW_e size to provide 123 MW_e, and the waste heat recovery system would be added to provide the other 17 MW_e (140 MW_e total) needed for the cells. It was estimated that the decks on each side of the platform for the alumina plant would add about $30 M, and two support ships to operate between the site and the shore facility would cost approximately $30 M.

Since it was not possible to develop this plant-ship concept in any depth during this limited program, the preliminary estimate of cost is subject to several uncertainties. The Kaiser Aluminum and Chemical Corporation advised that an appropriate size for a commercial plant would be nearer 600 STPD or more. Therefore, to obtain a first estimate of aluminum production cost we increased the foregoing plant size by a factor of 3 and assumed a 15% saving through economies of scale. Using recent cost figures for the raw materials and labor, together with financing similar to that in Tables 9 and 10, we estimated an investment (plant plus support) of $563 M and an aluminum production and delivery (S7 ton) cost of 33¢/lb, compared to recent prices (Table 11)[37] near 41¢/lb. Some of the most modern plants produce aluminum at a cost of over 40¢/lb even at 100% capacity, however.[38]

TABLE 11
ALUMINUM PRICE AND COST HISTORIES[a]

PRICES		COSTS	
1968	25.6 ¢/LB	1970	17.4 ¢/LB
1969	27.2	1/3/74	24.9
1970	28.7	4/6/74	29.1
1971	29.0	7/9/74	29.1
1972	26.5	10/12/74	30.5
1973	25.3	1/3/75	32.3
1974	34.1	4/6/75	33.5
1/8/75	39.0		
8/10/75	41.0		

[a]PRIVATE COMMUNICATION FROM MR. R. REAGAN, AMERICAN METALS MARKET MAGAZINE, NEW YORK, N.Y., OCT. 28, 1975.

Although the economic competitiveness of OTEC/aluminum plants appears to be marginal at present, the present U.S. aluminum companies are paying only 14 mills/kWh or less for electricity based on old agreements for large volume use. The power cost for a new plant might be 25 mills/kWh or more, similar to rates now charged to smaller consumers, in new agreements with power companies. If so, the OTEC/aluminum plant will become very attractive economically. Table 12 compares the projected investment costs and production costs over an 18-year period (1982-2000) for an OTEC aluminum plant and new U.S. onshore aluminum plants using electricity at 15 and 25 mills/kWh in 1975, each producing 262,800 STPY. For the onshore plants, an estimated $150 million plant investment for an 87,600 STPY plant in 1975 was multiplied by 3 and then reduced by 10% for economies from the larger scale. In all cases, the 1982 plant investment was established by taking the 1975 plant investment and increasing it for inflation at 7% per year (5 years to contract plus 2-year construction period; 12% interest and escalation during construction) and the interest on plant investment was taken to be 8% through the 18-year period. The prices for alumina, coke, electricity, labor, and other maintenance and operating expenses increase at 7%/year. The production cost for the OTEC plant rises more slowly, from 91% of the new onshore plant with 15-mill power in 1975 to only 73% in the year 2000, because the OTEC plant does not need to purchase electricity. Since only about one third of the fuel energy used to produce electricity onshore reaches the user, the reason for the improvement in the OTEC position with time is apparent. Even if the initial capital requirement for the OTEC aluminum production plant-ship exceeds our initial estimate, an attractive picture still will be expected; the interest and depreciation costs, once fixed, do dot escalate during the plant life.

TABLE 12

COMPARISON OF ALUMINUM REDUCTION PLANT PRODUCTION COSTS CHANGES OVER AN 18-YEAR PERIOD

262,800 SHORT TON/YEAR PLANTS

ALUMINUM PLANT	1975 POWER COST, MILLS/kWh	1982 PLANT INVESTMENT, $'S MILLIONS	ESTIMATED PRODUCTION COST ($/LB)				YEAR 2000 PRODUCTION COSTS, % OF U.S. NEW PLANT COST
			1975	1982	1900	2000	
OTEC PLANT SHIP	(ONBOARD)	789	0.33	0.50	0.74	1.29	73%
U.S. ONSHORE	15	636	0.39	0.55	0.96	1.77	100%
U.S. ONSHORE	25	636	0.46	0.64	1.15	2.14	121%
OTEC COST AS % OF 15-MILL ONSHORE CASE			89%	91%	77%	73%	

Liquid Hydrogen (LH_2) Production

The Long-Term Product for Tropical OTEC Plants

The present market for hydrogen is quite varied and ranges from small consumers paying relatively high prices to larger consumers with captive sources at relatively low cost.[27] A general market for hydrogen for use as a fuel for heating and cooking and for transportation does not yet exist but is foreseen by many for the longer term. Hydrogen stored as a liquid could be used to power all forms of ground and air transportation in the 1990s and beyond. Many competing methods for making hydrogen, including thermochemical decomposition of water, are being studied by others and will be subjects of papers at the First World Hydrogen Energy Conference to be conducted by the University of Miami at Miami, Florida, March 1-3, 1976.

For an OTEC plant-ship sited in tropical oceans, gaseous hydrogen obtained by water electrolysis would have to be liquefied for shipment to U.S. ports. It could then be fed into a gas pipeline network for heating and other uses. In this case, the LH_2 storage facility to which it is initially delivered should be associated with some industrial operation which could benefit from the refrigeration capacity it could provide during its vaporization. As a liquid, it could be transferred by rail or truck to plant sites or points for transportation fueling.

Although we can not see a large, near-term market for LH_2 from OTEC plants, we do believe that in the longer term it is likely to be the primary product to bring the benefits of the ocean thermal resource to the U.S. and the world.

OTEC/LH_2 Plant-Ship Costs

For OTEC/LH_2 plant ships, the General Electric Company's projection for electrolysis equipment was employed for a 500-MW_e, 230-STPD commercial plant in 1985. For the estimates of hydrogen liquefaction and storage costs we drew upon Ref. 27 (which drew upon Ref. 34). For liquefaction equipment the cost given was $0.5M/STPD of LH_2 produced plus 50% for installation for plant capacities from 10 to 250 STPD. It was stated that economies of scale could be expected near the upper end of this range and that technology improvements are expected. For the OTEC/LH_2 plant in 1985, a 30% reduction in cost was assumed, yielding a cost for liquefaction equipment of ($0.75M/STPD)(0.7)(230 STPD) = $121 M. For LH_2 storage a cost of $1.8 M for 10^8 SCF was given. For 30-day storage on the plant-ship, the capacity required will be 26.4 times this large, and it was assumed that the scaled-up LH_2 storage and transfer system cost would increase with the 2/3 power of the volume stored. Thus, a cost of $23 M was estimated. The resulting OTEC/LH_2 plant-ship cost if $487 M as shown in the first column of Table 13.

TABLE 13

ESTIMATED COSTS AND RATED CAPACITIES FOR 500-MW_e OTEC/LH_2 PLANT-SHIPS IN 1985 AND POSSIBLE PLANT-SHIPS IN THE 1990s (MILLIONS OF 1975 DOLLARS)

	1985	1990s
BASIC POWER-PLANT-SHIP COST	391	240[a]
ELECTROLYSIS INCL. FRESH-WATER PLANT[b]	35	32
HYDROGEN LIQUEFACTION	121	112
LH_2 STORAGE (30 DAYS) & TRANSFER SYS.	23	21
TOTAL OTEC/LH_2 PLANT COST	570	405
CONSTRUCTION INTEREST (12% OF COST)	68	49
GROSS PLANT-SHIP COST	638	454
GOVERNMENT COST-SHARING	−153	−94
NET COST	485	360
DEPLOYMENT TO SITE	2	2
PLANT INVESTMENT	$487 M	$362 M
RATED LH_2 CAPACITY, STPD	230	267

[a] REDUCED COST ACHIEVABLE WITH AGGRESSIVE R&D PROGRAM AND OTHER FACTORS

[b] HYDROGEN LIQUEFACTION EFFICIENCIES (FRACTIONS OF THE HIGHER HEATING VALUE OF H_2) ARE ASSUMED TO BE 0.75 AND 0.80 IN 1985 AND 1990s, RESPECTIVELY. FOR 1990s, 15% COST REDUCTIONS DUE TO R&D AND 98% ELECTROLYSIS CELL EFFICIENCY ARE ASSUMED

[c] 35% OF BASIC POWER PLANT SHIP COST AND CONSTRUCTION INTEREST ON SAME

As previously mentioned, an estimate was made of numerous improvements in the basic OTEC power-plant ship cost that might be achieved through R&D and other factors (which included use of enhanced heat transfer surfaces, credit for sharing cold-water system cost with a mariculture operation, a small credit for the LO_2 produced, sea-water surface temperature enhancement, and use of large water pumps). If all of these improvements are achieved by the 1990s, the estimated cost for the basic 500-MW$_e$ power-plant-ship will be reduced to \$240 M. If 15% improvements in cost of each of the LH_2 plant components also are achieved through R&D, and hydrogen liquefaction efficiency as a percentage of the higher heating value of hydrogen is increased to 80%, the *possible* 1990 OTEC/LH_2 plant-ship investment (in 1975 dollars) becomes \$362 M for a rated production capacity of 267 STPD as shown in the second column of Table 13.

Unit Production Costs of LH_2 Delivered to U.S. Ports

The plant investment costs in Table 13 lead to the estimated production and delivery costs shown in Table 14. For the 1985 case, the delivered cost is \$815/short ton or \$7.90/10^6 Btu based on the lower heating value (LHV) of hydrogen. The possible cost for the 1990s is \$558/ST or \$5.40/10^6 Btu based on the LHV of H_2 (or \$4.60/10^6 Btu based on the higher heating value).

TABLE 14
DELIVERED COSTS (1975 DOLLARS) OF LIQUID HYDROGEN FROM 500-MW$_e$ OTEC/LH_2 PLANT-SHIPS

	1980	1990s
PLANT INVESTMENT	\$ 487M	\$ 362M
WORKING CAPITAL (120 DAYS)	\$13M	\$11M
RATED CAPACITY (345 DAYS/YR), STPY	79,400	92,100
	PROD.	COST
LABOR AND OVERHEAD[a]	\$42	\$42/ST
MAINTENANCE MATERIALS (1% OF PI)	61	39
INSURANCE (2.8% OF PI – ODS)	86	55
DEPRECIATION (20 YEARS, 5% OF PI)	306	196
INTEREST (8% OF ½ PI)	245	157
PRODUCTION COST	740	489
INTEREST ON WORKING CAPITAL (8%)	13	9
SHIPMENT TO U.S. PORT[b]	54	54
COST AT PORT (w/o BOIL-OFF)	807	552
ADD. 1% FOR BOIL-OFF LOSS	8	6
COST AT PORT PER SHORT TON	\$815	\$558/ST
PER 10^6 BTU (LHV, 19.4 LB)[c]	\$7.90	\$5.40
PER 10^6 BTU (HHV, 16.4 LB)[c]	\$6.70	\$4.60
CASE I SALE PRICE PER 10^6 BTU (LHV)	\$18.25[d]	\$8.00
GROSS PROFIT MARGIN AS % OF SALES	57%	38%
CASE II SALE PRICE PER 10^6 BTU (LHV)	\$25.00[d]	
GROSS PROFIT MARGIN AS % OF SALES	68%	

[a] CREW OF 49 ON BOARD AND 25 ASHORE, EACH AT \$45,000/YEAR AVERAGE

[b] ESTIMATED TO BE 6 TIMES THE COST FOR SHIPPING AMMONIA

[c] LOWER HEATING VALUE (LHV) = 51,570 BTU/LB; HIGHER HEATING VALUE (HHV) = 61,030 BTU/LB

[d] CASE I, 1985, FOR SMALL VOLUME USERS = \$5/1000 SCF; CASE II, 1985, CORRESPONDS ROUGHLY TO A RECENT NASA CONTRACT FOR LH_2 FOR THE SPACE SHUTTLE

The sales price of LH_2 depends strongly on the customer's volume requirement in the current market. For customers needing about one million SCF per day, the price is approximately \$5/1000 SCF.[37] This price corresponds to \$18.25/10^6 Btu (based on LHV of H_2) and is shown as case I for 1985 in Table 14. At this price, the estimated gross profit margin as percent of sales would be 57%. A recent NASA contract for LH_2 for the space shuttle during the period 1975-1985[38] is calculated to correspond to a price near \$26/10^6 Btu. As Case II in the table, a price of \$25/10^6 is considered, which would yield an estimated gross profit margin of 68% for the OTEC/LH_2 plant.

For hydrogen users in the 100 million SCF/day class, the forecast prices of LH_2 delivered from land-based, fossil-fuel-feedstock plants are considerably lower. For a plant using partial oxidation of coal, the *cost* estimated[37] for production of *gaseous* hydrogen, when adjusted to late 1975, to a higher coal price (\$28.50/ton),* and to the lower heating value of H_2, is approximately \$4/10^6 Btu. For production of LH_2, this would yield approximately \$8/10^6 Btu. Thus, the essentially state-of-the-art OTEC/LH_2 plant in 1985 would have only a marginal chance of returning a substantial gross profit margin in competition with such land-based plants. However, there will be many other demands for fossil fuels that will make additional R&D on the OTEC/LH_2 resource very worthwhile to achieve the more attractive LH_2 cost of \$5.40/10^6 Btu in the 1990s. Compared to a sale price of \$8.00/10^6 Btu, this cost would yield a 32% gross profit margin.

This *cost* of LH_2 is still rather high for direct use as a fuel for, say, automobiles and commercial aircraft. However, it is not far greater than the cost of synthoil made from coal, which has been estimated to *cost* \$25/bbl or \$4.31/10 Btu.[37] Since future automobile engines,[37] aircraft engines, and other heat engines will operate at higher efficiency on LH_2 than on synthoil, operating costs could be comparable.

Cost of Electricity from OTEC LH_2 Used in Fuel Cells on Shore

An interesting possibility is that the LH_2 shipped from OTEC plants could be used in fuel cells on shore to generate electricity. The General Electric Company's electrolysis cells can be operated reversibly to serve as fuel cells. The efficiency of operation in this mode currently is 57%, but laboratory tests have shown 61% at 100 amp/ft^2 in continuous operation. A reasonable projection for 1990 is judged to be 70% efficiency. Table 15 shows that the estimated 1990 cost (in constant 1975 dollars) of the electricity generated on shore by this approach is 27.3 mills/kWh, a figure that surely will be of interest.

Concluding Remarks

A concept has been developed for Ocean Thermal Energy Conversion plant-ships for use at selected sites in tropical oceans to produce energy-intensive

---

*In September 1974 the TVA negotiated a contract with Webster County Coal Co. for 1.5 million tons/yr for 3 years at \$28.50/ton, subject to price adjustment (*Energy Users Report*, Nov. 28, 1974.)

TABLE 15

POSSIBLE 1990 COST FOR GENERATING POWER WITH FUEL CELLS ON SHORE USING LH_2 FROM OTEC PLANT

POSSIBLE OTEC/LH_2 PLANT-SHIP INVESTMENT AT SEA[a]	\$ 723/kW_e
EFFICIENCY FOR DELIVERY OF LH_2 TO SHORE[b]	0.511
EFFECTIVE OTEC/LH_2 PLANT-SHIP INVESTMENT PER kW_e OUTPUT FROM FUEL CELLS	\$1415/kW_e (OUT)
FUEL CELLS INSTALLED ON SHORE[c]	\$ 156
STORAGE SYSTEM INSTALLED ON SHORE	56
SUBTOTAL COST PER kW_e OUTPUT	\$1627/kW_e
RECOVERY FACTOR (PARTIAL RECOVERY OF ENERGY OF LIQUEFACTION)	1.06
EFFECTIVE TOTAL INVESTMENT	\$1535/kW_e
WEIGHTED FIXED CHARGE RATE (13% ON PLANT-SHIP, 15% ON SHORE FACILITY)	13.26%
FIXED CHARGE	23.2 MILLS/kWh
OPERATING COSTS, SHIP + SHORE	2.0
FUEL COST (TRANSPORTATION OF LH_2 TO SHORE)	2.1
	27.3 MILLS/kWh

[a] PLANT-SHIP INVESTMENT IS \$362M FOR 500 MW_e GENERATED ONBOARD

[b] PRODUCT OF THE FOLLOWING: PLANT FACTOR AT SEA (345 DAYS/YR), 0.945, ELECTROLYSIS EFFICIENCY 0.98, LIQUEFACTION EFFICIENCY FRACTION OF HHV, 0.80, FUEL CELL EFFICIENCY, 0.70; STORAGE EFFICIENCY (BOILOFF LOSSES), 0.98

[c] BASED ON 15% IMPROVEMENT ON FUEL CELL COST DUE TO R&D, 30% ADDITION FOR INSTALLATION, 0.70 FUEL CELL EFFICIENCY, AND 0.90 PLANT FACTOR ON SHORE.

products on board. It employs a novel concept for the OTEC heat exchangers, which are made of aluminum and are integrated structurally with the barge-like hull to minimize cost. These slowly grazing (1/2 to 1 knot) platforms will be very stable under normal operating conditions and could serve many other needs simultaneously (e.g., oceanographic research, and cold-water supply for mariculture).

The most attractive candidate product from such plants in the near term (early 1980s) is ammonia, which is presently produced mainly from natural gas; both are expected to be in increasingly short supply in the U.S. Estimated costs for producing ammonia on OTEC plant ships via electrolytically-produced hydrogen are attractive. This means for obtaining ammonia for U.S. agricultural and chemical needs would appear to be more attractive economically and far more attractive environmentally and socially than producing it from coal, the most abundant fossil fuel in the U.S. It could be very attractive to any nation not having an abundant and assured supply of natural gas.

Some consideration has been given to the onboard reduction of alumina to aluminum, a process which requires 7-8 kWh/lb of aluminum produced. An OTEC/aluminum plant-ship would be much larger and more costly than an OTEC/ammonia plant ship and would require more complex engineering for the plant-ship installation. A preliminary estimate indicates, however, that aluminum could be produced economically and that it will become very attractive if new competing onshore plants have to pay power rates of 25 mills/kWh or more. Alumina reduction also could be done on shore using power from an offshore OTEC plant-ship, but the number of sites where this would be economically and environmentally acceptable probably is small.

Tropical OTEC plants producing liquid hydrogen for delivery to the U.S. probably would have limited market access and be considered higher risk for investment in the near term (1985). However, an aggressive R&D program on OTEC and the technologies for water-electrolysis and hydrogen liquefaction, storage, and shipping would lead to a competitive position for LH_2 from OTEC plants. If fuel cell technology also advances as expected, this LH_2 could serve for production of electricity on shore as well as for transportation, heating, and chemical and industrial uses.

The key sister technology to OTEC for both ammonia production and LH_2 production is water electrolysis. It is strongly recommended that at least two paths for development of electrolysis systems be given priority support along with OTEC.

A strong reason for giving high priority to the development of OTEC technology now can be appreciated by considering the situation if an OTEC/ammonia plant existed now. The ammonia production cost would be only \$90 per ton. If this plant-ship proved to be still fully usable with only routine maintenance beyond the 20 years we have projected, the forecast production cost for 1996 and beyond (depreciation no longer included) would be only \$121/ton, increasing at, say, only 5% per year thereafter, while the production cost using coal feedstock would have exceeded \$200/ton by 1996 and would increase at 7%/year.

We believe it would be possible to develop and produce enough OTEC/ammonia plants by the mid-1980s to meet the projected additional U.S. requirement for ammonia by that time, estimated at 10 million tons per year. After satisfying this need, many additional OTEC plants could be used to produce liquid hydrogen or aluminum or other energy-intensive products. The attractive potential for related mariculture operations also warrants further study.

A priority plan to build OTEC/ammonia plant ships will have positive nationwide economic significance on the employment of American workers and, if utilized for foreign sales, on the U.S. balance of payments. The impact will commence with the pilot and demonstration plant-ships and become pronounced with the building of commercial plant-ships in 1981. With 21 commercial OTEC/ammonia plant-ships in operation by 1986, economic impacts can be expected in the following major areas:

1) Every natural gas consumer will benefit from reduced pressure on limited natural gas resources. Twenty-one plant-ships producing domestic ammonia would relieve the natural gas demand by 500 billion SCF, the equivalent of 0.25 million barrels of crude oil per day.

2) Increased shipyard revenues and employment would result. Seven plant-ships constructed in the year 1985 would produce additional shipyard revenues in that one year of \$4.0 billion in 1975 dollars and provide an estimated employment increase of 101,000 private shipyard workers.

3) U.S. aluminum companies would have higher revenues and more jobs. The estimated aluminum requirement to build each plant ship deliverable in 1985 is 17,700 short tons. The expected additional

1985 revenues to aluminum companies in that one year in 1975 dollars would be $257 million, and jobs would be provided for about 1900 additional workers.

4) Farmers would benefit from reduced pressure on the nitrogen fertilizer marketplace, particularly over the longer term. The estimated OTEC ammonia price in the 1990s is only half that for ammonia made from coal on shore.

5) U.S. Flag shipping would be increased by eleven 70,000 DWT tankers, providing jobs for about 300-400 more crewmen. OTEC crews provide an additional 1286 jobs.

Many contacts with industry have indicated that industry will be willing to bear a share of the pilot plant and demonstration plant costs and participate in a major way in the first commercial-size plant, provided the demonstration is technically and economically successful. The program recommended is:

End of 1976: Complete heat exchanger performance and biofouling/cleaning tests.

End of 1978: Conduct tests on a 5- to 10-MW_e OTEC pilot plant.

End of 1980: Complete and demonstrate a 100-MW_e OTEC/ammonia plant ship.

End of 1982: Begin operation of first 500-MW_e commercial-size plant.

Have 20 more commercial-size plants in operation by 1986.

Acknowledgment

The authors gratefully acknowledge the support of the U.S. Maritime Administration (MARAD) for this work. Messrs. James Gross and James Lisnyk of MARAD provided helpful guidance. Many people at APL/JHU contributed to the program, including W. H. Avery, R. W. Blevins, W. B. Shippen, H. L. Olsen, P. P. Pandolfini, M. B. Tate and A. S. Polk, Jr. The Sun Shipbuilding & Dry Dock team headed by E. Schorsch and E. C. Hunt, the Hydronautics, Inc. team headed by E. R. Miller, Jr. and R. A. Barr, and A. R. Miller of the Woods Hole Oceanographic Institution made major contributions. To them and many others from industry,[1] as well as the law firm of LeBouef, Lamb, Leiby & MacRae, we are indebted.

References

1. Francis, E. J. (Principal Investigator), "An Analysis of the Maritime and Construction Aspects of Ocean Thermal Energy Conversion (OTEC) Plant Ships," APL/JHU final report in process for the U.S. Maritime Administration, Department of Commerce, Contract No. 5-38054.

2. Olsen, H. L. and Pandolfini, P. P., "Analytical Study of Two-Phase-Flow Heat Exchangers for OTEC Systems," APL/JHU final report in process for Division of Solar Energy, U.S. Energy Research and Development Administration, Task ZE8 under Contract N00017-72-C-4401, Department of the Navy.

3. Anderson, J. Hilbert and Anderson, James H., Jr., "Thermal Power from Sea Water," Mechanical Engineering, Vol. 88, April 1966, pp. 41-46.

4. Claude, G., "Power from Tropical Seas," Mechanical Engineering, Vol. 52, December 1930, pp. 1039-1044.

5. Brown, C. E. and Wechsler, L., "Engineering an Open Cycle Power Plant for Extracting Solar Energy from the Sea," Paper OTC 2254, Offshore Technology Conference, Houston, May 5-8, 1975.

6. Beck, E. J., "Ocean Thermal Gradient Hydraulic Power Plant," Science, Vol. 189, July 1975, pp. 293-294.

7. Zener, C. and Fetkovich, J., "Foam Solar Sea Power Plant," Science, Vol. 189, July 1975, pp. 294-295.

8. Goss, W. P., Heronemus, W. E., Mangarella, P. A. and McGowan, J. G., "Summary of University of Massachusetts Research on Gulf Stream Based Ocean Thermal Power Plants," Proceedings, Third Workshop on Ocean Thermal Energy Conversion, Houston, Texas, May 8-10, 1975, APL/JHU Report SR 75-2, August 1975, pp. 51-62.

9. Lavi, A., "Final Report, Solar Sea Power Project," Report NSF/RANN/SE/GI-39114/PR/74/6, Carnegie-Mellon University, Pittsburgh, Pa., Jan. 31, 1975.

10. "Ocean Thermal Energy Conversion (OTEC) Power Plant Technical and Economic Feasibility," Report NSF/RANN/SE/GI-C937/FR/75/1, LMSC-D056566, by Lockheed Missiles and Space Co., Inc. to the National Science Foundation, 12 April 1975 (2 volumes; Lloyd C. Trimble, Principal Investigator; see also pp. 3-20 of Ref. 28).

11. "Ocean Thermal Energy Conversion," Final Report by TRW Systems Group, Redondo Beach, Calif., to U.S. Energy Research and Development Administration, Contract NSF-C 958, June 1975 (5 volumes; Robert Douglass, Principal Investigator; see also pp. 22-36 in Ref. 28).

12. Gregory, D. P. and Biederman, N. P., "An Optimization Study of Ocean Thermal-Energy Delivery Systems Based on Chemical-Energy Carriers," Proceedings, Third Workshop on Ocean Thermal Energy Conversion, Houston, Texas, May 8-10, 1975, APL/JHU Report SR 75-2, August 1975, pp. 121-124.

13. Hornburg, C. D., Lindal, B. and El-Ramly, N., "Preliminary Research on an Ocean Energy Industrial Complex," Proceedings, Third Workshop on Ocean Thermal Energy Conversion, Houston, Texas, May 8-10, 1975, APL/JHU Report SR 75-2, August 1975, pp. 125-127.

14. Conn, A. F. and Rudy, S. L., "Parameters for a Ship Hull Cleaning System Using the CAVIJET™ Cavitating Water Jet Method," Hydronautics, Inc., Technical Report 7510-1, July 1975.

15. Chisholm, D., "Pressure Gradients Due to Friction During the Flow of Evaporating Two-Phase Mix-

tures in Smooth Tubes and Channels," National Engineering Laboratory, Glasgow, Scotland, Proceedings of the Institute of Mechanical Engineers, May 1972, pp. 347-357.

16. Chaddock, J. B. and Brunemann, H., "Forced Convection Boiling of Refrigerants in Horizontal Tubes--Phase 3," Report HL-113, School of Engineering, Duke University, Durham, N. C., July 1967.

17. Handbook of Fundamentals, American Society of Heating, Refrigeration, and Air Conditioning Engineers, (A.S.H.R.A.E.), New York, 1972.

18. Collier, J. G., Convective Boiling and Condensation, McGraw-Hill, London (1972).

19. Fink, F. W. and Boyd, W. K., "The Corrosion of Metals in Marine Environments," DMIC Report 245, May 1970, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio.

20. Verink, E. D., Jr., "Aluminum Alloys for Saline Waters," Chemical Engineering, Vol. 81, April 15, 1974, pp. 105-110.

21. Konopka, A. J. and Gregory, D. P., "Hydrogen Production by Electrolysis, Present and Future," Record of the Tenth Intersociety Energy Conversion Engineering Conference, Newark Del., August 18-22, 1975, IEEE Catalog No. 75 CHO 983-7 TAB, pp. 1184-1193.

22. Vogelberger, P. J., Jr. and Feldwick, R. D., Teledyne Energy Systems, Timonium, Md., private communications to E. J. Francis, APL/JHU, August 8 and September 15, 1975.

23. Nutall, L. J. and Titterington, W. A., "General Electric's Solid Polymer Electrolyte Water Electrolysis," Conference on the Electrolytic Production of Hydrogen, the Chemical Society, New Hall, City University, London, England, February 25-26, 1975.

24. Nuttall, L. J., General Electric Co., Wilmington, Mass., private communications to E. J. Francis, APL/JHU, Dec. 1, 1975, and other dates.

25. Francis, E. J., private communication with Dr. John Douglass, TVA National Fertilizer Research Center, Muscle Shoals, Alabama, July 14, 1975.

26. Dugger, G. L., Editor, Proceedings, Third Workshop on Ocean Thermal Energy Conversion, Houston, Texas, May 8-10, 1975, APL/JHU Report SR 75-2, August 1975; includes APL/JHU paper by Dugger et al., "Tropical Ocean Thermal Power Plants Producing Ammonia or Other Products," pp. 106-115.

27. Biederman, N., Darrow, K., Jr. and Konopka, A., "Utilization of Off-Peak Power to Produce Industrial Hydrogen," Final Report to Electric Power Research Inst. Research Project 320-1, August 1975, Inst. of Gas Technology Project No. 8793, Chicago, Ill.

28. "Water Loss Investigations, Lake Cachuma, 1961, Evaporation Reduction Investigations," U.S. Dept. of Interior Bureau of Reclamation, Chem. Eng. Lab. Rept. SI-33, Jan. 1, 1962; see also R. G. Vines, pages 146-147 in Retardation of Evaporation by Monolayers, F. K. LaMer, Ed., Academic Press, 1962.

29. "Export Import Bank Program Review," Senate Report S241-6, Feb. 1974.

30. Stamper, John, "Mineral Facts and Problems," U.S. Bureau of Mines, 1970.

31. Private communication from George E. Nagel and Michael A. Tallman, Frederick, Md., to E. J. Francis, APL/JHU, Sept. 27, 1975.

32. Private communication from Mr. R. Reagan, American Metals Market Magazine, New York, N.Y., to E. J. Francis, APL/JHU, Oct. 28, 1975.

33. Jacomet, Andre, Executive V.P. for International Affairs, Pechiney Ugine Kuhlman, address before the London Metal Forum, Oct. 20, 1975.

34. Anon., "Survey Study of the Efficiency and Economics of Hydrogen Liquefaction," Contract NAS-1-13395 for NASA Langley Res. Center, Inst. of Gas Technology, Chicago, Ill.

35. Aerospace Daily, July 8, 1975, p. 45.

36. Private communication from Mary White, ERDA, to W. H. Avery, APL/JHU, August 1975 (projected cost of synthoil, $24.94/bbl).

37. Billings, R. E., "Hydrogen's Potential as a Vehicular Fuel for Transportation," Record of the Tenth Intersociety Energy Conversion Engineering Conference, Newark, Del., August 18-22, 1975, IEEE Catalog No. 75 CHO 983-7 TAB, pp. 1165-1175.

38. Harre, E. A., Livingston, O. W. and Shields, J. T., "World Fertilizer Review and Outlook," TVA Report #TA(AO)6-69, 1974, National Fertilizer Development Center, Muscle Shoals, Ala.

RECIRCULATION AND THERMOCLINE PERTURBATIONS FROM OCEAN THERMAL POWER PLANTS

S.A. Piacsek and P.J. Martin, Naval Research
Laboratory, Washington, D.C.

G.O. Roberts, Science Applications, Inc. McLean, VA

Abstract

Numerical experiments were performed on the fluid motions resulting from the pumping action of ocean thermal power plants. In particular, the resulting thermocline distortions, sea surface temperature lowering and corresponding heat flow change was investigated. The object was to find engine discharge configurations and pumping rates that would minimize any alterations. This would accomplish both a minimal environmental impact and preservation of the temperature gradient across the engine, i.e. the energy resource. The results obtained to date, using 2-D turbulent flow calculations, indicate that near the engine ($200 \text{ m} \leq x \leq 500 \text{ m}$) the sea surface temperature perturbations will range from $.01^{\circ}\text{F} \leq dT \leq 3.0^{\circ}\text{F}$, depending on flow rates, season and geography. The results of the surface heat calculations showed that a depression of the sea surface temperature by $.1^{\circ}\text{C}$ leads to an increased heat flow from air to sea of 9.6 cal/cm^2/day in the Puerto Rico area. Accepting this as a permissible environmental perturbation, the area requirement for a 100 MW plant is 2500 km^2, with a radius of 28 km. The corresponding figures for Hawaii are 4 cal/cm^2/day, an area of 6000 km^2, and a radius of 44 km.

Introduction

The operation of one or more ocean thermal power plants (OTPP's) in a given geographical region can lead to several geophysical effects. Some of these are: a lowering of ocean surface temperatures; a reduction in the heat content of the surface layers; and an increase in the heat content of the layers at $\sim$500 m depth. A severe modification of the thermal structure near the plant could result in a lower temperature contrast across the plant, and thus a lower thermal resource available for power extraction. Furthermore, horizontal ocean currents and turbulence can disperse the perturbations to considerable distances beyond the region of operation, and the area-integrated cumulative effect may cause a slight alteration in the regional climate. It is important to demonstrate that the areal extent and magnitude of any alteration is within acceptable limits.

Turbulent flow near the plant

The first problem that must be solved before any of the above environmental impact questions can be tackled is the "exterior fluid dynamics" of the plant, i.e. the fluid motions directly forced by the engine pumps. The basic hydrodynamic flow problem associated with an OTPP is that of source-sink flows in a stratified fluid. The source-sink flows between the warm and cold intakes and between the warm and cold discharges are essentially a potential flow, i.e. irrotational, whereas the motions due to buoyancy in a stratified fluid are essentially rotational. The exact nature of the resultant flow is determined by the relative strengths of the pumping action and the ocean's stratification. The relevant nondimensional hydrodynamic parameter governing source-sink flow in a stratified fluid is the Froude number, defined as

$$Fr = U/DN$$

where U is the discharge velocity, D is the diameter of the discharge pipe and $N = (g/\rho_0)^{1/2} (d\rho/dz)^{1/2}$ i.e. the Brunt-Vaisala frequency of buoyancy motions in the respective thermocline.

A further important property of fluid flows associated with an OTPP is their turbulent nature. The nondimensional parameter governing the strength of turbulence is the Reynolds number, defined as

$$R = UD/\nu$$

where ν is the molecular viscosity of water. Although in the presence of viscosity the flow is never strictly irrotational, even in the absence of stratification, for low values of R ($\lesssim 1000$) the flow can be represented to a good approximation by the irrotational source-sink solutions. For values of $R > 2000$ the flow becomes irregularly time varying and approaches a statistically random or turbulent state for $R > 10^4$.

The primary effect of the turbulent eddies is to diffuse momentum, heat and salt, much as molecular diffusivity with a large value does (the effective diffusivity of wind-generated turbulence in the ocean is $\sim 10^2$ cm^2/sec). Unfortunately, a direct simulation of the turbulent eddies of all sizes is not feasible on computers with a finite memory size: present day large computers have a storage of the order of 10^6 words. Thus recourse must be made to some kind of closure method where the effects of the small eddies are represented as turbulent transport terms in the mean flow equations.

The particular type of closure method adapted in these studies is commonly referred to as a first order "ensemble average" or "statistical closure" model. This model is essentially phenomenological, and involves splitting the flow variables into mean and perturbation parts, with only the statistical average products computed for the perturbation parts (Mellor and Yamada[1], Lewellen[2,3]). The mean flow is an ensemble average over a large number of flow realizations, and the turbulence transport terms are determined from the divergence of fluxes that are the products of an eddy diffusion coefficient and mean flow gradients. Table I contains the relevant model equations. The eddy diffusivities are calculated from the turbulence kinetic energy $q = \overline{u_i' u_i'}$ and a length scale Λ, the integral length scale of turbulence. The turbulent energy q, in turn, is determined from a partly empirical transport equation, and Λ is an imposed function of position. As presented in Table I, the model has three arbitrary constants to be determined. Unfortunately, these constants are not universal but have to be changed for each physical situation, and are usually obtained from experiments.

In turbulent wakes it is usually assumed that $\Lambda = c.\ell$, where $c = .125$ and ℓ is a characteristic length scale of flow variation, usually the radius of the turbulent region. The constant Λ also enters into the prediction equation for q through the fourth term on the right-hand-side of (3), and controls the self-decay of the turbulence. The loss of turbulent energy through turbulent entrainment of different density layers is described by the term $K.dT/dz = - K.N^2$, the second term on the right-hand-side of (3). The appearance of this turbulence loss as potential energy of the mean field is represented by the term $K.dT/dz$ in the diffusion term of the temperature prediction equation (2).

In its crude form the diffusion constant is taken to be the same in both the vertical and horizontal directions, even though it is known that in stratified fluids vertical motions are greatly suppressed, so that the turbulent eddies will be very anisotropic and the vertical diffusivity will be reduced by orders of magnitude. A way of remedying this situation is to partition the turbulence energy into its vertical and horizontal parts, and predict them separately along with a separate length scale in each direction.

In order to prevent the turbulence from decaying in a finite time to zero according to the relation $dq/dt \sim q^{1/2}$, the usual relation $K = \Lambda \cdot q^{1/2}$ has been replaced by the form given in (5) of Table I. Then in regions of strong stratification the relation $dq/dt \sim q^{3/2}$ will hold and the decay of turbulence will slow down. This can also be looked upon as the inclusion of the small-scale, random internal waves generated in these regions into the shear-produced turbulence energy density.

The first and fifth terms on the right-hand-side of (3) represent the production of turbulence by the velocity shear and the diffusion of turbulence by its own eddies, respectively. The second term on the right-hand-side of (1) is the divergence of the Reynolds stresses, and represents the turbulent friction acting on the mean flow.

It was found that for small pumping velocities the turbulence generated becomes insufficient to damp out any further instability of the mean flow to continuous, random internal wave generation. To remedy this situation, a damping term was introduced in the form of a Rayleigh friction into the w prediction equation, with a dependence on the ratio N^2/q leading to strong damping in regions of weak turbulence. The third term on the right-hand-side of (3) represents the corresponding gain of the turbulence field from this loss of small-scale mean energy.

A series of experiments was run to test the effect of the Froude number on the nature of the flow. The experiments were kept simple by introducing linear stratification, so that only the top half of the

TABLE I

Turbulence Model

$$\frac{D\underline{u}}{Dt} = -\nabla p + \left\{K(u_{i,j} + u_{j,i})\right\}_{,j} + T\,\underline{k} - c_v \frac{KN^2}{q}\, w\,\underline{k} \tag{1}$$

$$\frac{DT}{Dt} = \nabla.(K \nabla T) \tag{2}$$

$$\frac{Dq}{Dt} = K\left\{\tfrac{1}{2}(u_{i,j} + u_{j,i})^2 - N^2 + \frac{c_v N^2 w^2}{q}\right\} - c_f \frac{Kq}{L^2} + \nabla.(K\nabla q) \tag{3}$$

$$\nabla.\underline{u} = 0 \tag{4}$$

where $N^2 = \frac{\partial T}{\partial z}$

$$K = \frac{L q^{\frac{1}{2}}}{1 + \frac{c_s N^2 L^2}{q}} \tag{5}$$

and usually $L = .3 \times$ depth of region

$c_f = 2$

$c_s = .1$

$c_v = .1$

separating the $\underline{u}$ equation components

$$\frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(2K\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial z}\left\{K\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right\} \tag{6a}$$

$$\frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial z}\left(2K\frac{\partial w}{\partial z}\right) + \frac{\partial}{\partial x}\left\{K\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right\} + T - \frac{c_v K N^2 w}{q} \tag{6b}$$

discharge jet and the bottom half of the intake flow needed to be included. The resultant streamlines are displayed in Figures 1 a,b,c. They show that for Fr = 3.2 (Fig. (a)) only 10% of the discharge flow exits through the right-hand boundary. For Fr = 1.6 (Fig. (b)) the corresponding figure is 55%, and for Fr = .80 (Fig. (c)) the outflow is over 100%, i.e. some flow is actually entrained from infinity and goes back without ever reaching the left wall. The above series was run with $c = 1$ and $\ell = 1.2\,R$, where R is the discharge tube radius.

The next series of experiments was designed to simulate a more realistic OTPP configuration. The source-sink flow consisted of a warm water intake and a discharge below it that ejected either the ingested water cooled by 3°F or cold water at 50°F. The latter case represents a discharge of the cold bottom water over the warm discharge, as suggested by TRW[4]. The depth of the simulation volume is 100 m, and the top represents the water surface. The intake is at 20 m below the surface, and the discharge at 50 m. The temperature at the bottom is $T_{100} = 69\,^{\circ}F$ and at the surface $T_s = 85\,^{\circ}F$. A realistic thermocline of the analytic form

$$T(z) = A + B \,.\, \tan^{-1}(z - z_c/\delta)$$

was used, where A and B are constants such that $T_{z=100}$ and T_s have the prescribed values. The center or point of inflection of the thermocline is at $z_c = 50$ m depth, and its "width" δ is 50 m. This corresponds to a typical August thermocline in the Gulf of Mexico.

Figures 2(a,b) depict the resulting thermocline deformations for a warm (75°F) and a cold (50°F) discharge, respectively. The approximately 4°F temperature drop at the intake depth in the case of the warm discharge indicates a reduction of ~10% for the temperature contrast across the engine. On the other hand, in the case of the cold discharge there is no temperature loss at the intake level, but there is an anomalously cold region of considerable width between the 50 m and the 100 m depth levels that has a horizontal extent of several kilometers. As a result, the surface temperature is lowered over a wider area and to a lower value in the case of the cold discharge over the warm discharge. Figures 3(a,b) show the corresponding streamlines of these "two-hole" experiments, for a Froude number of Fr = 4. In the case of the warm discharge (Fig. (a)) approximately half the flow recirculates, and about 10% is entrained to and from infinity. In the case of the cold discharge there is no recirculation but ~40% is entrained to and from infinity.

Finally, a series of "three-hole" experiments was run with both warm and cold discharges present. The geometry consisted of a 2-D equivalent of the Lockheed baseline design[5] with the tubes replaced by a slit 75 ft high and 100 ft wide in the azimuthal direction. The thermocline used corresponds to that of the Gulf of Mexico in August, and the Froude number based on slit height and N at the cold water

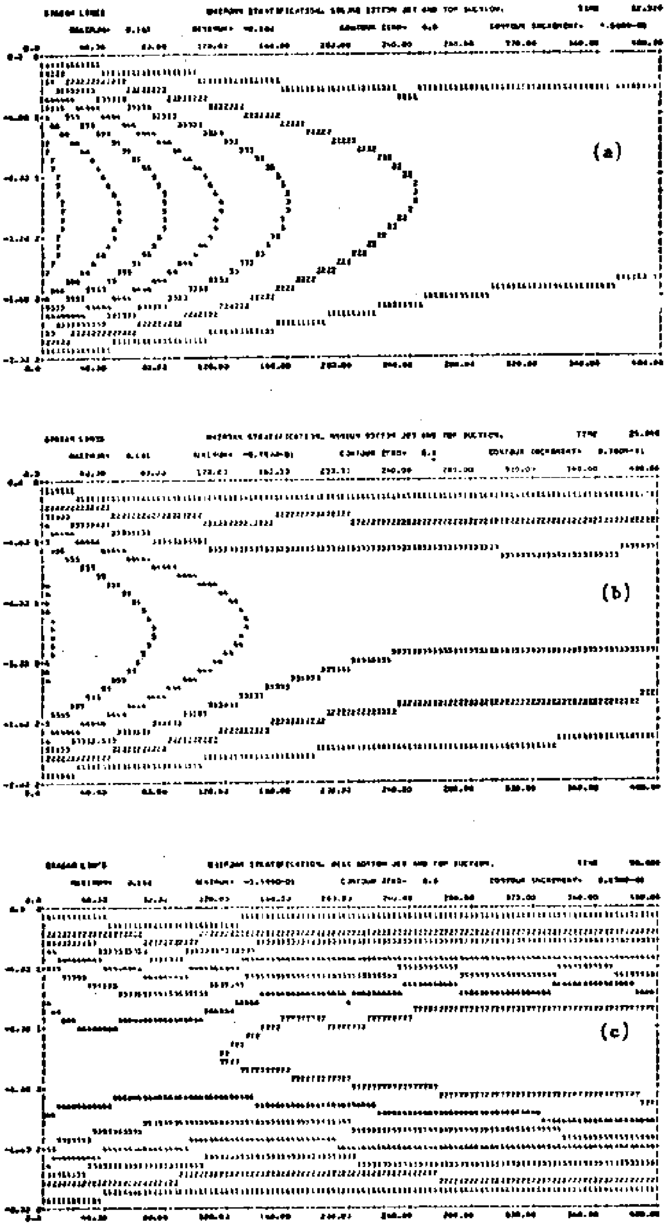
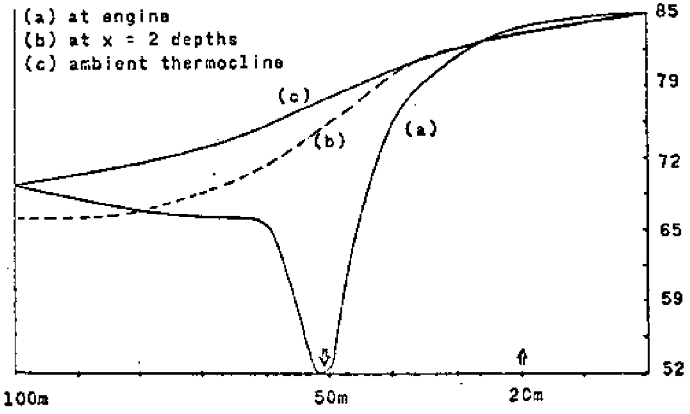
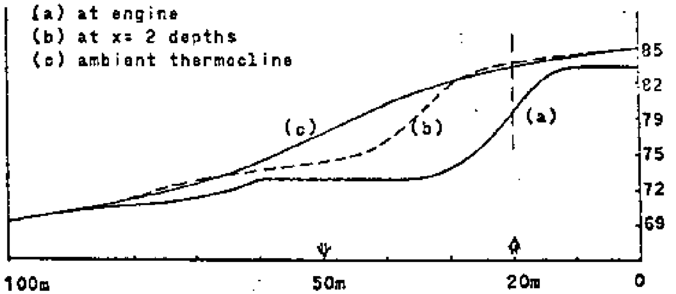


Figure 1(a,b,c)

STREAMLINES OF TEST PROBLEM FOR (a) Fr=3.2; (b) Fr=1.6; (c) Fr=.8

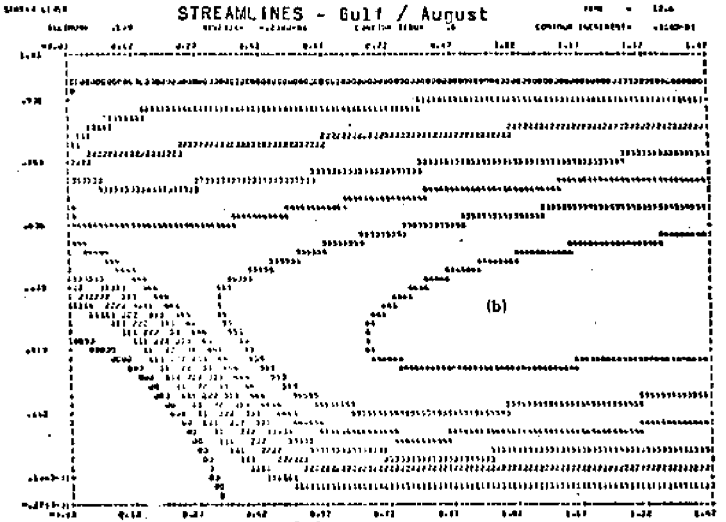


Thermocline deformation - Cold over warm discharge
- Gulf of Mexico
- August

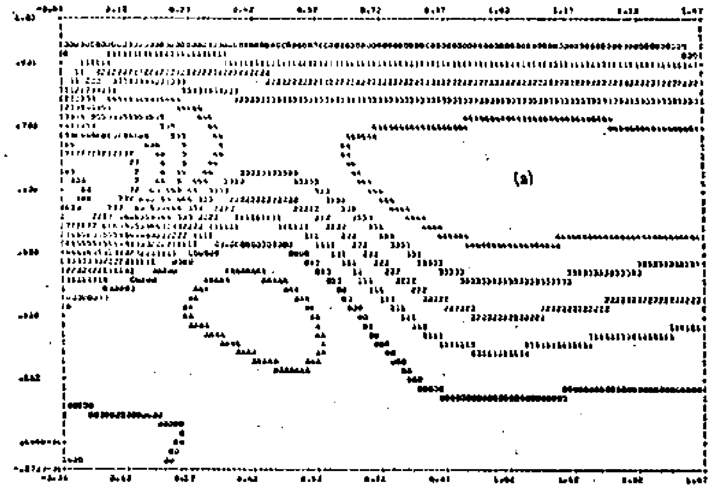


Thermocline deformation - Warm over cold discharge
- Gulf of Mexico
- August

Figure 2(a,b)



Cold over warm discharge



Warm over cold discharge

Figure 3(a,b) STREAMLINES OF 2-HOLE EXPER.

discharge depth is Fr = 1.8. The total depth of the simulation volume was 500 ft, the intake depth 50 m and the depths of the warm and cold water discharges 150 ft and 300 ft, respectively. Figure 4 illustrates the streamlines for this design. Each contour increment represents a flux of 2000 ft^3 of water; the total warm water circulation is 15% less than the total cold water circulation. There is an ~ 16% recirculation between intake and warm discharge, and approximately 50% of the "warm" discharge (5°F below intake temperature) sinks rapidly to join the cold discharge in a distance less than 100 ft from the plant.

Sea surface temperature depression

A series of "three-hole" experiments was performed on various thermoclines for areas east and southeast of the United States, for the months of August and February. Table II presents the relevant ocean temperature information and results for the case of Fr = .5, with warm over cold discharge configuration in the month of August. The temperature differences between the surface and the 100 m depth (dT(100m)) represent the relative strength of the stratifications in the depth region where most designs plan to discharge the warm and cold water. The temperature differences between surface and the 500 m depth (dT(500m)) represent the available thermal resource. The fourth column gives the respective sea surface temperature (SST) lowerings, dT(s). With this particular design, the perturbations are proportional to the temperature contrast dT(100m). Since the discharge water is a fixed 5°F cooler than the surface water, a steeper temperature

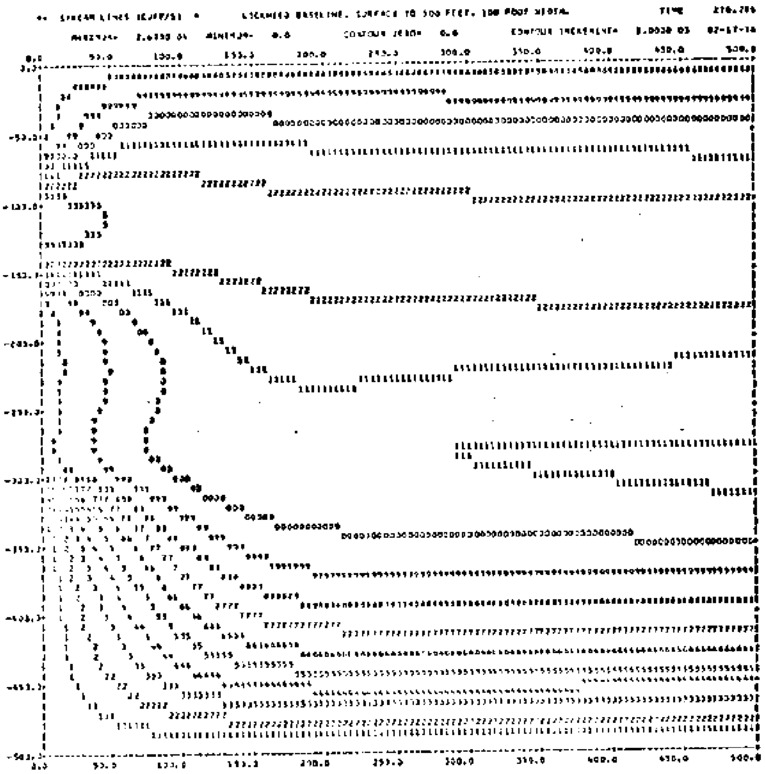


Fig. 4. STREAMLINES OF LOCKHEED BASELINE PLANT: Fr = 1.8.

TABLE II

OCEAN SURFACE PERTURBATION DUE TO DESIGN No. 2

August - in degrees Fahrenheit (°F)

Region	dT(100m)	dT(500m)	dT(surface)	Location
1	21	34	.20	West of Africa
2	16	33	.15	South Central Atlantic
3	7	29	.067	Caribbean and eastward
4	5	29	.048	Eastern Gulf, Cuba - Florida Straits
5	16	33	.15	Gulf
6	11	17	.11	East of Gulf Str., latit. Fla. - S.C.
7	9	29	.086	Gulf Stream
8	20	37	.19	Gulf Stream - Shore
11	9	21	.086	West of Africa

dT(100m) = temperature difference between surface and 100 m depth
dT(500m) = " " " " " 500 m depth
dT(surf) = sea surface temperature (SST) lowering due to plant operation

gradient implies that the buoyancy of the discharge will be either positive or less negative, and stronger recirculation and upwelling will take place. The discharge jet entrains cooler fluid near its exit from the plant, and despite a stronger suppression of vertical motions due to the stronger stratification, brings cooler fluid parcels to the surface. Mathematically, it can be seen as follows: the effect of stratification is such that for strong stratification the term responsible for loss of turbulence to entrainment across density surfaces (and thus potential energy generation), $-KN^2$ in equation (3), goes to $-q^{3/2}/Lc_s$ (see relation (5) for large N). Thus the process becomes independent of N. On the other hand, the temperature of the fluid particles that reach the surface is $T(s) \sim T(e).\exp(-\gamma d)$, where $T(e)$ is the temperature of the discharge water after entraining double or more of its mass, $\gamma = K/\overline{w}$ with $\vec{w}$ the average upwelling velocity, and d the depth of the discharge. Thus the relation $dT(s) \sim T(e)$ becomes plausible.

Table III summarizes the results for various designs and Froude number ranges; the average values of dT(s) over the indicated Froude number range is given. In general, the resultant SST depression is a function of the discharge configuration (warm over cold, etc.), the cold water discharge temperature, and the stratification present in the top 100 m of the ocean. The cold over warm discharge configuration results in a consistently larger SST depression for both Froude number ranges. Typically, in the range $.5 \leq Fr \leq 1.5$ the SST depression is $\sim .25^\circ$F in August and $\sim .08^\circ$F in February, whereas in the range $2 \leq Fr \leq 8$ the cooling is $\sim 2^\circ$F in August and $\sim .50^\circ$F in February. Again, the larger stratifications in August result in larger SST depressions than in February, and can be explained by the above argument. Similarly, the stronger SST depressions associated with cold over warm discharges fall in line with the observed $dT(s) \sim T(e)$ rule. Finally, the large SST depressions associated with the high Froude number range are due to the stronger recirculation and stronger turbulence intensity produced by the stronger source-sink flow.

Air-sea heat flux perturbations

The operation of one or more OTPP's in a given geographical region has been shown to produce a reduction in ocean surface temperatures in that region. Furthermore, horizontal ocean currents and turbulence can disperse the effects to distances beyond the region, and the cumulative effect may cause a slight alteration in the regional climate. It is important to demonstrate that the areal extent and magnitude of any alteration is within acceptable limits.

It is interesting to note that the far-field rate of recovery of the ocean toward its undisturbed thermal structure is also determined by the area and magnitude of sea surface temperature lowering. It has been observed experimentally, and is predictable from theoretical calculations, that a lowering of the sea surface temperature generally leads to an increased heat flow from air into the water. This is because the process most susceptible to change, evaporation, responds to a sea surface temperature lowering by decreasing the heat flux from the water to the air.

An OTPP extracts heat at a rate ≃ 50 times its power output (2% efficiency) from the warm surface waters of the ocean passing through its evaporators. Unless the ocean replenishes the extracted heat at a sufficiently rapid rate over the area affected by the intake motions, the available temperature contrast and thermal resource entering the plant will be continuously reduced, at least in the absence of a current. Furthermore, the impact of the engine on the surface temperatures and the marine atmospheric boundary layer will be continuously enhanced. In this study we performed specific heat flux perturbations due to SST depressions caused by OTPP operations. The sea surface temperature perturbations were taken from the result of the near-field hydrodynamic calculations. By calculating the integrated heat-flux effect over the whole area affected by the intake motions, an estimate has been made for the areal requirement for thermal resource of an OTPP. The sea surface temperature T_s acts somewhat as a feedback mechanism for regulating the heat budget of the upper ocean. Both the latent heat flux and the sensible heat flux depend upon the air-sea temperature difference, decreasing the net heat flux from air to water as T_s decreases. Thus, neglecting heat storage due to seasonal temperature variations which are small in the tropical regions considered for OTPP operation, T_s tends to be maintained at a value such that the

TABLE III

		1	2	3	4
Caribbean and East	Aug	.12	.11	.92	.64
	Feb	.051	.045	.39	.28
Gulf	A	.27	.24	2.10	1.48
	F	.085	.075	.66	.46
Gulf Stream to Shore	A	.34	.30	2.62	1.84
	F	.10	.09	.79	.55

Maximum Surface Temperature Perturbation Near Engine (in °F)

Design 1: cold over warm discharge, low Froude number $.5 \leq Fr \leq 1.5$
Design 2: warm over cold discharge, low Froude number "
Design 3: cold over warm discharge, high Froude number $2.0 \leq Fr \leq 8.0$
Design 4: warm over cold discharge, high Froude number "

surface heat flux Q just balances the heat carried away by horizontal advection and diffusion. If, for example, more heat is added to the upper ocean than is being carried away by advection and diffusion, T_s increases, decreasing the surface heat flux and driving T_s down toward its equilibrium value.

Major departures from the mean value of T_s can be caused by storms and hurricanes which can lower the sea surface temperature several degrees due to upwelling, evaporation and downward mixing. Leipper (1967) noted on a cruise that the Gulf of Mexico waters had returned to normal two months after passage of hurricane Hilda had lowered the sea surface temperature up to 5° C.

The speed with which T_s returns to its equilibrium value after being perturbed depends upon the rate of change of Q with T_s, dQ/dT_s, etc. Bathen et al.[6] (1975) analysed the oceanic heat budget off Keahole Point, Hawaii, a proposed OTPP site, using bulk aerodynamic formulas and local meteorological data to determine surface heat fluxes. They repeated the budget calculations with a postulated .67° C sea surface temperature decrease assumed to simulate OTPP operation, and found a net increase in surface heat flux of 40 - 50 cal/cm^2-day. Thus, the rate of change of Q with T_s was 60 - 75 cal/cm^2-day-°C.

Although we were unable to repeat the calculations of Bathen et al. due to the lack of meteorological data, a similar prediction of the change in surface heat flux with T_s was made for a proposed site off the SE coast of Puerto Rico at 17.5°N, 67.5°W. Heat fluxes were estimated using the bulk formulas detailed in Laevastu[8], and the meteorological data were taken from Atwood[9]. The heat budgets, calculated for each month and averaged to obtain a yearly mean, are listed in Table IV, along with values of other important meteorological parameters.

The uncertainty of the value for the net solar radiation is not known. Bathen et al[7] have reported that a solar radiation formula obtained from Wyrtki[10] allowed for a much greater correction for cloud cover than Laevastu's formula used here and predicted solar radiation levels about 20% lower. Bathen notes that the type of cloud cover as well as the extent of the cover may govern the intensity of solar radiation of the sea surface.

Recently published estimates of the drag coefficient for latent heat loss vary within a range ± 20%. Thus, allowing for an uncertainty of 15% in windspeed and humidity values, the uncertainty of the latent heat loss is about 30%.

A Bowen ratio of .1 was used to estimate the sensible heat flux. Based on the uncertainty regarding the latent heat flux and the Bowen ratio, the uncertainty of the sensible heat loss may be 40% or more.

Due to the fairly large uncertainties regarding the components of the net heat flux, not much can be

PUERTO RICO DATA. ALL AVE VALUES ARE AVERAGED OVER THE 12 MONTHS.

SEA SURFACE TEMPERATURE LOWERED 0.0 DEG C FROM OBSERVED VALUE

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVE
NOON SUN ANGLE (DEG)	49.	57.	68.	79.	88.	93.	91.	84.	72.	62.	52.	47.	70.
LENGTH OF DAY (MIN)	672.	695.	721.	757.	778.	790.	785.	764.	734.	705.	679.	665.	729.
MEAN CLOUDINESS IN TENTHS	0.33	0.34	0.30	0.36	0.41	0.43	0.42	0.32	0.37	0.36	0.37	0.34	0.36
AIR TEMP IN DEG C	25.0	25.0	25.0	25.6	26.7	27.2	27.2	27.8	27.8	27.2	27.2	25.6	26.4
WATER TEMP IN DEG C	25.6	25.5	25.6	26.1	27.2	27.8	27.8	28.3	28.3	28.3	27.8	26.7	27.1
AIR PRESS IN MB	1019.	1018.	1017.	1017.	1017.	1017.	1018.	1017.	1016.	1016.	1017.	1017.	1017.
MEAN WIND CM/SEC	935.	895.	815.	740.	740.	740.	735.	735.	735.	730.	730.	730.	772.
VAPOR PRESS MB	24.334	24.334	24.507	25.349	27.130	28.364	28.069	29.038	29.036	28.067	28.069	25.349	26.808
SPECIFIC HUMIDITY AIR	0.01511	0.01511	0.01513	0.01565	0.01675	0.01735	0.01733	0.01795	0.01797	0.01736	0.01735	0.01565	0.01656
SPECIFIC HUMIDITY SURF	0.02034	0.02034	0.02036	0.02107	0.02256	0.02334	0.02332	0.02415	0.02417	0.02417	0.02334	0.02180	0.02241
INCIDENT RADIATION	425.	512.	646.	728.	732.	731.	730.	748.	671.	556.	449.	404.	611.
REFLECTED RADIATION	-46.	-51.	-55.	-56.	-56.	-56.	-56.	-56.	-56.	-52.	-47.	-44.	-53.
NET SOLAR RADIATION	379.	461.	591.	672.	676.	675.	674.	692.	615.	503.	401.	360.	558.
BACK RADIATION	-126.	-126.	-129.	-122.	-115.	-111.	-111.	-112.	-111.	-122.	-114.	-131.	-119.
EVAPORATIVE HEAT LOSS	-340.	-340.	-341.	-294.	-315.	-325.	-323.	-334.	-334.	-364.	-321.	-329.	-330.
SENSIBLE HEAT LOSS	-34.	-34.	-34.	-29.	-31.	-33.	-32.	-33.	-33.	-36.	-32.	-33.	-33.
NET HEATING OF OCEAN	-121.	-39.	88.	226.	215.	206.	208.	212.	137.	-19.	-66.	-134.	76.

TABLE IV

An estimate of the sea surface heat fluxes for the ocean thermal power plant site SE of Puerto Rico. The heat fluxes were calculated for each month and the monthly values were averaged to obtain the yearly mean values. The heat fluxes are in units of cal/cm^2-day.

said about the accuracy of the net heat flux itself. However, we are here more interested in the components of the net heat flux that are strongly affected by changes in the sea surface temperature. Table V shows the heat budget estimation for Puerto Rico repeated with the sea surface temperature lowered in increments of .5° C from 0 to 1 from its observed value. It was assumed that the air temperature well above the sea surface was not affected by the local change in the sea surface temperature.

Table V shows a fairly linear change of sea surface heat flux with sea surface temperature of ~ 96 cal/cm^2-day-°C. For small temperature changes of less than a few degrees centigrade, the back radiation and latent and sensible heat flux vary almost linearly with sea surface temperature.

Most of the change in the surface heat flux, almost 80%, is due to a decrease in the evaporative heat loss. And if the Bowen ratio R is used to estimate the sensible heat loss, the bulk formula for latent heat loss effectively models about 85% of the change in surface heat flux with sea surface temperature.

TABLE V

ESTIMATE OF THE CHANGES IN SEA SURFACE HEAT FLUX WITH INCREASE IN SEA SURFACE TEMPERATURE AT PUERTO RICO OTPP SITE

Decrease of T_s from ambient value		0° C	.5° C	1.0° C
Net solar radiation (cal/cm^2-day)		558	558	558
Back radiation	"	-119	-112	-105
Latent heat loss	"	-330	-292	-255
Sensible heat loss	"	-33	-29	-26
Net surface heat flux	"	76	125	172

Note: positive heat flux means flow from air into water

References:

1. Mellor,G.L.,Yamada,T. "A Hierarchy of Turbulence Closure Models for Planetary Boundary Layers", J. Atmos. Sci. 31, p.1791, 1974.
2. Lewellen,W.S.,Teske,M. "Prediction of the Monin-Obukhov Similarity Functions from an Invariant Model of Turbulence", J. Atmos. Sci. 30, p.1340, 1973.
3. Lewellen,W.S. et al. "Invariant Modeling of Turbulence and Diffusion in the Planetary Boundary Layer", ARAP Rep. 225, Aeronautical Research Associates of Princeton, N.J., 1974.
4. Douglass,R. et al. "Ocean Thermal Energy Conversion: An Engineering Evaluation". Third Annual OTEC Workshop Proc., Houston, May 1975.
5. Trimble,L. et al. Third Annual OTEC Workshop Proc., Houston, May 1975.
6. Leipper,D.F. "Observed Ocean Conditions and Hurricane Hilda", J. Atmos. Sci. 24, p. 182, 1967.
7. Bathen,K.H. et al. "A further evaluation of the oceanographic conditions found off Keahole Point, Hawaii, and the environmental impact of nearshore OTEC plants on subtropical Hawaiian waters. Final report to Dep't of Planning and Economic Devel. of State of Hawaii, Dep't of Ocean Engin., Univ. of Hawaii.
8. Laevastu, T., "Factors affecting the temperature of the surface layer of the sea". Soc. Scient. Fennica, Comm. Phys. Mat. 25, p.1, 1960.
9. Atwood,D.K. et al. "Ocean Thermal Energy Conversion: Resource Assessment and Environmental Impact for Proposed Puerto Rico Site. Interim Report, NSF Grant No. AER 75-00145, Dep't of Marine Sciences, Univ. of Puerto Rico, Mayaguez.
10. Wyrtki,K. "Seasonal Variation of Heat Exchange and Surface Temperature in the North Pacific Ocean. Report No. 66-3, Hawaii Institute of Geophysics, University of Hawaii.

OCEAN TEMPERATURES OFF OUR SOUTHEAST COAST AND THEIR SEASONAL FLUCTUATIONS AS PERTINENT TO OCEAN THERMAL PLANTS

By

Fred M. Vukovich
and
James J. B. Worth
Research Triangle Institute
Research Triangle Park
North Carolina 27709

Abstract

It has been shown that ΔT's as large as 25°C can be obtained off the southeast coast of the United States, depending on the lower reference depths used. It has been suggested that ocean thermal systems be located off the shelf break since large ΔT's can be obtained in smaller depth intervals. Based on available data, it appears that the cold water pipe associated with the ocean thermal systems should extend to the depth interval of 400 to 600 m, depending on the required ΔT. Further extension will not increase the ΔT appreciably.

Even though it appears from average or representative data that a ΔT favorable for ocean thermal systems can be found off the southeast coast of the United States and in the Gulf Stream, it has been shown that perturbations produced the western and eastern boundaries of the Gulf Stream can profoundly change the value of ΔT. Therefore, it is critical to the operation of ocean thermal system that they be cited in regions where such factors are minimized. From the present state of knowledge of the Gulf Stream and its dynamics, it appears that the perturbations described in this paper can be the controlling influence on the economics of operation of an ocean thermal system.

1.0 The ΔT Distribution from Vertical Cross-Section Data

The purpose of this paper is to describe the vertical structure of temperature and its variation off the southeast coast of the United States as it pertains to ocean thermal systems. In an attempt to describe seasonal variations of the vertical temperature distribution off the coast, two sets of data are presented. These data are vertical cross-sections obtained in two to six-day periods in each of the four seasons. They are not mean data, but can be considered representative seasonal data.

The first set of cross-sections (Figures 1 through 4) are based on data collected by Iselin (1936). These particular cross-sections were obtained from data collected along the line from Montauk Point, New York to Bermuda. It is important to note that large vertical temperature differences (from hereon vertical temperature differences will be referred to as ΔT) can be obtained in relatively shallower water off the shelf break than further out into the open ocean. For example, using the summer cross-section (Figure 1), a ΔT of approximately 20°C can be obtained in the first 400 m off the shelf break. However, in order to obtain the same ΔT further out requires a depth of 1100 m, almost three times that at the shelf break.

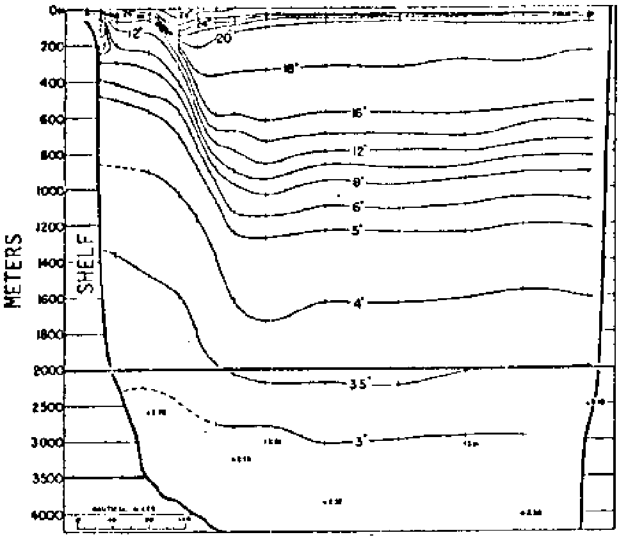


Figure 1. Vertical temperature cross-section established from data collected along a line from Montauk Point, New York to Bermuda from 28 August to 3 September 1932 (Iselin, 1936).

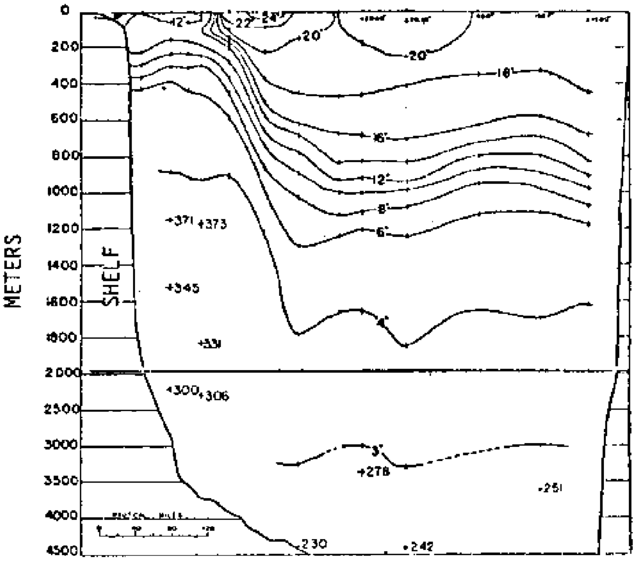


Figure 3. Vertical temperature cross-section established from data collected along a line from Montauk Point, New York to Bermuda from 11 to 18 February 1932 (Iselin, 1936).

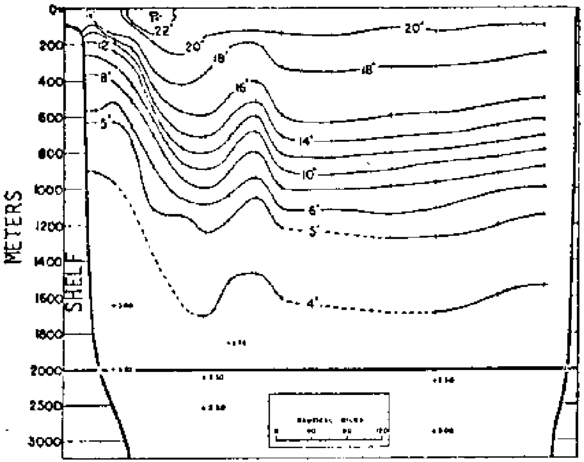


Figure 2. Vertical temperature cross-section established from data collected along a line from Montauk Point, New York to Bermuda from 30 November to 5 December 1932 (Iselin, 1936).

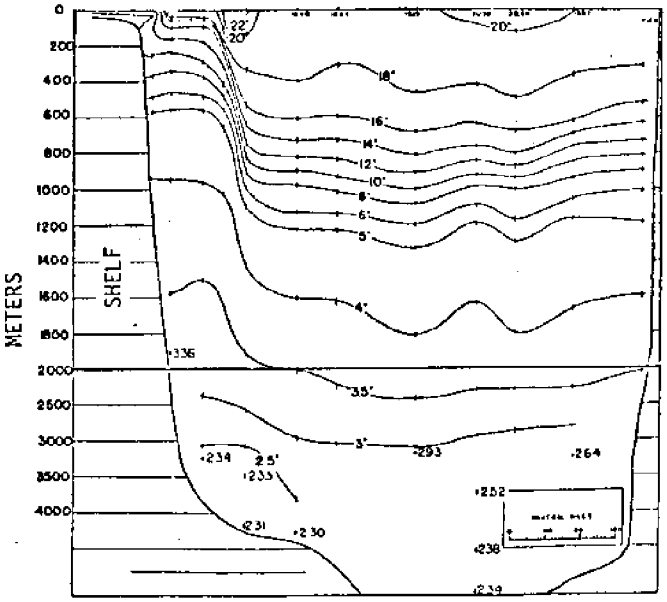


Figure 4. Vertical temperature cross-section established from data collected along a line from Montauk Point, New York to Bermuda from 17 to 23 April 1932 (Iselin, 1936).

The data in Figures 1-4 indicate that if the ΔT in the first 3000 m is used as a base, on the average approximately 95 percent of the 3000 m ΔT is manifested in the first 1000 m and somewhere between 85 and 90 percent of the 3000 m ΔT is manifested in the depth range 400 to 600 m. These data suggest that in terms of ocean thermal systems that there is no significant gain in ΔT by having systems which go much deeper than 500 m.

Table 1 summarizes the seasonal variation of ΔT in the first 400 m off the shelf break. The table indicates that the maximum ΔT is attained in the summer and the minimum ΔT is found in the spring.

There is an interesting point that must be made at this time. It should be noted that the temperature off the shelf break at the 900-m level remains fairly stable from season to season. The value of temperature at the 900-m level was 4°C. This factor will be employed later.

Figures 5 through 8 give vertical temperature cross-sections obtained off the North Carolina coast from Raleigh Bay out into the Gulf Stream. These temperature cross-sections, however, only represent the

Table 1. Seasonal variation of ΔT in the first 400 m off the shelf break derived from Iselin's data (1936).

Season	ΔT (°C)
Summer	20
Fall	19
Winter	14
Spring	12

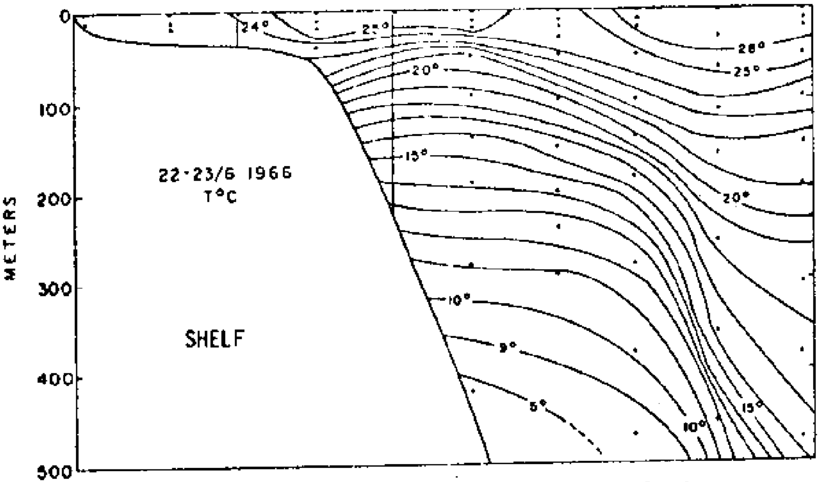


Figure 5. Vertical temperature cross-section established from later collected off Raleigh Bay, North Carolina in the summer 1966 (Stefansson et al., 1971).

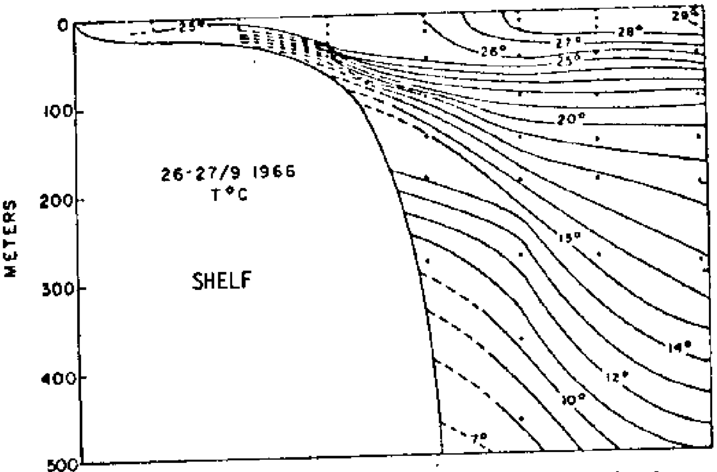


Figure 6. Vertical temperature cross-section established from later collected off Raleigh Bay, North Carolina in the fall 1966 (Stefansson et al., 1971).

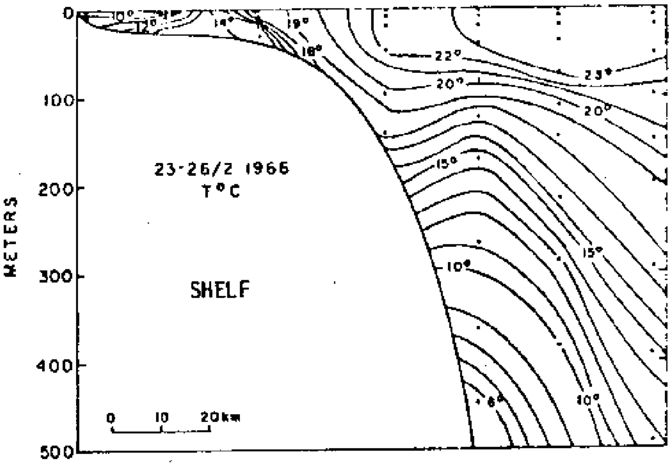


Figure 7. Vertical temperature cross-section established from later collected off Raleigh Bay, North Carolina in the winter 1966 (Stefansson et al., 1971).

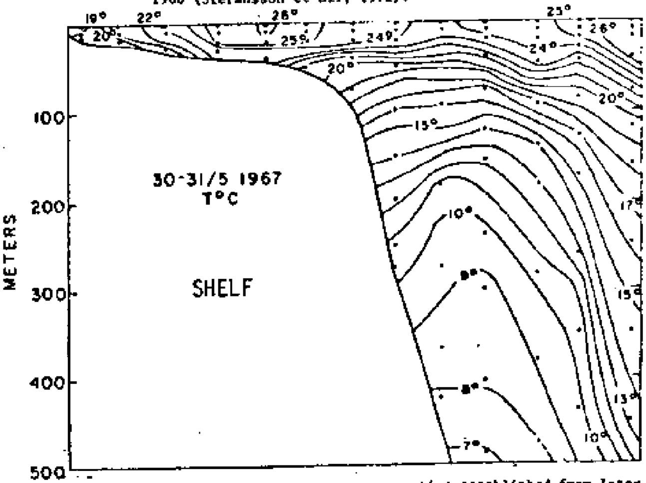


Figure 8. Vertical temperature cross-section established from later collected off Raleigh Bay, North Carolina in the spring 1966 (Stefansson et al., 1971).

first 500 m of depth. The data were collected by the Stefansson et al. (1971). As in the previous case, they were collected over a number of days in each season and can be considered representative seasonal data rather than average data.

Table 2 summarizes the seasonal distribution of ΔT in the first 400 m off the shelf break. As in the case of Iselin's data, these data indicate a maximum ΔT in the summer and a minimum ΔT in the spring.

2.0 Spatial Distribution of ΔT

The data presented in the previous section yield a value of ΔT seasonally at two locations off the shelf break. In order to obtain estimates of the spatial distribution of ΔT off the southeast coast, average sea-surface temperature distributions were employed along with the assumption that the temperature at the 900-m level was constant and had an approximate value of 4^0C. The assumption was derived from discussions in the previous section. Figures 9 through 12 yield the average sea-surface temperature distribution for each season off the southeast coast of the United States (Schroeder, 1966). Based on the 4^0C temperature at the 900 m level and these sea-surface temperature values, the following spatial distribution of ΔT were derived. In the summer ΔT would vary from 24^0 off the coast of the Carolinas to 25^0 off the coast of Florida and Georgia; in the fall, 21^0 off the coast of the Carolinas to 22^0 off the coast of Florida and Georgia; in the winter, 18^0 off the coast of the Carolinas to 20^0 off the coast of Florida and Georgia; and in the spring, 21^0 off the coast of the Carolinas to 22^0 off the Georgia and Florida coast. These data suggest the minimum value of ΔT can be found in the winter months and the maximum value can be found in the summer months. Differences between these data and the data presented in the previous section may be attributed to the fact that in this section we are dealing with average data and in the previous section with representative date. However, there also is a possibility that these differences may be a result of using different reference depths (in the previous section 400 m were used and in this section 900 m were used).

One other important factor should be pointed out concerning Figures 9 through 12. Inspections of these figures will show that the horizontal gradients in temperature between the Gulf Stream and the near-shore

Table 2. Seasonal distribution of ΔT in the first 400 m of the shelf break from the data derived by Stefansson et al. (1971).

Season	ΔT (°C)
Summer	20
Fall	19
Winter	17
Spring	15

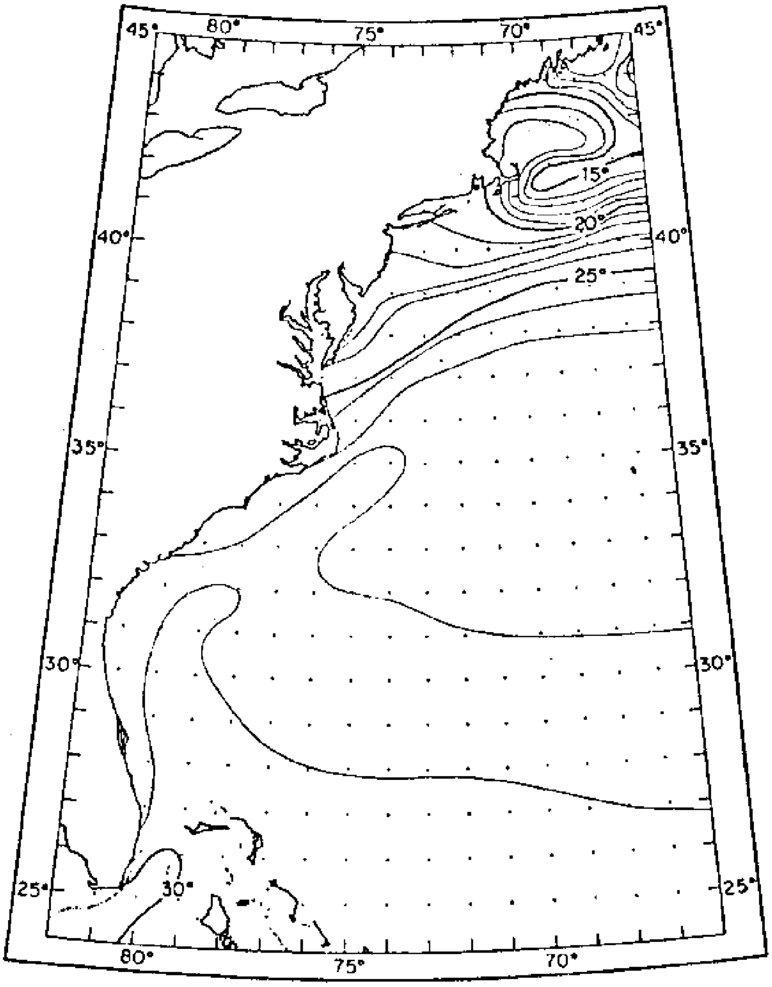


Figure 9. Average sea-surface temperatures off the southeast coast of the United States for summer (Schroeder, 1966).

Figure 10. Average sea-surface temperatures off the southeast coast of the United States for fall (Schroeder, 1966).

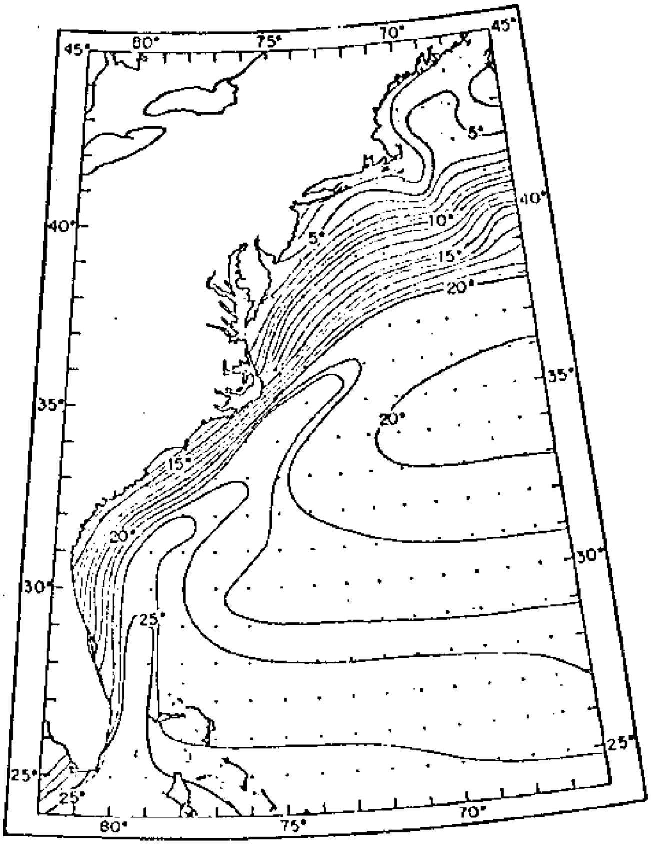


Figure 11. Average sea-surface temperatures off the southeast coast of the United States for winter (Schroeder, 1966).

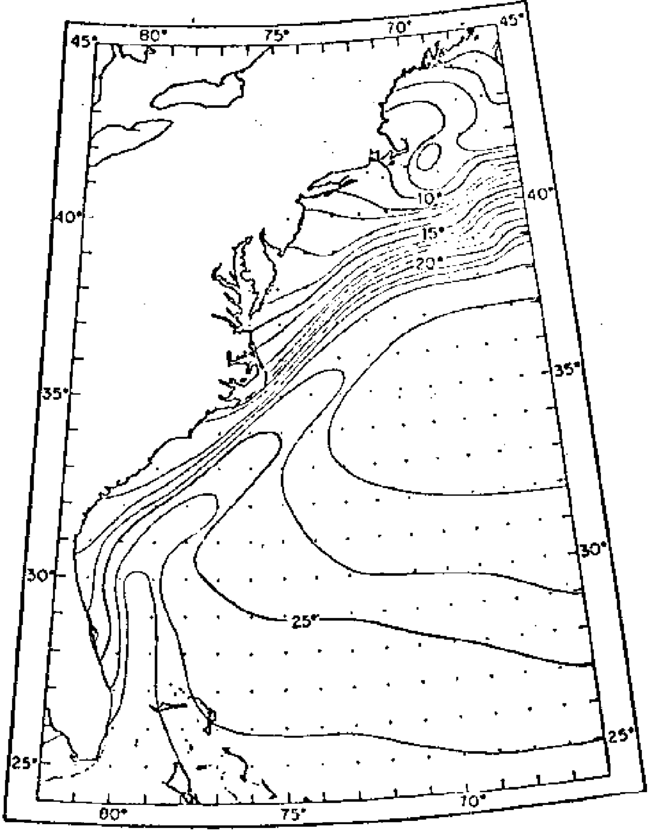


Figure 12. Average sea-surface temperatures off the southeast coast of the United States for spring (Schroeder, 1966).

water off the southeast coast of the United States is approximately 1 to 2°C in the summer; 8°C in the fall; 10°C in the winter; and 5°C in the spring. The importance of this factor will be demonstrated in the next section.

3.0 Perturbations in the Gulf Stream and its Affect on the ΔT Distribution

In the previous sections, data were presented on the distribution of ΔT. These distributions were established from either a representative or average data base. The problem with using this data base is that the Gulf Stream is seldom in a representative nor an average state. The Gulf Stream is a jet which undergoes all the instabilities which are normally subjected to such systems. Instabilities may be manifested by the fact that the flow is in the β-plane; that is, on a rotating earth. Other instabilities may be manifested by the fact that weather systems (a major forcing function of currents in the ocean) vary markedly in time and in space. It has been shown that such variations can produce marked accelerations in the Gulf Stream. Furthermore, changes in bottom topography can manifest perturbations in the Gulf Stream also. It has been shown that the Blake Plateau can compress the vertical shear of the Gulf Stream currents, thus producing concentrated zones of available potential energy which are rapidly converted into kinetic energy. Large accelerations and currents which deviate from the normal currents found in the Gulf Stream are a result of the energy conversion. The perturbations produced by the forcing functions mentioned above can have a profound influence on the variations of ΔT off the southeast coast of the United States.

Figure 13 is an infrared photograph of the coastal area off the southeast coast of the United States obtained from the NOAA-4 satellite in April 1975. Since this is an infrared picture, the gray scale representation is a function of temperature with black indicating warm temperature and white indicating cold temperature. Of particular interest is a cold tongue of water off Cape Romain which extends to the central core of the Gulf Stream. The north-south dimension of the cold tongue is approximately 500 km. The east-west dimension ranges from approximately 100 km near the origin at the shelf to approximately 10 km at its northern tip. It

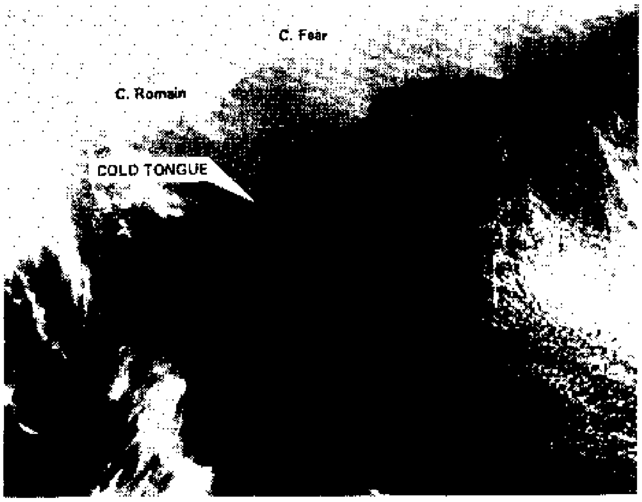


Figure 13. NOAA-4 infrared photograph off the southeast coast of the United States obtained in April 1975.

has been shown that in the spring, which is the period in which the photograph is taken, the ΔT off the southeast coast of the United States in the first 400 m is approximately 15°C, and that, on the average, the surface shelf water has a temperature approximately 5°C lower than the surface Gulf Stream water. If an ocean thermal system was located in the Gulf Stream in the region where this perturbation is now pumping cold shelf water into the Gulf Stream, the ΔT in that region can be reduced by approximately 5°C; that is, the ΔT in the spring which is normally 15° can be reduced to 10°C.

Figure 14 is an infrared photograph off the southeast coast of the United States from NOAA-4 in early March 1975. This can be considered a winter case. In the winter, the average ΔT off the Carolina coast is approximately 17°C and the surface shelf water has a temperature approximately 10° lower than the Gulf Stream. Of interest in this figure is the tongue of cold water originating from the shelf just south of Cape Romain and extending approximately 300 km to the north. As in the previous case, if an ocean thermal system were located in the region where this perturbation is now pumping cold shelf water into the Gulf Stream, the winter ΔT could be lowered by 10°C reducing it to 7°C.

Figure 15 is an infrared photograph off the southeast coast of the United States from NOAA-4 in late March 1975. This, too, can be considered a winter case in which the ΔT off the Carolina coast is approximately 17°C in the first 400 m and the horizontal temperature differences between the shelf water and the Gulf Stream at the surface is approximately 10°C. Note the cold tongue off Cape Romain and the cold bulge off Cape Lookout. It is believed that this picture describes the initial stages of development of two of the types of perturbations described in previous figures. As in the previous case, the winter ΔT can be reduced by approximately 10°C due to the transport of the cold shelf water.

Figure 16 demonstrates the great variability that can be manifested in or near the Gulf Stream. The figure is an SMS GOES infrared photograph, and shows an eddy similar to those described in the last three figures east of Long Bay. There are also two cold eddies found on the eastern side of the Gulf Stream, east of Florida. These cold eddies

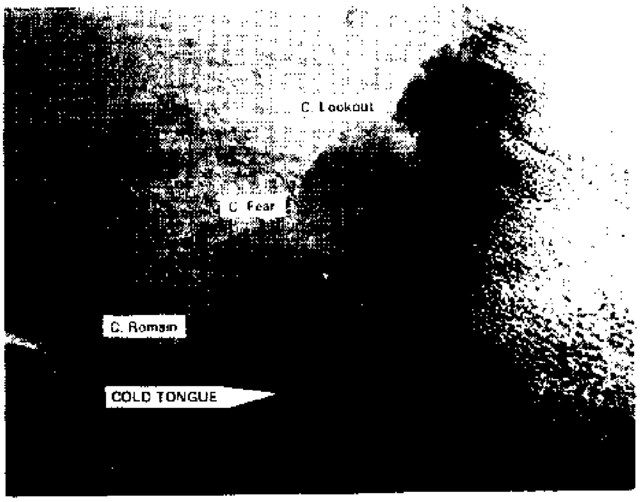


Figure 14. NOAA-4 infrared photograph off the southeast coast of the United States obtained in early March 1975.

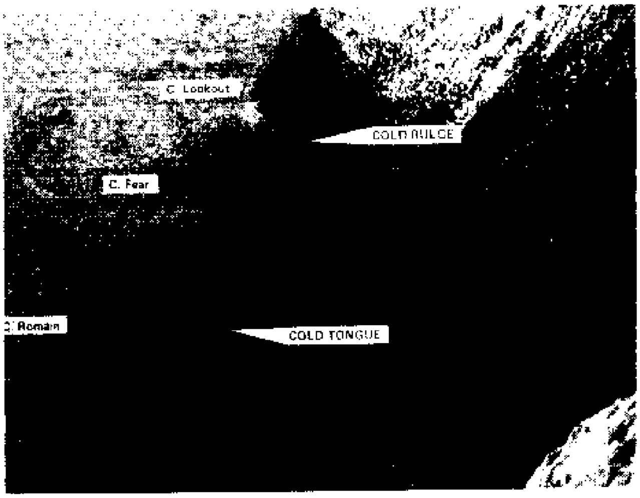


Figure 15. NOAA-4 infrared photograph off the southeast coast of the United States obtained in late March 1975.

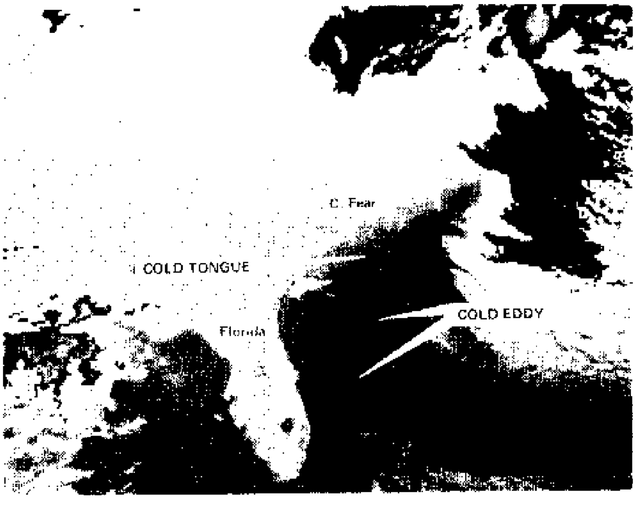


Figure 16. SMS GOES infrared photograph off the southeast coast of the United States obtained in April 1975.

can reduce the surface temperature approximately 10°C. However, they may not reduce the ΔT as much as the perturbations found on the western boundary of the Gulf Stream due to the fact that the cold eddies have deep vertical extent (approximately 1500 m).

4.0 Conclusions

It has been shown that ΔT's as large as 25°C can be obtained off the southeast coast of the United States, depending on the lower reference depths used. It has been suggested that ocean thermal systems be located off the shelf break since large ΔT's can be obtained in smaller depth intervals. Based on available data, it appears that the cold water pipe associated with the ocean thermal systems should extend to the depth interval of 400 to 600 m, depending on the required ΔT. Further extension will not increase the ΔT appreciably.

Even though it appears from average or representative data that a ΔT favorable for ocean thermal systems can be found off the southeast coast of the United States and in the Gulf Stream, it has been shown that perturbations produced the western and eastern boundaries of the Gulf Stream can profoundly change the value of ΔT. Therefore, it is critical to the operation of ocean thermal system that they by cited in regions where such factors are minimized. From the present state of knowledge of the Gulf Stream and its dynamics, it appears that the perturbations described in this paper can be the controlling influence on the economics of operation of an ocean thermal system.

REFERENCES

1. Iselin, C., 1936: "A Study of the Circulation of Western North Atlantic", Papers in Physical Oceanography and Meteorology, Vol. 4, No. 4, 101 pp.

2. Stefansson, U., L. Atkinson, and D. Bumpus, 1971: "Hydrographic Properties and Circulation off the North Carolina Shelf and Slope Waters", Deep Sea Research, Vol. 18, pp. 383-420.

3. Schroeder, E., 1966: "Average Sea-Surface Temperatures Off the Western North Atlantic", Bulletin of Marine Science, Vol. 16, pp. 302-323.

A GULF STREAM BASED OCEAN THERMAL DIFFERENCES POWER PLANT

William E. Heronemus, Professor of Civil Engineering
University of Massachusetts (Amherst)
for the U.Mass Energy Alternatives Team

Abstract

The significance of the Gulf Stream Ocean Thermal Difference Power Plant to the energy market of the contiguous 48 states is discussed. The controlling characteristics of the Site are enumerated and a macro examination of the size and quality of the resource is made. Then an examination of daily fluctuations in the resource is made, and the significance of the U.Mass OFF-DESIGN power plant studies is demonstrated. The general features of U.Mass power plant configurations proposed for the Gulf Stream Site are enumerated together with a more specific examination of Site controlled design characteristics. The general features and certain specific details of the more recent U.Mass power plant are then illustrated in a series of figures. The essentiality of a total systems approach by a large enough team of experts whose efforts are orchestrated and controlled by a bonafide ocean engineer is woven throughout the paper, obvious to those who understand the ancient art of ship design and construction, but probably invisible to those lacking that sobering experience.

1. Introduction

This paper bears the name of Heronemus, but it really is based on the work of a team of ten professors and almost forty students as of January 1976. The grasp of the ocean thermal differences process, held by the University of Massachusetts research team is a team grasp which permits a broad integrated system usage of the more narrow sharply-honed competence of each of its subsystem experts. From the original desire to pursue this subject in 1969 it has always been a mixture of mechanical, civil and ocean engineering, a blend of heat transfer, hydraulics, physical oceanography, naval architecture, marine engineering, machine design, structures and materials engineering. One man can attempt to "manage" all of that, but no one man can pretend that he is an expert in all those fields. The U.Mass team has always been generous enough to assist the manager in his attempt to understand all, but charitable in their knowledge that he could not.

A Gulf Stream Ocean Thermal Differences Power Plant is a many-splendored thing. It is first of all a site, or rather a large but discrete area of sites. It is a creature of the sea. In our first four versions it is a submersible creature: in the fifth version it will be a surface ship looking from the outside very much like a 1975 very large crude carrier. In the sixth version it will be a relatively small surface ship, a test and trial unit matched to the small minds and pocketbooks of those in charge of our nation's energy destiny who have not yet agreed to the correct, large, test and trial unit.

A Gulf Stream OTEC to us is a fully afloat unit that must ride to an anchor in a relatively strong current and must occasionally take the battering of the most severe of hurricanes. We started off, it seemed, battling everyone else about anchoring in that fearsome current. We knew then, and each additional study has confirmed, that that current is the most magnificent subsystem of the entire OTEC, that which does most of the pumping for free, that which releases us from any concern about thermal gradient destruction.

We still think that a power plant of 400 megawatt electrical is close to an optimum size, and we now can demonstrate how such power plants can be built on shipways or in basins with only 100 feet of beam, 900 feet of length, launching at a launching draft of as few as fifteen feet. We still think steel reinforced concrete is an appropriate hull material, but we have trouble understanding cost estimates of over 300 dollars per cubic yard when we participate daily in the construction of sizeable steel reinforced concrete structures, with complex form work, at 50 to 80 dollars per yard.

For years we have known what the circulating water pumps, both hot and cold, should be like, and have so stated: they should be essentially the opposite of our windmills, and they should cost no more than 100 dollars per kilowatt, complete. We are about ready to demonstrate that number.

We were convinced early on that the heat exchangers should best be one configuration --- J. Hilbert Anderson started us toward that conviction, then our own thorough research into two-phase heat transfer at low temperatures convinced us completely. We've described those heat exchangers over and over in words: we are now ready to demonstrate a full scale mock-up of a portion of such a heat exchanger and also get on with proof of manufacturing processes in a variety of materials.

We were denied funds to investigate an anchor and mooring system, but have managed to do so anyway, and will soon publish a complete analysis and prototype design. Again, cost per kilowatt is very close to our original estimate.

The most significant result, perhaps, of our latest work, is conviction that in collaboration with Pacific Power and Protein, Inc., we have invented a complete solution to any fouling problem that might beset a closed-cycle OTEC: patents have been applied for.

J. Hilbert Anderson convinced us that OTECs could be built at relatively low capital cost. We could never match his low figure, but we came close. We have lived through a year and a half of aerospace OTEC cost estimates and have held our tongues: we hope only that shipbuilders not flying machine or rocket builders will be assigned the responsibility for detailed design and construction of the first OTEC.

We have expanded our knowledge of the hot and cold water resource variations in the proposed Gulf Stream deployment site and have strengthened our conviction that the site is a good and reliable site; but "Site One" has had to be moved one mile east from where it was originally set. We have long accepted the idea that seasonal variation in resource in that deployment area will require some "maneuvering" of the power plant, and are well along with the necessary analysis of those off-design situations and what they should mean to the overall design and machinery detail of a Gulf Stream OTEC.

The Gulf Stream OTEC is a specific OTEC. It will be much more costly than a 40 to 45 F ΔT tropical OTEC. But the Gulf Stream OTEC is very close to a ravenous energy customer, a customer conditioned to pay more and more for electricity or fuel. Tropical OTECS will in time outnumber by orders of magnitude Gulf Stream OTECS, for everything other than electricity or synthetic hydrogen fuel. We intend to be party to those tropical systems, too, in due course.

2. <u>The Gulf Stream OTEC Site and Resource</u>

Peter Mangarella and Robert Kirchhoff have done more than all others to describe and quantify the bountiful magnificance of the Gulf Stream Resource. The <u>Site</u> is still a broad swath about 15 miles west to east astride the axis of the Gulf Stream (itself an imaginary line), extending at least 550 miles south to north from Key Sombrero to abreast Charleston. The first pinpointed site was named "Site One" -- about 17 miles eastward from Miami. "Site Two" is due east of Charleston, and it figures strongly in an OTEC system designed specifically to replace all of the New England electric utilities.

The resource at Site One has been quantified and described in "An Assessment of the Ocean Thermal Energy Potential of the Florida Current" by Peter A. Mangarella, Technical Report NSF/RANN/SE/GI-34979/TR/75/6 of June 1976. Figure (1) locates Site One and the stations of Project Strait Jacket from which our original data were taken. Figure (2) shows the significant inclination of isotherms upward and westward in this region which bring the cold water up into the 600 meter depth range. Figure (3) shows the available power output per unit meter width of the Miami to Bimini Cross Section for different cold water intake depths, with temperature gradient across the evaporator held constant at 1° Centigrade. Figure (4) shows the available power per volume flowrate across the Florida current during various months for a cold water inlet depth of 500 meters and the same 1°C temperature gradient across the evaporator. Figure (4) suggests some significant minimization of power variation with season the closer one gets to the axis of that Gulf Stream.

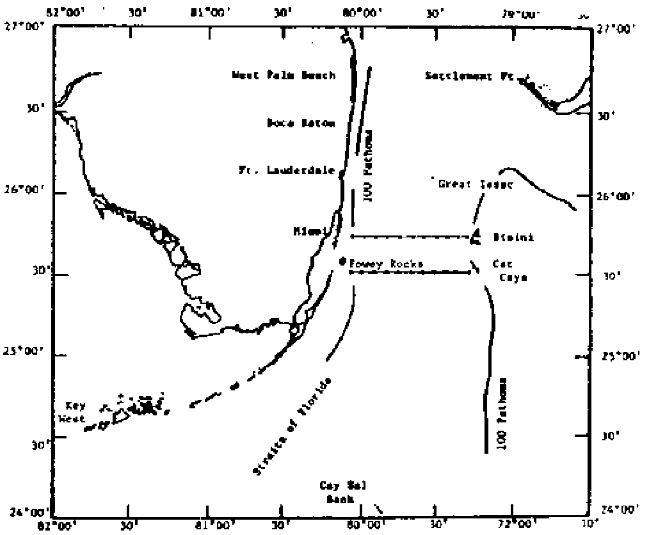


FIG. 1 - Station Locations

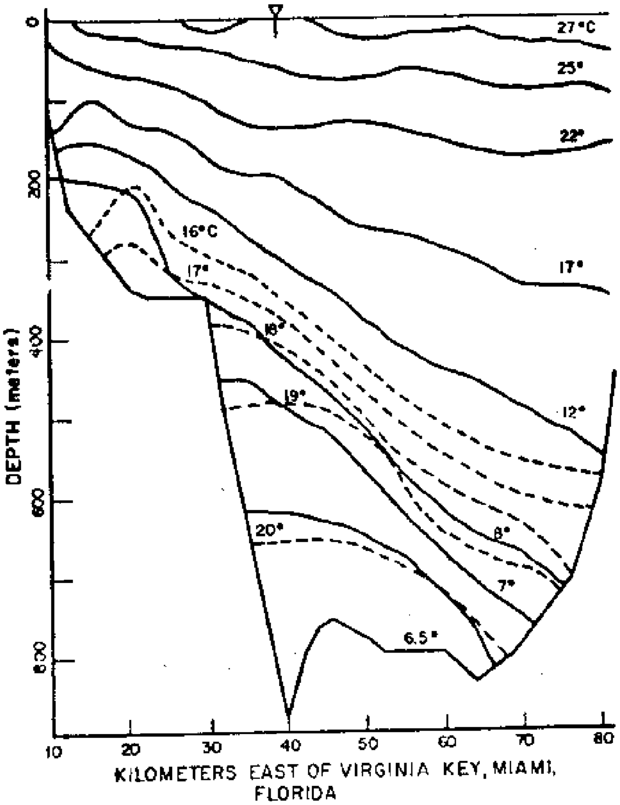


FIGURE 2 ISOTHERMS OF TEMPERATURE (—) AND ΔT (--) REFERENCED TO 30 METER DEPTH FOR CROSS SECTION 19, 18 JUNE 1965

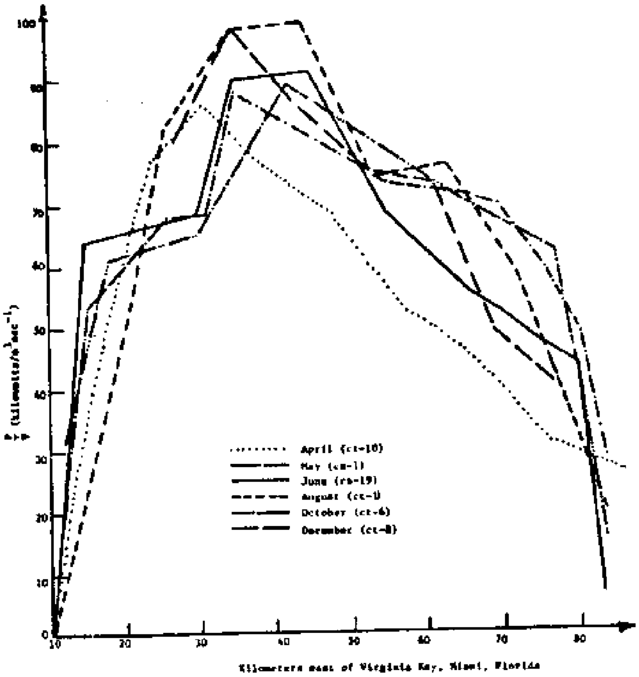


FIG. 4 - Available power per volume flowrate across the Florida Current during various months (ΔT_h = 1°C. Intake depth 500m).

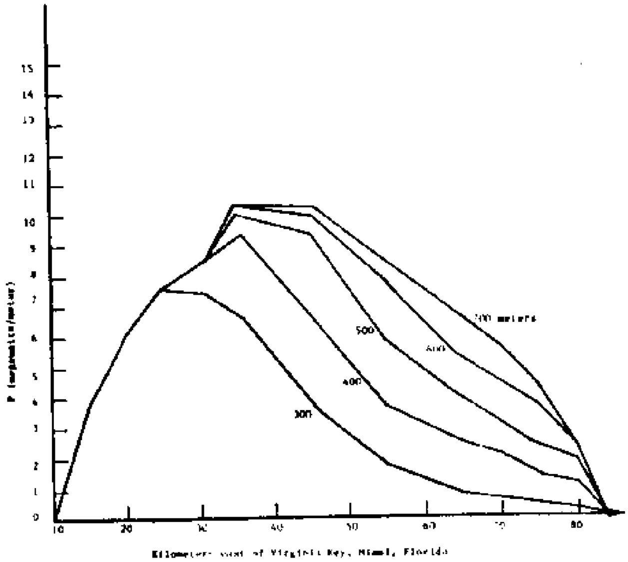


FIG. 5 - Available power output per unit meter width of Cross Section 19 for various intake depths (ΔT_i = 1°C).

From that study and its predecessors, the U.Mass Team, led by Peter Mangarella in this instance, decided that:

(a) If the cold water inlet were run down to 600 meter depth, 30 to 35 km off the Florida coast, seasonal variation would be minimized.

(b) If the entire upper 60 meters of the Current were passed through the evaporators and reduced by 10C while cold water was drawn from only 500 meters depth, 3.6×10^{12} kWh per year could be extracted using OTECs of the U.Mass type.

(c) Since that entire band 60 meters deep could not be passed through a single plane of evaporator entrances, OTECs comprising that total evaporator frontal area could be spread out west to east and south to north and achieve that same result. This confirmed that the resource was large enough to support the earlier concept of as many as 15 south to north columns, with a 400mWe power plant at each 2 mile interval thereon.

(d) With the cold water inlet at 600 meters (or more) the available power would increase to over 4 trillion kWh per year.

(e) The seasonal variation is significant, and the daily variation must be understood well, i.e., Larry Ambs' Off-Design Analysis must proceed to a meaningful conclusion point.

3. The Short-Term Fluctuations in the Gulf Stream OTEC Resource

The work of Walter Duing first seen by us in 1973 (Project SYNOPS) had worried us considerably because it showed significant instability of thermal stratification in the mid waters of the Florida Current. The U.Mass power plant design had decided from the start that the hot water resource would be taken from as close to the surface as practical without encountering near-surface effects, and that the cold water would be taken from as near the bottom as possible without encountering scouring. We settled on a 30 meter average depth of water into evaporators inlets, and, later on, a minimum depth of 600 meters for the cold water inlet.

Dr. Ambs' close-grain analysis was facilitated by NODC data. He chose a data analysis technique whose final result is as close to a daily plot of Hot Water Temperature, Cold Water Temperature and ΔT as we've been able to prepare. (Another technique to complement this is being used by Dr. Mangarella in further analysis of NODC and U.S. Navy data). The preliminary results of Ambs are shown here in advance of his publishing, Figures 5, 6, 7, and 8, to reassure this audience that even the micro-scale data show the Site and the Resource to be excellent and practical of utilization. Figures 5, 6, 7, and 8 all use the 30 meter depth as the evaporator inlet depth, but have different cold water intake depths, 300m, 400m, 500m, and 600m, respectively. Note the significant smoothing out of variability in T,Cold,in, as inlet depth increases.

The need for 600 meters of cold water intake depths is indicated by these four figures. The variability in available ΔT is considerable: Figure (8) shows a ΔT of only 17°C for the entire month of March, and a ΔT of 22°C for August, September and October. The 17°C is one degree lower than our baseline design case whereas the 22°C is 4 degrees larger. If the U.Mass OTEC is to deliver 400mWe net during January, February and March, what will that same plant deliver during late summer and fall? The answers to such questions are the essence of the Off Design Problem: and they will be forthcoming. The baseline configuration may change considerably as a result.

4. Iterations on the Gulf Stream Ocean Thermal Differences Power Plant Configuration

A. The design requirements for a power plant dictated by the Site have not changed much during the four years of investigation except for:

(a) a minimum depth of 600 meters of water rather than 500 meters has now been accepted

(b) surface ship (deep draft) configurations are now thought to be feasible, perhaps even preferrable, to the very deeply submerged semi-

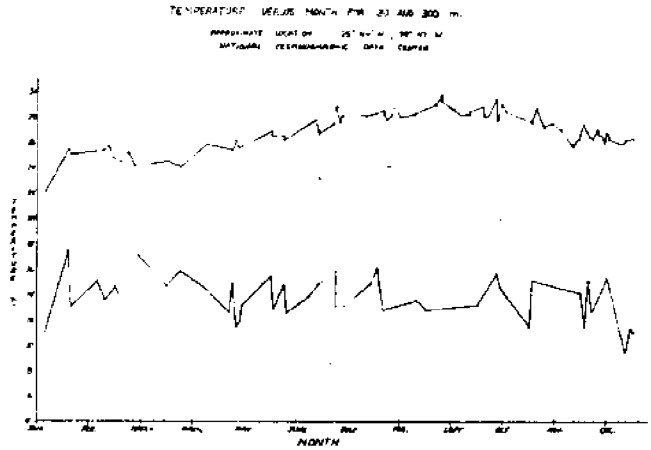


FIG (8)

TEMPERATURE VERSUS MONTH FOR 30 AND 400 m.

APPROXIMATE LOCATION: [illegible]
NATIONAL OCEANOGRAPHIC DATA CENTER

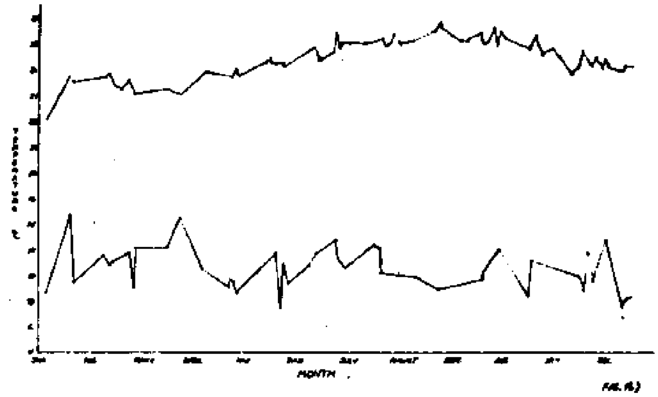


FIG. (6)

TEMPERATURE VERSUS MONTH FOR 30 AND 500 m.

APPROXIMATE LOCATION: [illegible]
NATIONAL OCEANOGRAPHIC DATA CENTER

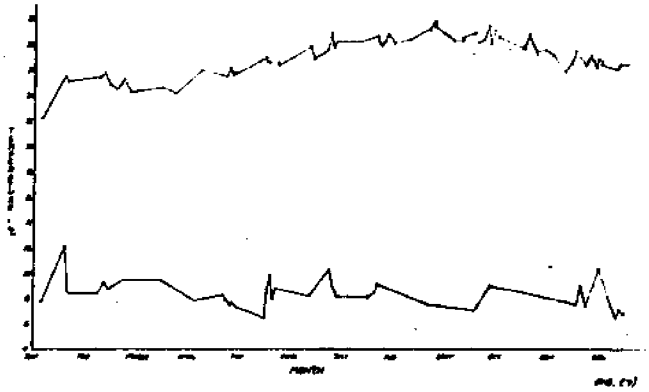


FIG. (7)

TEMPERATURE VERSUS MONTH FOR 30 AND 600 m.

APPROXIMATE LOCATION: [illegible]
NATIONAL OCEANOGRAPHIC DATA CENTER

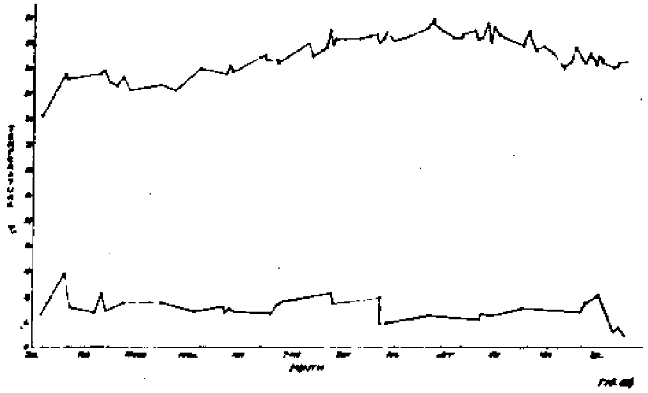


FIG. (8)

submersibles of the earlier baseline configurations.

B. We still think in terms of:

(c) closed Rankine Cycle: our own minimal investigation of the Open Cycle produced disappointing results. The results of others are encouraging, but we've not had time to use them.

(d) Either Propane or Ammonia as the working fluid. We found the Bechtel contribution on an Ammonia working fluid "clean-up system" helpful and reassuring that ammonia need not, perhaps, be feared as much as we feared it in 1972, '73.

(e) We remain totally addicted to the small-passage pressure-proof plate-fin heat exchanger. Our most prolific investigators have gone over small-bore parallel tube and small-bore staggered tube and a broad spread of plate-fin geometries and tests for optimal configurations always come back to that 1/8-inch vertical rectangular or triangular cross-section tube.

(f) We are convinced that small-passage pressure-proof plate fin heat exchangers can be produced in subassemblies using production-line techniques, and that the manufacturing cost will be a small percentage of the material cost. We are prepared to proceed with actual construction of several competitive concepts in several metals. The patentability of this Heat Exchanger Assembly Concept is being investigated.

(g) Except for Off-Design considerations, turbine design is set, prototype manufacturing could be started. We are satisfied that reasonable space for exhaust diffusion will add one to two percent back onto turbine efficiency. Our latest configurations thus permit turbine plus diffuser arrangements that should give us 94% total-to-total efficiency.

(h) All of our iterations to date have made provision for on-site repair-by-replacement of defective heat exchanger components while enduring a fractional shut-down of power plant.

(i) Part-load operation, minimum disruption in load during maintenance operations, a complete damage-control capability for coping with possible accidents, consolidated power plant control from a topside control station, have influenced the iterations.

(j) Practicality of power plant construction at the maximum possible number of existing U.S. shipbuilding locations has been given serious consideration. The largest (400mWe) of either our semi-submerged or surfaced configurations can be constructed on 900' x 100' ways adjacent to 12 foot deep launch receiving waters. Much deeper outfitting basins (up to 53' depth) are required, and a completion site (perhaps alongside a floating barge complex) with 84' depth would be desirable. For a proper multiple-construction program of many power plants, some auxiliary flotation devices (similar to the WWII Manitowoc Submarine Transport Dock) would be desirable.

(k) The Cold Water Inlet Pipe has taken on a variety of configurations. The original concept of a CWIP extending forward from the bow of the power plant, forming part of the mooring line, built as one welded aluminum hull structure, is still a viable concept. The concepts of subdividing that CWIP into 2, 3 or even 4 articulated sections is also still very attractive. We have liked the vertically telescoping CWIP and have decided on a version of it which could be built from welded aluminum to the streamlined shape required for the Gulf Stream Site, as an alternate. A telescoping CWIP dropped down from a location abaft the midships section, in some sketches all the way aft at the stern, of the surface ship configurations appears very attractive: the mooring to the bow would then be a bundle of mooring structural material plus the energy umbilical(s), cables and/or hoses.

(l) We have moved past the very lofty topside evaporator array of our Mark II configuration to two other candidates, each of which requires hot water pumping to overcome the hydraulic losses incurred by that lowering. Dr. Kirchhoff has estimated the additional pumping power requirement as minimal, however, and we feel very comfortable with the resulting compromise.

(m) With the help of the Naval Underwater Systems Center (Art Carlson, et al), we looked at some other basic configurations, both "wet condenser" and "dry condenser." We learned a great deal from the detailing of the required concrete structures and have incorporated those results indirectly into our latest configurations.

C. The U.Mass Power Plant Configurations are, to date, all characterized by a multiplicity of machinery compartments, each of which contains:

(1) A Dry Condenser, parts of which may be replaced on site, after isolation of that condenser from the cold water path.

(2) A Turbine Diffuser sitting on top of that condenser, occupying pressure-hull (one-atmosphere) space ... as long a diffuser as possible ... a diffuser which costs a great deal in terms of hull space which it occupies.

(3) A Turbo-Generator sitting on top of the diffuser, occupying pressure-hull space. The Turbo-Generator is of such a size that it produces 25 mWe net power, at this time. More detailed analysis, particularly after the OFF-DESIGN work is completed, may suggest a somewhat larger turbine-generator set.

The Turbine Diffuser can be opened up and entered for repair to its underlying condenser. The interior arrangement and structural details lend themselves to the moving in and out of replacement condenser core Heat Exchanger assemblies

(4) An Evaporator Array on top of the hull containing the dry condenser-turbine-generator stack. The semi-submersible configurations all use wet evaporators in a topside array. The surface ship configurations use dry evaporators located at the same relative elevation in the hull as the condensers. The topside Wet Evaporator Array can be maintained by repair-by-replacement with minimal plant turn-down.

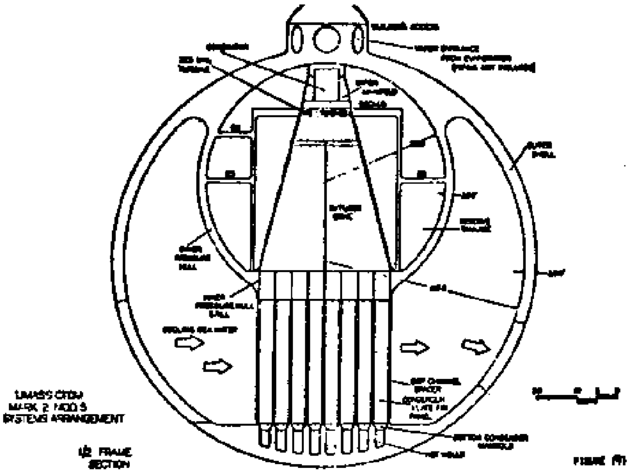
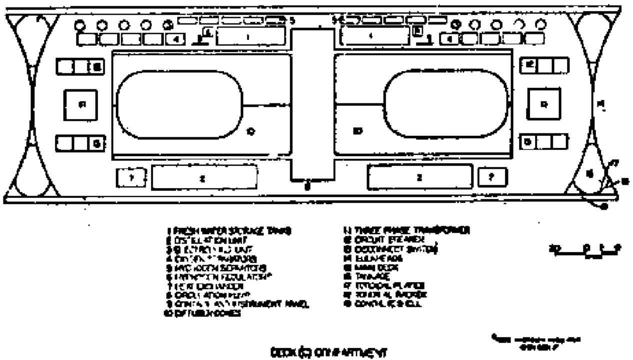


FIGURE (9)

D. Much of the above can be seen in the following series of illustrations:

In Figure (9) one sees a typical transverse section through a semi-submersible hull configuration. One sees the condenser hanging down below the Inner Pressure Hull Grill inside that Outer Shell, which when closed off at its Cooling Sea Water inlets and outlets gives us the Dry Condenser feature. On top of the condenser is the Inner Pressure Hull Grill which provides structural integrity for the large opening in the bottom of the Inner Pressure Hull as well as all the necessary damage control features. On top of the Grill is the Turbine Diffuser. On top of that is the Turbine-Generator set. All machinery is contained within the one-atmosphere Inner Pressure Hull. Access for building and for the entrance of vapor from the Topside Evaporator Array is shown via a cylindrical entrance penetration which is fitted with double closures to each opening.



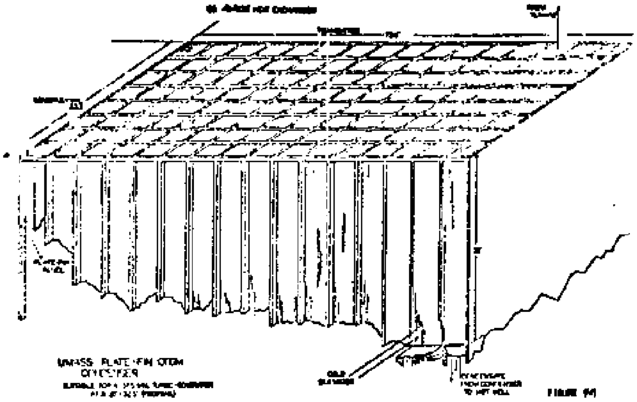
DECK (2) COMPARTMENT LAYOUT

FIGURE (10)

In Figure (10) one sees a compartment layout, deck plan, for a two-turbine compartment. In a 200 mWe hull we plan to have a short one turbine compartment at each end of the hull and three two turbine compartments, separated by holding bulkheads, for damage control purposes.

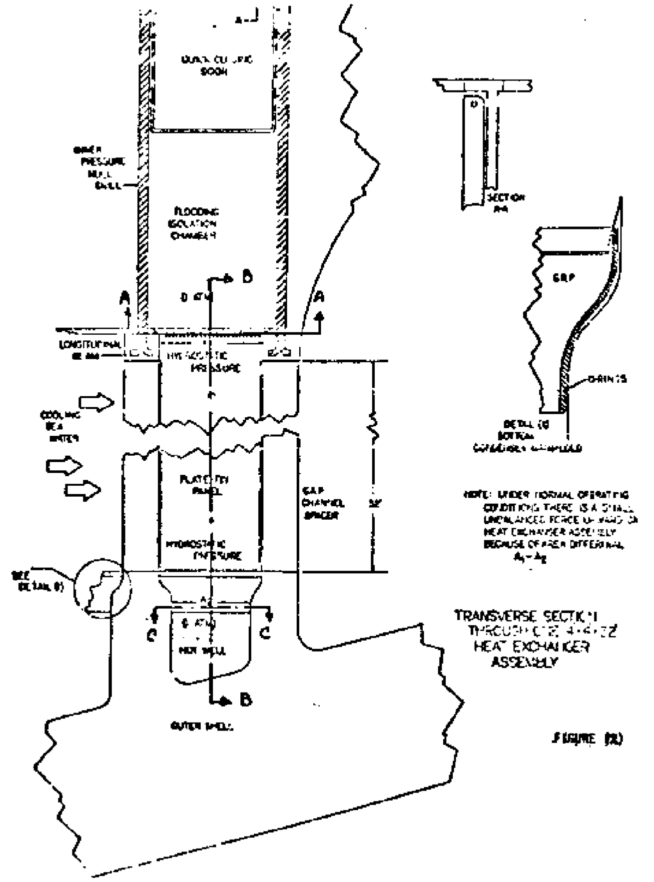
Figure (11) shows the cellular nature of the condenser and the structure in which it is carried.

Figure (12) shows some more detail of one of those structural cells in which one Heat Exchanger Assembly is suspended. The Turbine Exhaust Vapor flows downward through the Diffuser into the Inner Pressure Hull Grid, then enters to tops of the open condenser panels. As it flows down through the cooled plate-fin panels it condenses and collects in



UMASS PLATE-FIN OTEC CONDENSER

FIGURE (94)



TRANSVERSE SECTION THROUGH OTEC HEAT EXCHANGER ASSEMBLY

FIGURE (95)

the pressure-proof Hot Well. There is to be a Hot Well for each Heat Exchanger Assembly because each must be isolable, drainable, purgeable, to permit condenser repair by replacement.

Shifting now to the Evaporator Array, Figure (13) shows the basic dimensions of three parallel plate-fin panels in an evaporator core. Those panels are fabricated into Heat Exchanger Assemblies which will be identical to the condenser Heat Exchanger Assemblies for some power plants, but which may have different sea water passage widths for other power plants. In this concept, eight 4'x4'x32' Heat Exchanger Assemblies are manifolded together to create one Evaporator Modular Insert. Eight of those Modular Inserts are shown side-by-side in a structural frame in Figure (14). That subassembly of eight was selected to facilitate a certain topside arrangement.

Figure (15) shows one Evaporator Modular Insert and the concept for piping it which permits it to be isolated, withdrawn from, replaced, and then cut back on line in a power plant with minimum interference with power plant productivity.

Figure (16) is further detail at the top of an Evaporator Modular Insert, and Figure (17) shows similar detail at the bottom of an Insert. A repair crew working from an awash platform will be able to isolate, remove, and replace any Insert which the Evaporator Salinity Sampling and Alarm System has shown to be leaking.

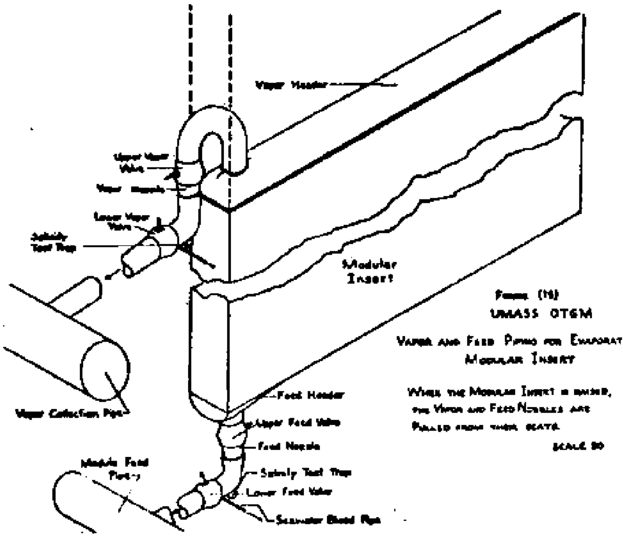
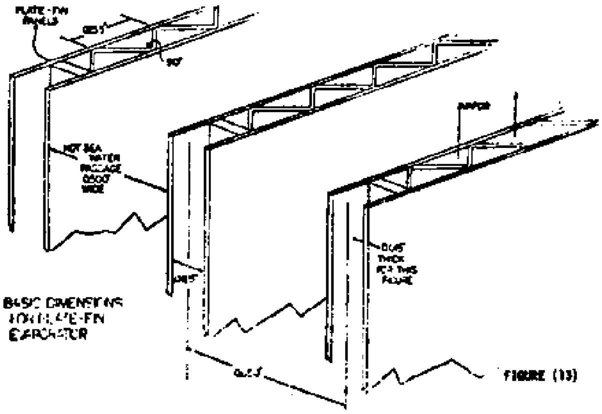


Figure (15)
UMASS OTGM
Vapor and Feed Piping for Evaporator Modular Insert

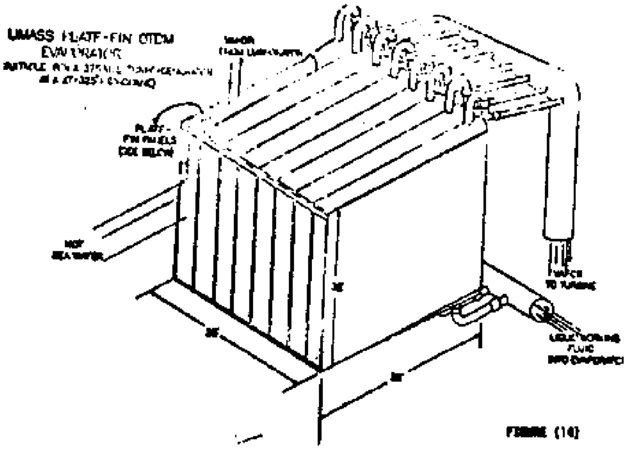
When the Modular Insert is raised, the Vapor and Feed Nozzles are pulled from their seats.

Scale 80



BASIC DIMENSIONS FOR PLATE-FIN EVAPORATOR

FIGURE (13)



UMASS PLATE-FIN OTGM EVAPORATOR

FIGURE (14)

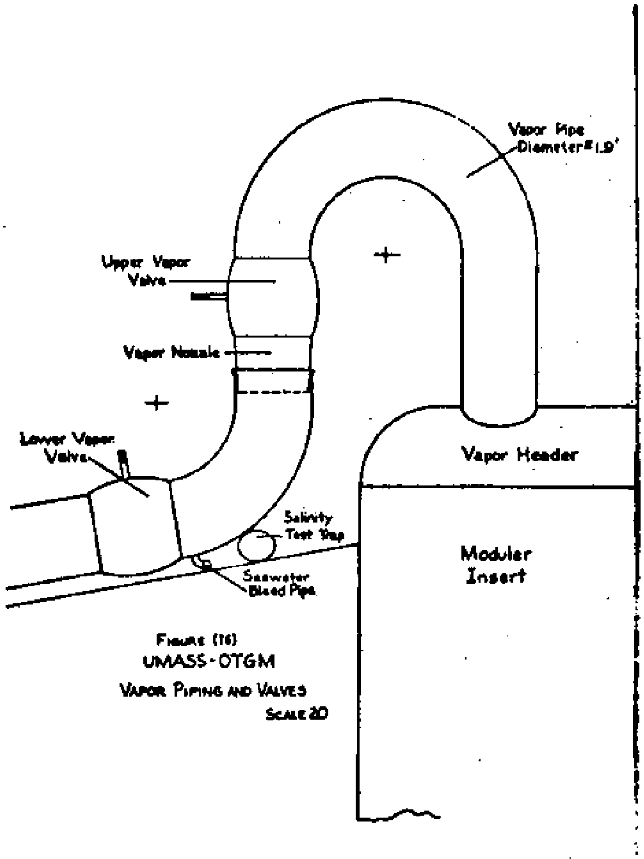
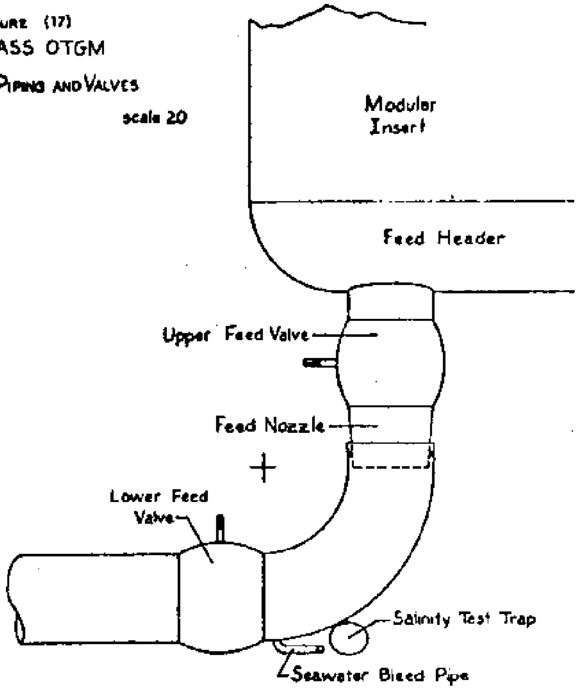


Figure (16)
UMASS-OTGM
Vapor Piping and Valves
Scale 20

All of these features are put together, partially, in the last of the figures. In Figure (18) we see an isometric view of the submersible hull power plant showing how the hull construction would proceed, from concrete bottom "saucer", thru erection of the transverse vertical floors which subdivide the condenser boxes. Then the Inner Pressure Hull Grill would be landed as one complete steel weldment subassembly on top of those floors, if adequate weight lifting capacity be available, or the Grill will be built up in place on top of the floors. Then the forms for the interior bulkheads and the Inner Pressure Hull will rise, step-by-step, with steel and concrete going into them until the raw boundary of the builder's access is reached. The Outer Shell will rise concurrently, slip-formed up and around, to join the other concrete at the hull top. Launch will occur when the largest (deepest) saucer which the building site can accept has been reached: construction will proceed afloat, symmetrically, thereafter. After all machinery has been shipped, located, foundationed, piped and wired, the large raw builder's access will be filled in to the permanent cylindrical access trunks and towers. Topside Evaporator piping, structural framing, crane ways will be added, then towers and the evaporators themselves. As mentioned earlier, a deep-draft fitting-out site with passage to the sea will be required to complete the hull.

Figure (17)
UMASS OTGM
Feed Piping and Valves
scale 20



The middle Cold Water Hull, built separately will at the appropriate time be brought to the Starboard

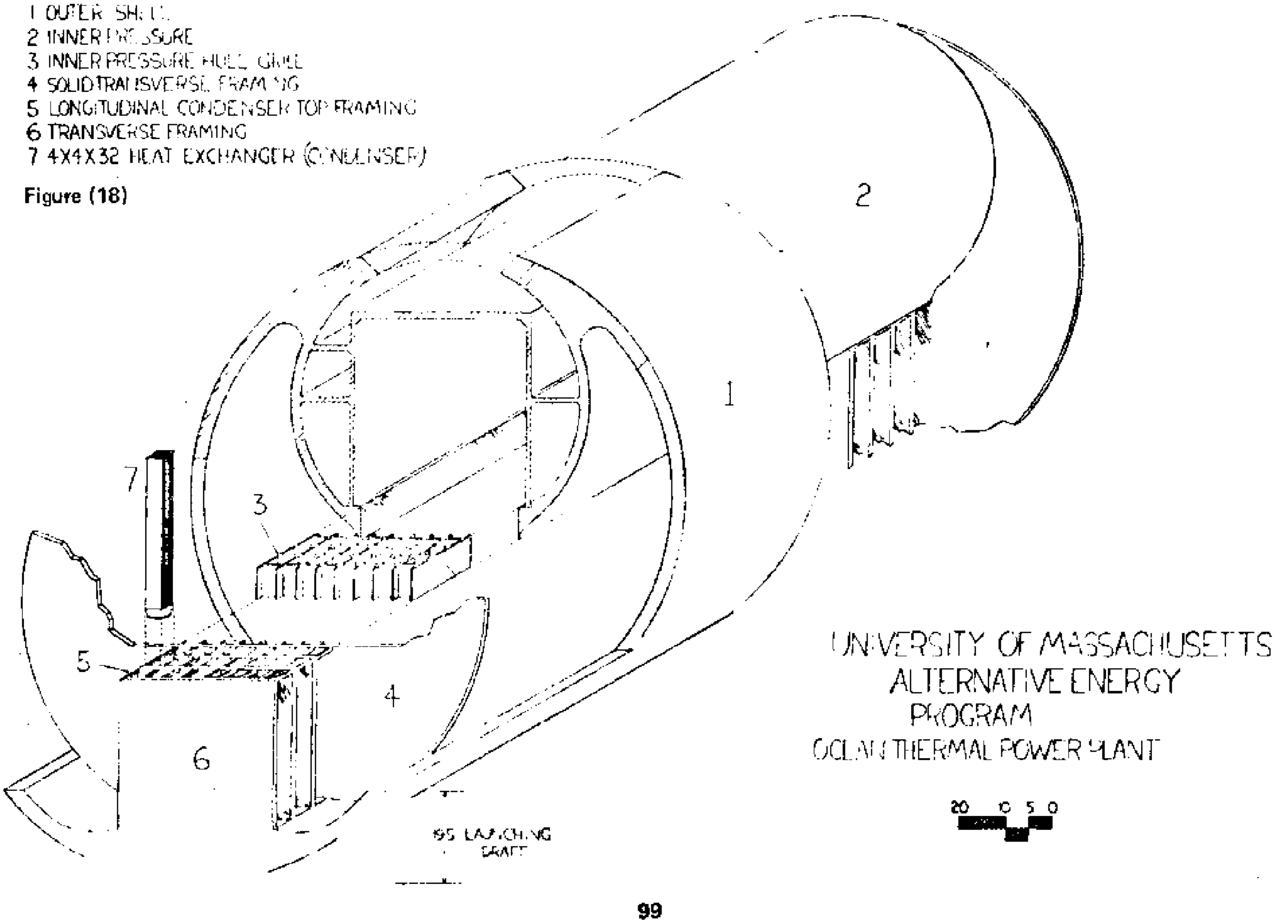


Figure (18)

Hull, mated and fastened. Then the Port Hull, built separately will be brought to it, mated and fastened. The Cold Water Inlet Pipe Swivel Section will be installed, ready to receive the rest of the CWIP.

Figures (19) and (20) show one recent version of a topside evaporator arrangement whose maximum height above top of pressure hull is about 90 feet: a double-tiered arrangement of evaporator assemblies in a sinuous path along the top of the hull. The Evaporator Repair Crane Ways and the Repair Crane are shown integrated into that structural frame work. The total added hot water parasitic pumping loss for this configuration in the Gulf Stream has been estimated at 2 megawatts for a 400 mWe (net) configuration.

Figure (21) shows another recent topside evaporator arrangement in which total upward projection of the evaporator array has been kept under 45 feet by accepting additional hot water pumping. Dr. Kirchhoff has not yet estimated that loss, but it is thought it too will be relatively minor. The Cold Water Hull has been tapered in height from bow to stern to create a hot water dump channel for the inboard evaporators of the after rows. The channel grows in cross sectional area along the hull to match the increased water flow. The Repair Crane concept will be used with the arrangement of Figure (20) also.

There are many changes to be made to the arrangements of Figures (18),(19),(20) and (21). For

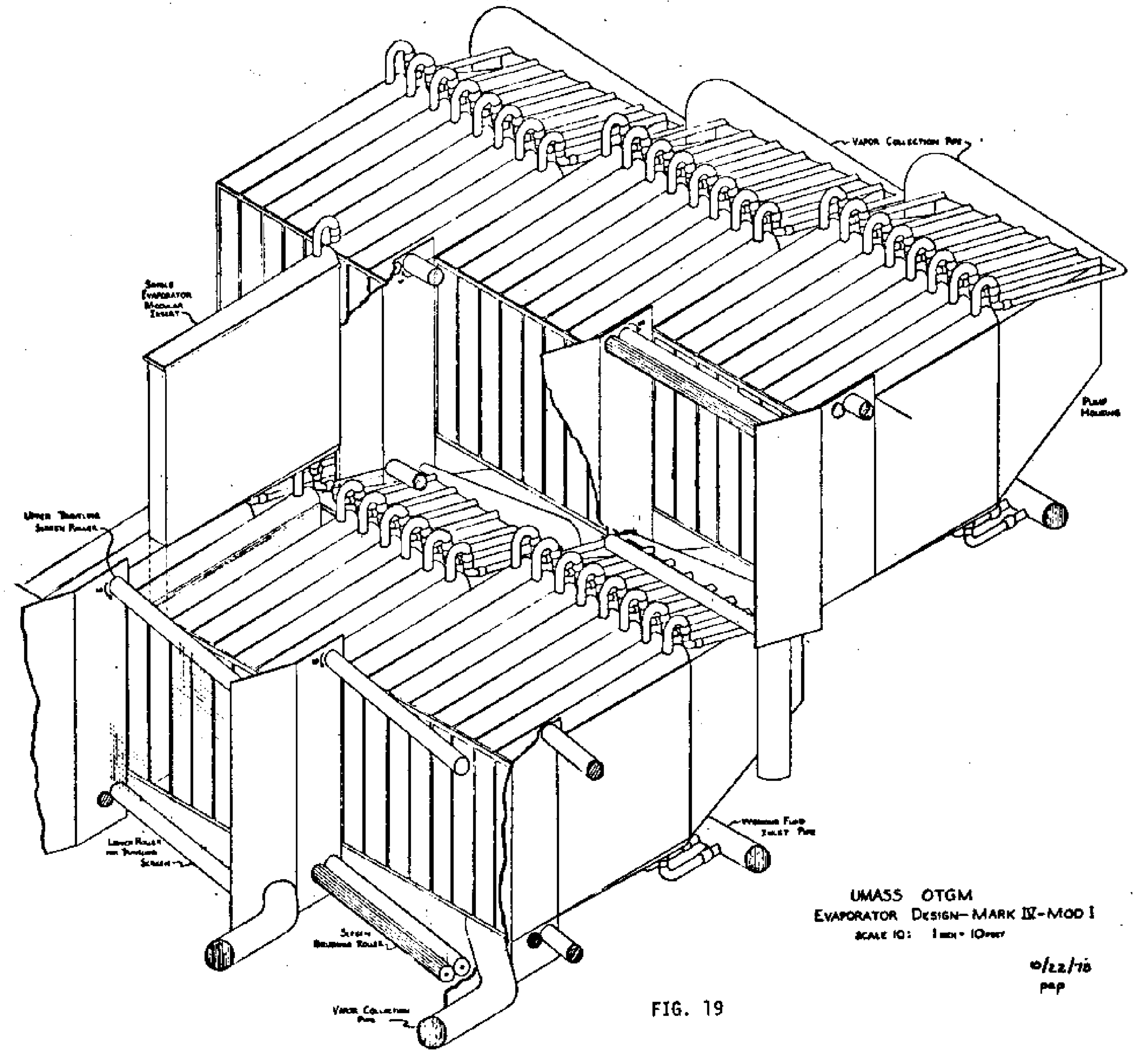


FIG. 19

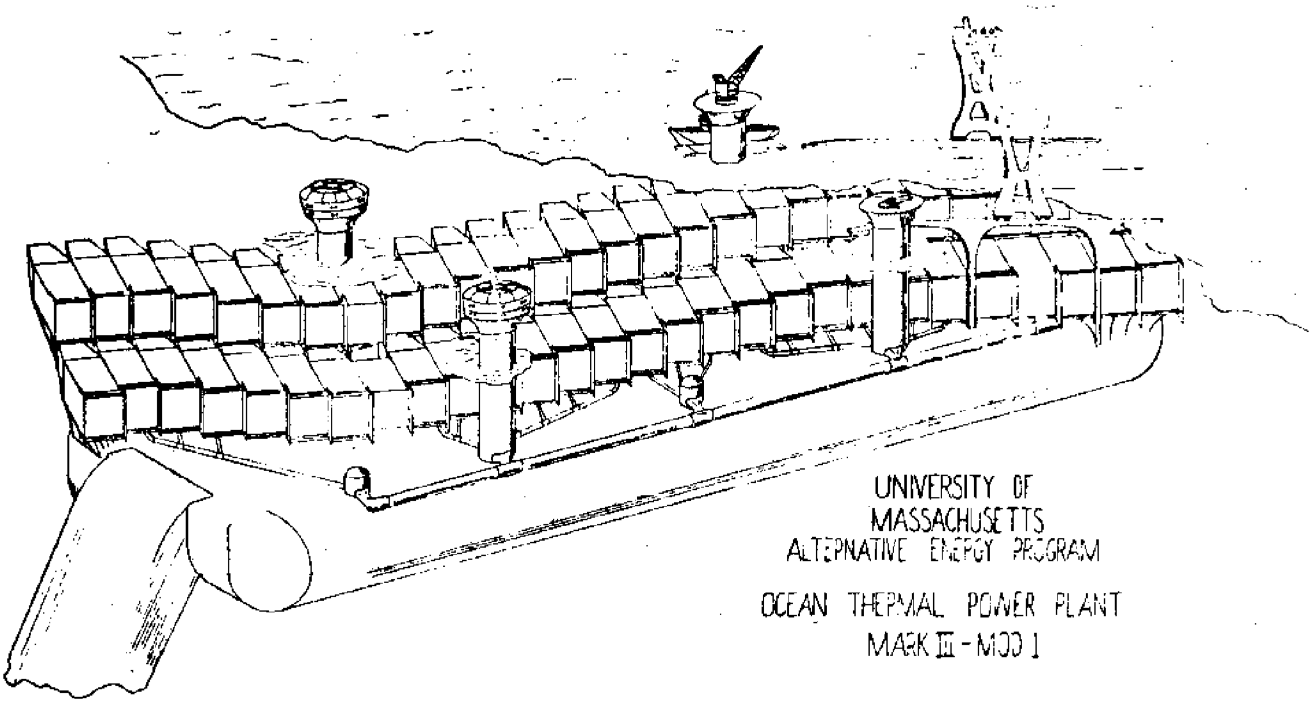


FIGURE 20

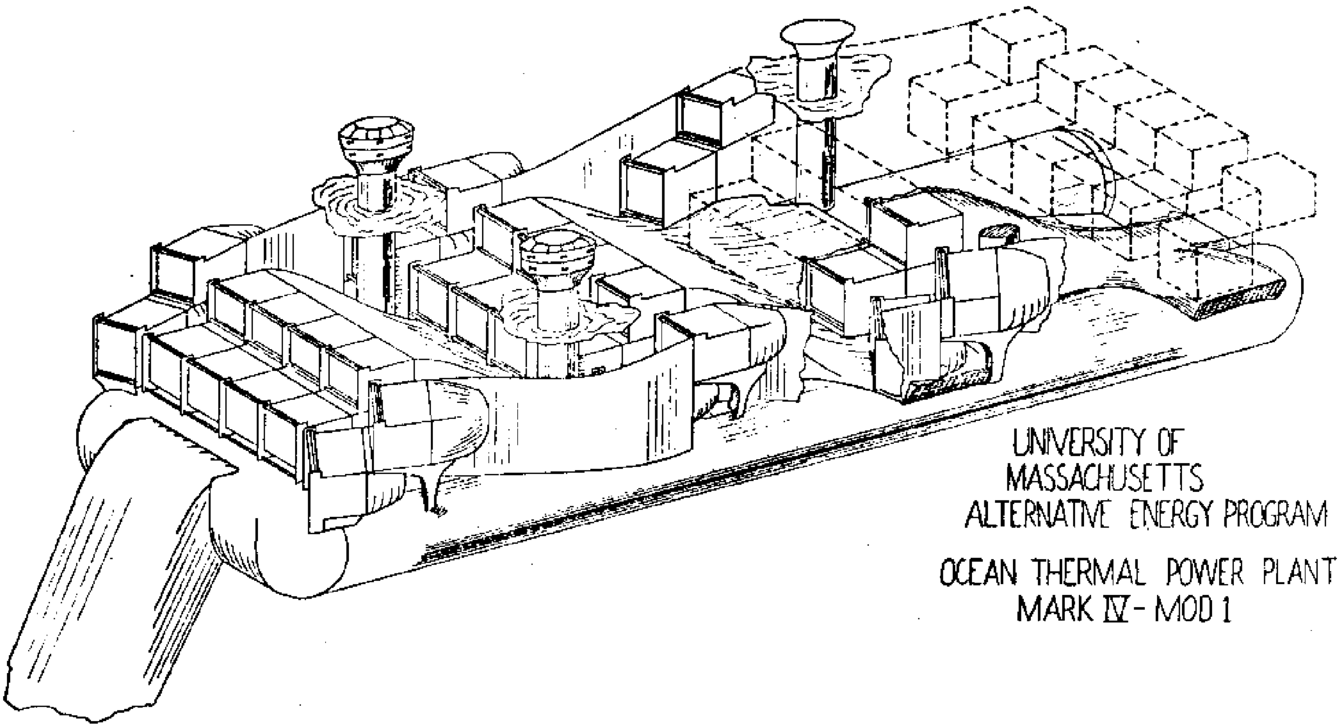


FIGURE 21

example, it is clear that we should abandon the circular cross-section Outer Hull, for instance, and move our Condenser Box Isolation Doors inboard to seat gate-valve fashion on sloping outward extensions of the strong concrete transverse floors. That will permit our outer hull to take on vertical sides, reducing fabrication cost and probably reducing overall beam.

The Weight and Moment Sheets for these new configurations have been completed. Balance and adequate stability in the many different conditions of operation which one of these power plants must see during construction&normal operations on station has been verified. There is room in the bottom of the Cold Water Hull to build in air-blown ballast tankage that could provide a very large measure of casualty buoyancy. Whether or not the certifying agencies would be willing to equate that with required reserve buoyancy is questionable, but it would be every bit as useful to the same purpose, and would facilitate the semi-submerged hull configuration. (The semi-submerged power plants could be built to the rules for oil-drilling rigs and overcome these kinds of problems in that way, too.) The total resistance of the semi-submersible on station in the Florida Current has been reduced markedly by these recent iterations from the value calculated by Adams in 1973. Therefore anchor and mooring requirement are about one-fourth what we had thought necessary before. The surface ship iterations show even more reduction in anchor and mooring requirement.

5. One Suggested Application for Gulf Stream OTECS

We are not aware of any great clamor at Florida Light and Power Company, or other investor-owned utility along the Florida Current, to get into the OTEC business. Indeed we understand that they need the waste heat from as many additional nuclear power plants as possible to qualify for an ERDA project in Biomass called the Great Biscayne Bay Sea Lettuce Project; thus their lack of interest in cheaper electricity from OTEC. We also understand that OTECS are looked upon with great suspicion by that new Florida industry boomer, Offshore Power Systems, and are thus not mentioned in polite society north of Palm Beach.

But we think we have one customer, a municipal power company in Taunton, Massachusetts, who has an outlet to the sea near Fore River. This municipal, like most of the 40 municipals in Massachusetts does very little generating today and is primarily a retailer of electricity produced by the New England Cartel, NEPOOL. It has been suggested that if Taunton could buy electricity cheaper than that which Boston Edison, etc., sells to them, then Taunton would in time sell to Boston Edison and indeed take over the entire NEPOOL market. Electricity will flow in either direction in most cables, and there is an ever increasing number of activist groups who would be willing to help arrange the necessary legislation, disenfranchisements, etc.

So, a completely independent analysis of projected demand, 1990, for all of New England has been made. The number 146 billion kWh per year, twice the 1975 73 billion kWh per year, has been arrived at after considerable effort. This projection could of course be off by 100 percent. For example, the New England economy could continue down hill so far because of ever increasing conventional energy costs and taxes that population growth will become strongly negative and electricity growth will resume the negative slope of 1974, and early 1975. Be that as it may, a market of 146 x 10^9 kWh, 1990, has been used.

It was decided to moor UMass. type 400 mWe power plants near Site Two, due east of Charleston, S.C. Careful analysis of a vast collection of NODC and U.S. Navy data confirmed that the Site Two resource is as rich and as steady (actually steadier than) as the Site One resource provided a cold water intake depth of 800 meters is used. That number corresponded well with the preliminary assessment of 1969 where maximum depths to 900 meters in the proposed deployment area were predicted.

Ninety 400 mWe (net) power plants, six rows of 15 each, in a sea area 16 miles by 14 miles, are to be used. All of the power plant net electricity is to be used via electrolysis to generate hydrogen gas. Three separated 44 inch diameter pipelines buried in the shelf in about 300 feet of water, each pipe 810 miles long, are to carry the hydrogen to Fore River. Those three pipes provide 100% redundancy, and very elaborate damage control concepts have been worked into the system. An alternate scheme calls for one pipe to be laid ashore, along the route of the coastal highway, to increase the security of the system from unfriendly frogmen; the ashore pipeline looks to be somewhat more expensive. Off the Jersey Coast, some 40 miles to sea, near the forthcoming oil platforms of the Baltimore Canyon Field, there will be a compressor platform which will absorb a continuous 180,000 horsepower maintaining the least-cost gas flow situation. Farther north and east in another canyon off Nantucket there will be an underwater pressure-balanced 3000 psi hydrogen storage of size adequate to smooth out the New England load-demand curve and provide three days' emergency storage.

The hydrogen going ashore into Taunton will at first be converted to electricity right there. The desired conversion will use hydrogen-air fuel cells. The by product process water will be sold to the Boston Metropolitan District Commission to add to their drinking water supply. By the time (1990) this system reaches its maximum size, arrangements will probably have been made to pipeline hydrogen gas around New England to a multiplicity of reconversion stations rather than doing it all in Taunton.

This study has assumed an overall electrolyzer-fuel cell efficiency of 45%, about 12% higher than that achievable with today's reasonably-priced commercial electrolyzers and the equivalent of a P&WA Powercel^{R} fuel cell. The improvement of 12%

can be made within 5 years by improving the electrolyzer alone, in the opinion of the General Electric Direct Energy Conversion Group. The theoretical maximum efficiency of this electrolysis-fuel cell reconversion process is 100% no Carnot efficiency limitation at all.

Assuming a 5% steady inflation rate, 1975 to 1985, and an OTEC capable of delivering bus bar d.c. at 16 mills per kWh, the projected cost of gaseous hydrogen at the end of the system in Taunton, 1985 dollars, is 32 cents per pound. An existing hydrogen-air fuel cell can produce 10 kilowatt hours of electricity from a pound of hydrogen. The total cost of delivered bulk power, 1985, baseload through peak, the entire schedule would be near 41 mills per kWh. Add 14 mills for distribution and the average kWh price becomes 55 mills, 1985. The best current projection of average New England electricity price, 1985, using some combination of nuclear and fossil generating plant, is 85 mills per kWh (from the experts outside the electricity industry). The 16 mill per kWh power cost at Site Two requires a capital cost of $850 or less per installed kW. The difference between 85 mills and 55 mills would permit another 30 mills per kWh capitalization of OTEC, about $1594 additional per installed kW, or a total of $2544 per kW, to achieve a break-even competitive price. There is in our opinion considerable elbow room in those numbers, considerable room to take risks in OTEC development, considerable opportunity for large rewards to risk capital. The largest remaining risk, probably, is that Site Two produced hydrogen would find itself competing against offshore windpower produced hydrogen at the New England sea coast! The clever entrepreneur may decide to develop both resources simultaneously. Figure (22) diagrams this system as going into Providence: the Taunton system is somewhat shorter in pipeline length, all other facets being the same. This study is the product of Wm. J. Rowan, one of the 29 outstanding graduate research assistants who have helped with our OTEC research at UMass. (Amherst).

6. Conclusions

The Gulf Stream site in the Florida Current is a good place for the United States to deploy Ocean Thermal Differences Power Plants. The resource is very large, capable of supplying all of the United States' electricity by itself if only one two-thousandth of it were converted. The flowing waters of the Gulf Stream replenish that resource in a very admirable way, overcoming any possible problem with breakdown of thermal stratification as might occur in stagnant water. The market is near at hand for the electricity-in-cable product and more distant markets could be reached by delivering the best of synthetic fuels, hydrogen, via pipeline.

The UMass. research team still favors large anchored power plants of the 100 to 400 mWe (net) size which use metallic pressure-proof plate-fin heat exchangers working in either a propane or ammonia closed cycle for the Gulf Stream Site.

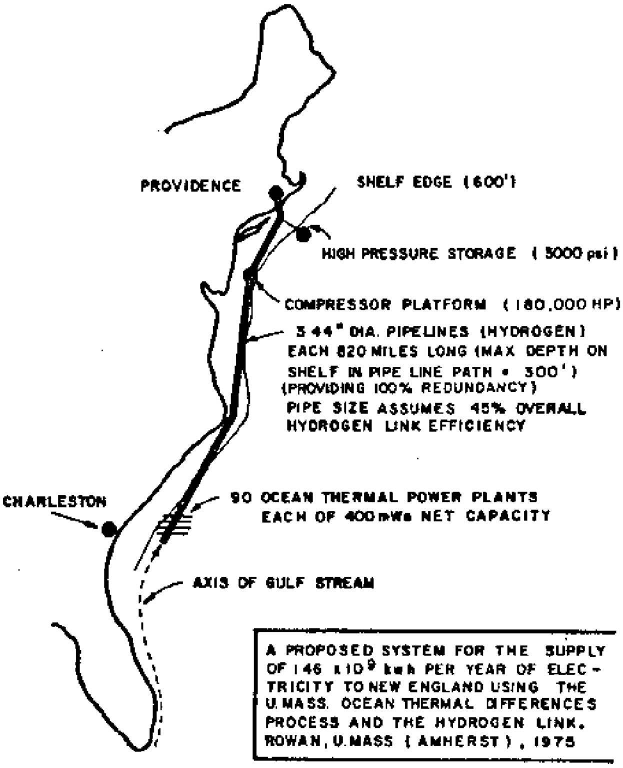
Experimentation that will decide the exact length of passage for those heat exchangers has been proposed as has a program that will demonstrate heat exchanger manufacturability. The seasonal variation of the Gulf Stream Site must be dealt with intelligently, and more Off-Design investigation is needed to decide the best machinery arrangement to cope with waxing and waning thermal resource: the final answer must be determined by economics.

Small, medium or large Gulf Stream semi-submersible or surface-ship power plants could be built at hundreds of existing ship building sites by using the Japanese method of waterborne joining of hull portions into one hull. Anchors and moorings for even the largest of the proposed power plants have been shown to be of manageable complexity. Many competitive cold water inlet pipe concepts have been sketched: some have been detailed but many more deserve detailing.

A large scale program for development and acquisition of a large fleet of Gulf Stream Power Plants was proposed by UMass. in March, 1975; the existing national OTEC program ignored completely its content and went instead to the Congress for an insignificant FY '76 budget. There persists some strange attitude that "the existing investor-owned utilities will develop OTEC as soon as economic viability has been assured and as soon as EPRI says it's OK". If the United States of America intends to permit EPRI and the investor-owned utilities to decide the energy

NEW ENGLAND ELECTRICITY

1990 - PROJECTED DEMAMD = 146 x 10^9 kwh/YEAR



A PROPOSED SYSTEM FOR THE SUPPLY OF 146 x 10^9 kwh PER YEAR OF ELECTRICITY TO NEW ENGLAND USING THE U.MASS. OCEAN THERMAL DIFFERENCES PROCESS AND THE HYDROGEN LINK. ROWAN, U.MASS (AMHERST), 1975

FIGURE 22

future of this country, Toynbee's pessimistic prediction about the disappearance of the human race will only be hastened into reality.

7. References

The reader who is truly interested in the ocean thermal differences process is urged to read the Technical Reports produced in this field since 1972 by the UMass. Team, all listed below. Each was to have been introduced into the NTIS system by NSF/ERDA, made available to the public via that route, but no listing of NTIS retrieval numbers has as yet been provided to the UMass. Team. Xerox or black-and-white copies can be obtained from the Dept. of Civil Engineering, University of Massachusetts, Amherst, Mass. 01002, by sending a check payable to that department, five cents a page, plus two dollars for postage and handling of each request. Complete sets of these reports have been distributed, free, to 247 individuals around the world: their copies may be available to other readers. A copy of that distribution list may be obtained from the same UMass. address for thirty cents.

1. Technical Report NSF/RANN/SE/GI-34979/TR/72/1, "Boiler Requirements for an Ocean Thermal Gradient Power Plant," J. Connell and J. McGowan, published as Appendix 1 to PR/72/4, December 1972. (50 pgs)

2. Technical Report NSF/RANN/SE/GI-34979/TR/72/2, "An Analysis of the Cooling Water Pumping Power Requirements of the Ocean Thermal Gradient Electricity Generating System (OTGEGS)," P.D. Cloutier and W. Goss, published as Appendix 2 to PR/72/4, December 1972. (24 pages)

3. Technical Report NSF/RANN/SE/GI-34979/TR/73/1, "A First Arrangement and Loads Analysis for a Twin Turbine 1100 mWe Cylindrical Turbine Hull," B.A. Johnson and W.E. Heronemus, March 1973. (69 pages)

4. Technical Report NSF/RANN/SE/GI-34979/TR/73/2, "Economic Evaluation of Non-Pollution Energy Generation Systems," M.W. Belevicz, G. March Choate, et al., March 1973. (29 pages)

5. Technical Report, NSF/RANN/SE/GI34979/TR/73/3, "Condenser Requirements for an Ocean Thermal Gradient Power Plant," J.W. Connell and J.G. McGowan, June 1973. (9 pages)

6. Technical Report NSF/RANN/SE/GI-34979/73/4, "Initial Investigation of Boiler and Condenser Tube Design," J.W. Connell and J.G. McGowan, June 1973. (34 pages)

7. Technical Report NSF/RANN/SE/GI-34979/TR/73/5, "A Summary of the Anderson and Anderson Analysis of the Sea Solar Power Process, 1964 to 1972," J. Hilbert Anderson, June 1973. (107 pages)

8. Technical Report NSF/RANN/SE/GI-34979/TR/73/6, "Working Fluids for the Sea Solar Power Process," J. Hilbert Anderson, June 1973. (25 pages)

9. Technical Report NSF/RANN/SE/GI-34979/TR/73/7, "Turbine Design: Sea Solar Power Plants," J. Hilbert Anderson, June 1973. (23 pages)

10. Technical Report NSF/RANN/SE/GI-34979/73/8, "A Preliminary Analysis of Power Plant Architecture and Statics," C.R. Adams, June 1973. (17 pages)

11. Technical Report NSF/RANN/SE/GI-34979/TR/73/9, "Ocean Thermal Difference Power Plant Design," J.G. McGowan, W.E. Heronemus, J.W. Connell and P.D. Cloutier, June 1973. (24 pages)

12. Technical Report NSF/RANN/SE/GI-34979/73/10, "Submerged Thermal Discharges from Ocean Sited Power Plants," P.A. Mangarella and E.S. Van Dusen, June 1973. (26 pages)

13. Technical Report NSF/RANN/GI-34979/TR/73/11, "Elasticity Solutions for Thick Wall Submersible Spheres," F.J. Dzialo, June 1973. (23 pages)

14. Technical Report NSF/RANN/SE/GI-34979/TR/73/12, "Plane Strain Solutions for Thick Cylindrical Submersible Shells," F.J. Dzialo and F.S. Stoddard, June 1973. (22 pages)

15. Technical Report NSF/RANN/SE/GI-34979/TR/73/13, "Preliminary Investigation of an Open Cycle Ocean Thermal Difference Power Plant Design," J. Boot and J.G. McGowan, August 1973. (45 pages)

16. Technical Report NSF/RANN/SE/GI-34979/TR/73/14, "Spherical and Cylindrical Hulls of Reinforced Concrete," E.C. Osgood, August 1973. (21 pages)

17. Technical Report NSF/RANN/SE/GI-34979/TR/73/15, "Heat Exchangers for Sea Solar Power Plants," J. Hilbert Anderson, September 1973. (46 pages)

18. Technical Report NSF/RANN/SE/GI-34979/TR/73/16, "Stress Analysis for a Cylindrical Shell (Axis Horizontal) Submerged in Water and Loaded for Neutral Buoyancy," Elmer C. Osgood, September 1973. (25 pages)

19. Technical Report NSF/RANN/SE/GI-34979/TR/73/17, "Ocean Thermal Difference Power Plant Turbine Design," L.L. Ambs and J. Marshall, November 1973. (32 pages)

20. Technical Report NSF/RANN/SE/GI-34979/TR/73/18, "Technical and Economic Evaluation of Ocean Thermal Difference Power Plant Turbomachinery," R.D. Lessard, December 1973. (17 pages)

21. Technical Report NSF/RANN/SE/GI-34979/TR/74/1, "A Preliminary Technology Assessment of Ocean Thermal Gradient Energy Generation," P.D. Cloutier, July 1974. (210 pages)

22. Technical Report NSF/RANN/SE/GI-34979/TR/74/2, "An Analysis of the Thermal and Nutrient Properties of the Condenser Discharge Plume Created by an Ocean

Thermal Difference Power Plant," by E. Van Dusen and P.A. Mangarella. (60 pages)

23. Technical Report NSF/RANN/SE/GI-34979/TR/74/3, "Feasibility Study of a 100 Megawatt Open Cycle Ocean Thermal Difference Power Plant," by J.L. Boot and J.G. McGowan. (71 pages)

24. Technical Report NSF/RANN/SE/GI-34979/TR/74/4, "Variations in Heat Exchanger Design for Ocean Thermal Differences Power Plants," by J.G. McGowan J.W. Connell and R. Breran. (49 pages)

25. Technical Report NSF/RANN/SE/GI-34979/TR/74/5, "Evaluation of the Major and Support Fluid Subsystems Necessary for the Operation of a Rankine Cycle Ocean Thermal Difference Machine," by J. Marshall and L. Ambs, November 1974. (22 pgs)

26. Technical Report NSF/RANN/SE/GI-34979/TR/75/1, "Mechanics and Structural Design of Large Diameter Immersed Reinforced Concrete Cylindrical Shells," by F.J. Dzialo and P. Heravi, January 1975. (24 pages)

27. Technical Report NSF/RANN/SE/GI-34979/TR/75/2, "Hot Side Hydraulics for Ocean Thermal Difference Plants Using Ocean Pumped Boilers," by D.C. Seluk and R.H. Kirchhoff, February 1975. (74 pages)

28. Technical Report NSF/RANN/SE/GI-34979/TR/75/3, "An Analysis of the Fluid Motion into the Condenser Intake of a 400 mWe Ocean Thermal Differences Power Plant," by P.A. Mangarella, February 1975. (25 pages)

29. Technical Report NSF/RANN/SE/GI-34979/TR/75/4, "A Proposed Ocean Thermal Energy Conversion System Program Plan (the OTECS Plan)," by W.E. Heronemus. (71 pages)

30. Technical Report NSF/RANN/SE/GI-34979/TR/75/5, "Design and Off-Design Performance Analysis of Ocean Thermal Differences Power Plant Turbines," by R.J. Veenema, Jr. and L.L. Ambs. (116 pages)

31. Technical Report NSF/RANN/SE/GI-34979/TR/75/6, "An Assessment of the Ocean Thermal Energy Potential of the Florida Current," by P.A. Mangarella. (27 pages)

32. Technical Report NSF/RANN/SE/GI-34979/TR/75/7, "Detailed Analytical Model of Rankine Cycle and Heat Exchangers for Ocean Thermal Differences Power Plants," by J.W. Connell and J.G. McGowan. (288 pages)

33. Technical Report NSF/RANN/SE/GI-34979/TP/75/8, "An Investigation of Heat Exchangers for Ocean Thermal Energy Conversion (OTEC) Systems," by R. Braren and J.G. McGowan. (136 pages)

34. Technical Report NSF/RANN/SE/GI-34979/TR/75/9, "Investigation of Competitive Arrangements, 400 mWe Ocean Thermal Differences Power Plants, for the United States' Southeast Coast Deployment Site," by T.A.L. Poole and W.E. Heronemus. (144 pages)

35. Technical Report NSF/RANN/SE/GI-34979/TR/75/10, "Hydrodynamics of Gulf Stream Ocean Thermal Power Plants," by R.H. Kirchhoff, P.A. Mangarella and J.G. McGowan. (50 pages)

36. Technical Report NSF/RANN/SE/GI-34979/TR/75/11, "On The Minimization of the Ocean Thermal Differences Machine Vehicle Sea Motions," by B.A. Johnson and C.R. Adams. (69 pages)

List of Attendees

Energy From The Oceans - Fact Or Fantasy?

January 27 - 28, 1976, Raleigh, N. C.

A. G. Alexiou
Office of Sea Grant
Dept. of Commerce NOAA
Washington, D. C.

A. C. Barefoot
N. C. State University
140 Harrelson
Raleigh, N. C. 27607

William M. Barwick
Route 5, Box 234
Washington
North Carolina

David Bevan
N. C. State Library
109 E. Jones Street
Raleigh, North Carolina

Jack Blanton
US ERDA Environmental Program
OBER/USEROA
Washington, D. C. 20545

Daniel M. Bragg, P.E.
Industrial Economics Research
Box 83 FM, Texas A & M University
College Station, Texas 77843

Dr. David A. Brooks
N. C. State University
Dept. of Geoscience
Raleigh, N. C. 27607

Clinton L. Brown
N. C. Department of Education
Division of Science
Raleigh, N. C. 27602

Dale R. Buck
Cape Fear Tech. Inst.
411 N. Front St.
Wilmington, N. C. 28401

A. G. Bullard
Carolina Power & Light Co.
P. O. Box 1551
Raleigh, N. C. 27602

Ernie Carl
N. C. Office of Marine Affairs
116 W. Jones St.
Raleigh, N. C. 27603

Tony Clark
Marine Affairs
% General Delivery
Kure Beach, N. C. 28449

Ted Colburn, Lt.
USCG
USCG R & D Center
Groton, Ct. 06340

Peter Cornillon
University of Rhode Island
Lippitt Hall
Kinston, R.I. 02881

Michael A. Covington
East Carolina University
School of Technology
Greenville, N. C. 27834

Jim Culpepper
N. C. Marine Affairs
P. O. Box 967, Airport Road
Manteo, N. C. 27954

Thomas L. De Fazio
Fla. Institute of Technology
P. O. Box 1150
Melbourne, Fla. 32901

J. S. Demaree
Suppliers Inc.
540 Albany
Lexington, Ky. 40502

Prof. J. S. Doolittle
N. C. State University
3211 Broughton
Raleigh, N. C. 27607

J. H. Durfee
BDM Corporation
Vienna
Virginia 22180

Buddy Eaton
Rt. 2
Mocksville
North Carolina 27028

William J. D. Escher
Institute of Gas Technology
3424 S. State Street
Chicago, Illinois 60616

Tom Fahnestock
Dept. of Natural & Economic Resources
P. O. Box 27687
Raleigh, N. C. 27611

Edward A. Gallagher III
George Transfer & Rigging Co., Inc.
P. O. Box 500
Parkton, Maryland 21120

James A. Gallager
George Transfer & Riggins Co., Inc.
P. O. Box 500
Parkton, Maryland 21120

Ozzie Gray
N. C. Dept. of Natural & Economic Resources
P. O. Box 27687
Raleigh, N. C. 27611

Wayland C. Griffith
Engineering Design Center MAE, NCSU
2405 Broughton Hall
Raleigh, N. C. 27607

Zachariah R. Hallock
University of Miami
10 Rickenbacker Causeway
Miami, Florida 33149

Wyman Harrison
Argonne National Lab.
9700 South Cass Avenue
Argonne, Illinois 60439

Dr. H. A. Hassan
N. C. State University
3211 Broughton
Raleigh, N. C. 27607

Stanley Hecker
N. C. Office of Marine Affairs
116 W. Jones St.
Raleigh, N. C. 27603

Lt. (JG) Donald J. Hilliker
U. S. Coast Guard R & D Center
Avery Point
Groton, Ct. 06320

Jules Hirshman
Tracor Marine
P. O. Box 13114
Port Everglades, Fla. 33316

Don Huisingh
N. C. State University
140 Harrelson
Raleigh, N. C. 27607

Violet D. Hunsucker
Daniels School
2313 Van Dyke Ave.
Raleigh, N. C. 27607

Eileen B. Justus
Military Chaplains Assn.
5613 Southwick St.
Bethesda, Maryland 20034

John R. Justus
Science Policy Research Division
U. S. Library of Congress
Washington, D. C. 20540

Vinod Kumar
Sun Shipbuilding & Drydocks Co.
Foot of Morton Avenue
Chester, Pa. 19013

George S. Leach
Route 3, Box 133
Leicester
North Carolina 28748

Thomas N. Lee
University of Miami
Miami
Florida 33157

Lloyd F. Lewis
United States Navy
Washington Navy Yard
Washington, D. C. 20274

James T. List
N. C. Marine Resources Center
P. O. Box 967
Manteo, N. C. 27954

Dr. Thomas E. Little
Westinghouse Oceanic Div.
Box 1488
Annapolis, Maryland 21404

D. Preston Lowrey
1011 Burch Avenue
Durham
North Carolina 27701

Dr. Carl A. Ludeke
NYIT Research Center
8000 N. Ocean Dr.
Dania, Florida 33004

David Mager
Pacific Power & Protein Inc.
1 Lincoln Plaza
New York, N. Y. 10023

John D. Marks
Westinghouse Oceanic Division
M.S. 9845, Box 1488
Annapolis, Maryland 21404

Edith Marsh
N. C. Marine Science Council
P. O. Box 9533
Raleigh, N. C. 27611

Fowler Martin
N. C. State University
1911 Building - Basement
Raleigh, N. C. 27607

Daniel Meier
Carnegie-Mellon University
5000 Forbes Ave., Dept. of Physics
Pittsburgh, Pa. 15217

Kenneth L. Money
The International Nickel Company Inc.
P. O. Box 656
Wrightsville Beach, N. C. 28480

Dr. Clifford J. Moore, Jr.
N. C. State University
3211 Broughton
Raleigh, N. C. 27607

Dr. J. C. Mulligan
N. C. State University
3211 Broughton
Raleigh, N. C. 27607

Richard W. Murphy
Union Carbide - Oak Ridge National Lab.
300 Walker Springs Road
Knoxville, Tenn. 37919

John McAuley
British Embassy
3100 Mass. Ave. N. W.
Washington, D. C. 20008

Dr. Ross McCluney
Florida Solar Energy Center
P. O. Drawer N
Cape Canaveral, Florida 32920

Clive Grove Palmer
Energy Technology Support Unit
A.E.R.E. Harwell
Oxford Shire OXII ORA

Lewis A. Pitt
Environmental Data Service, NOAA
3300 Whitehave St., N. W.
Washington, D. C. 20235

Robert G. Quayle
National Climatic Center
Federal Building
Asheville, N. C. 28801

Dr. Abobakr Radwan
Florida Institute of Technology
P. O. Box 1150, Country Club Road
Melbourne, Fla. 32901

Jonathan Rogoff
N. C. Energy Division
215 E. Lane Street
Raleigh, N. C.

Alexander Samson
N. C. State University
2221 Broughton
Raleigh, N. C. 27607

Gerry Sauer
3314 Tennyson
Washington, D. C.

C. F. Schrieber
Dow Chemical
Building A-2301
Freeport, Texas 77541

H. W. Shepherd
Samson Cordage Works
99 High Street
Boston, Mass. 02110

Ned Smith
N. C. Marine Affairs
Rt.1, Bridge Road
Morehead City, N. C. 28557

Russell Stoutt
Aquatic Genetics Systems
Raleigh
North Carolina 27602

Hai C. Tang
N. C. Dept. of Natural Economics Res.
216 W. Jones St.
Raleigh, N. C. 27611

Paul H. Taylor
State Dept. of Public Instr.
Raleigh
North Carolina 27611

James Dana Thompson
Jaycor
205 S. Whiting St.
Alexandria, Va. 22303

Harry M. Tollerton
University of Delaware
Center for the Study of Marine Policy
Newark, Delaware 19711

L. Van Hemelryck
Columbia University
Torrey Cliff
Palisades, N. Y.

Paul E. Waldrop, Jr.
East Carolina University
School of Technology
Greenville, N. C. 27834

Kendall H. Wellman
Westinghouse Oceanic Division
Box 1488 Mail Stop 9845
Annapolis, Maryland 21404

Joseph M. Wetzel
University of Minn.
Minneapolis, Minn. 55414

J. S. Wroblewski
Florida State University
2203 W. Pensacola C-8
Tallahassee, Florida 32304

Jay E. Yaffo
Pacific Power & Protein Inc.
1 Lincoln Plaza
New York, N. Y. 10023

ENERGY FROM THE OCEANS - FACT OR FANTASY?

Hilton Inn
Raleigh, North Carolina
January 26 - 28, 1976

Program Participants

Dr. Robert Cohen, Manager
Ocean Thermal Conversion Program
Division of Solar Energy, ERDA
Washington, D. C.

Dr. B. J. Copeland, Director
UNC Sea Grant Program
Raleigh, N. C.

Dr. Earl G. Droessler
Vice Provost and Dean for Research
Professor of Geosciences
North Carolina State University
Raleigh, N. C.

Dr. G. L. Dugger
Applied Physics Laboratory
Johns Hopkins University

Dirk Frankenberg, Director
Marine Sciences Program
University of North Carolina
Chapel Hill, N. C.

Wayland Griffith, Director
Engineering Design Center
North Carolina State University
Raleigh, N. C.

Clive Grove-Palmer
Harwell

L. Van Hemelrijck
Lamont-Doherty Geological Observatory
Columbia University

Prof. William E. Heronemus
Department of Civil Engineering
University of Massachusetts

H. Gary Knight, Professor
Marine Resources Law
Louisiana State University Law Center

Jerome Kohl
Chairman of Program Committee
Engineering Extension Specialist
North Carolina State University
Raleigh, N. C.

Dr. J. Langfelder, Director
Center for Marine & Coastal Studies
Professor of Civil Engineering
North Ccarolina State University
Raleigh, N. C.

S. Laurence
Lamont-Doherty Geological Observatory
Columbia University

Dr. Abrahim Lavi
Professor of Engineering
Carnegie Mellon University

James A. Lisnyk
Program Manager
Office of Maritime Technology

Dr. Michael E. McCormick
Professor of Ocean Engineering
U. S. Naval Academy

Dr. Bruce Muga
Professor & Chairman of Civil Engineering
Duke University
Durham, N. C.

Frederick E. Naef
Regional Marketing Manager
Lockheed Missiles and Space Corporation

Dr. Steve Piacsek
Section Head
Geophysical Simulation
Naval Research Laboratory

Prof. S. H. Salter
University of Edinburgh
School of Engineering Science

Dr. Harold A. Spuhler
Solar Energy Coordinator
NSF

Col. Beverly C. Snow, Jr.
Director of Coastal Plains Center for
Marine Development Services

Fred Vukovich
Research Triangle Institute
Research Triangle Park, N. C.

James J. B. Worth
Research Triangle Institute
Research Triangle Park, N. C.

PREVIOUS PUBLICATIONS PUBLISHED
By
THE CENTER FOR MARINE AND COASTAL STUDIES

Wave-Current Force Spectra, C. C. Tung and N. E. Huang, Report No. 72-2, December, 1972.

A Survey of North Carolina Beach Erosion by Air Photo Methods, H. E. Wahls, Report No. 73-1, May, 1973.

Sediment Movement in Tubbs Inlet, North Carolina, Robert P. Masterson, Jr., Jerry L. Machemehl and Victor V. Cavaroc, Jr., Report No. 73-2, June, 1973.

Influence of Current On Some Statistical Properties of Waves, C. C. Tung and N. E. Huang, Report No. 73-3, December, 1973.

CTD Sensors, Specific Conductance and the Determination of Salinity, C. E. Knowles, Report No. 73-3, August, 1973.

Planning for North Carolina's Coastal Inlets - An Analysis of the Present Process and Recommendations for the Future, William S. Tilley, Report No. 73-4, September, 1973.

A Preliminary Study of Storm-Induced Beach Erosion for North Carolina, C. E. Knowles and Jay Langfelder and Richard McDonald, Report No. 73-5, October, 1973.

A Historical Review of Some of North Carolina's Coastal Inlets, Jay Langfelder, Tom French, Richard McDonald and Richard Ledbetter, Report No. 74-1, January, 1974.

Statistical Properties of Kinematics and Dynamics of a Random Gravity Wave Field, C. C. Tung, Report No. 74-2, June, 1974.

A New Technique of Beach Erosion Control, Tom French, Jerry L. Machemehl and N. E. Huang, Report No. 74-3, June, 1974.

Citizen Participation in North Carolina's Coastal Area Management Program, Steve Tilley, Report No. 74-4, June, 1974.

An Experimental Study of Scour Around Marine Foundations Due to Oscillatory Waves and Undirectional Currents, Greg N. Abad and Jerry L. Machemehl, Report No. 74-5, September, 1974.

Proceedings of A Conference on Coastal Management, Report No. 74-6, September, 1974.

Statistical Properties of Fluid Motion and Fluid Force in A Random Wave Field, Keikhosrow Pajouhi and C. C. Tung, Report No. 75-1, May, 1975

"A Numerical Method for Solutions of Systems of Non-Linear Algebraic Equations", John M. Klinck and Leonard J. Pietrafesa, Report No. 75-2, July, 1975.

"Wave-Current Interactions in Water of Variable Depths", A. M. Radwan, C. C. Tung and N. E. Huang, Report No. 75-3, August, 1975.

"Conference Proceedings Energy From The Oceans Fact or Fantasy?", Jerome Kohl, Report No. 76-1, UNC-SG-76-04, January, 1976.