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March 1981

Ocean Energy Conversion Systems Annual Research Report

Ocean Systems Program Branch

Solar Energy Research Institute
A Division of Midwest Research Institute

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Golden, Colorado 80401

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OCEAN ENERGY CONVERSION SYSTEMS ANNUAL RESEARCH REPORT

OCEAN SYSTEMS PROGRAM BRANCH

MARCH 1981

PREPARED UNDER TASK NOS. 1113.00 & 1115.00

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PREFACE

This report presents the status of research supported by the U.S. Department of Energy (DOE) toward developing ocean energy resources considered viable alternatives to the baseline DOE ocean energy system; i.e., the closed-cycle Rankine heat engine. Management of the reported research program is provided by the Ocean Systems Program Office (OSPO) of the Solar Energy Research Institute (SERI) with cooperation from Oak Ridge National Laboratory (ORNL).

The report deals with open-cycle systems (Claude cycle), alternative thermal cycles (mist and foam lift), and alternative ocean systems (waves, currents, salinity gradient, and thermoelectric). Each section is introduced by an overview written by the responsible SERI or ORNL staff member, followed by subsections prepared by the principal investigator of each subcontract concerned with a particular research area. In all cases, the report strives to describe the status of the research, plans for the future, and complementary relationships to the baseline ocean energy system.

We wish to acknowledge the principal investigators, who wrote the subsections, and the staff of the Ocean Systems Program Branch, who supplied the overviews: Peter H. Davidoff, John B. Miles, and Terry R. Penney. We also wish to thank David Johnson of the Solar Thermal Research Branch and Fang C. Chen of ORNL, and to acknowledge those who reviewed the draft: John W. Michel, ORNL; Michael McCormick, Department of Mechanical Engineering, U.S. Naval Academy; and Norman Sather, Argonne National Laboratory.

Also, a sincere note of appreciation is extended to the members of an advisory panel who attended an oral presentation of this report and offered their expert opinion regarding this research program: Richard N. Lyon, ORNL; William H. Avery, Applied Physics Laboratory; and John P. Craven, University of Hawaii.

Benjamin Shelpuk, Chief
Ocean Systems Program Branch

Approved for

SOLAR ENERGY RESEARCH INSTITUTE

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SUMMARY

OBJECTIVE

The objective of the advanced research and development program for alternative ocean energy resources is to generate, evaluate, and develop those ocean energy systems that can extract significant amounts of energy from the sea in a cost-effective and environmentally acceptable way.

DISCUSSION

That objective is met in three ways:

- Exploratory Research
- Concept Evaluation
- Subsystem Research and Development

The larger scale engineering focus of the ocean energy program is on closed-cycle ocean thermal energy conversion (OTEC). This focus encompasses OTEC-ocean energy conversion, a major experiment now on station in Hawaii, and the OTEC Pilot-Plant Project scheduled to begin in June 1981 and to be on station in 1985-86. These activities are shown in Fig. S-1. Commercialization decisions will be made by users, financiers, and system suppliers when the results of these experiments have been evaluated.

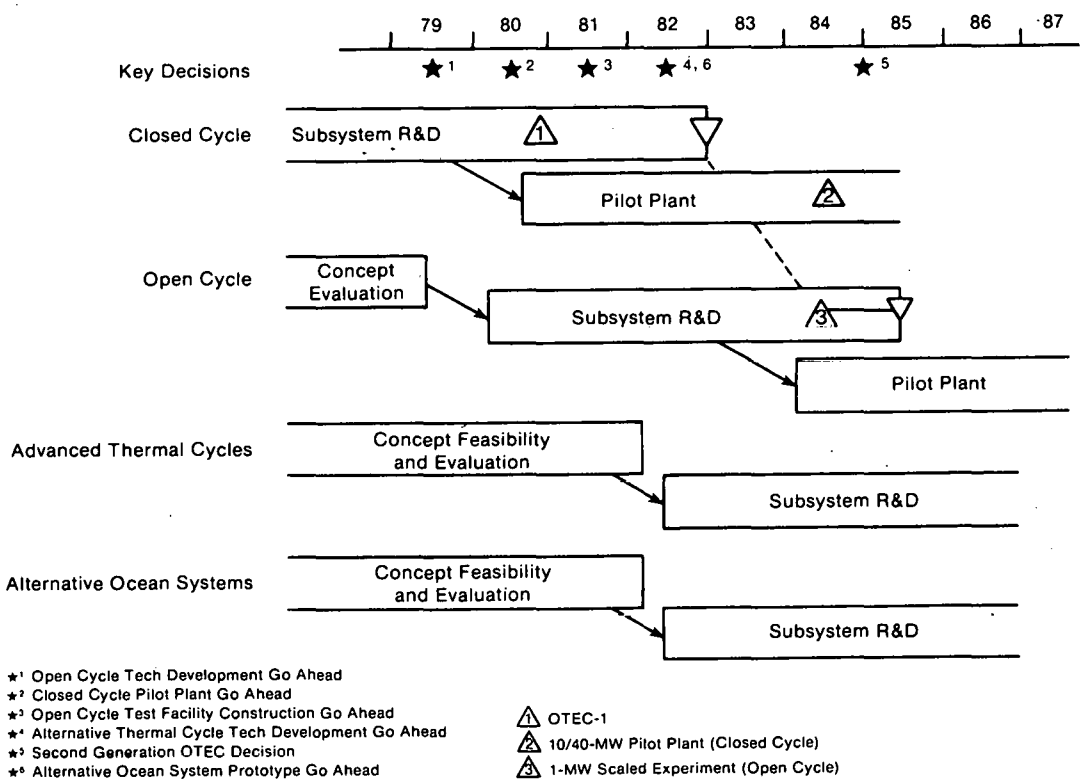

Figure S-1. Ocean Thermal Cycles Program Logic

The advanced R&D program for alternative ocean energy resources provides timely alternatives to closed-cycle systems. In most cases, the alternatives are comparable to closed-cycle systems in size and application. In other cases, alternatives could fulfill different roles. The second line of Fig. S-1 shows that open-cycle subsystem development will proceed parallel to the closed-cycle pilot plant and will culminate in the tesing of a large-scale experiment in 1984-85. The timing and scale of the planned experiment would be adequate to allow the ocean energy program to seriously consider open cycle as an alternative to closed cycle in any phase beyond the pilot plant. A second possibility would be that the open cycle might lend itself better to other complementary applications; e.g., a small system and/or a seawater desalination demonstration plant. This latter possibility is advantageous to small or underdeveloped island communities.

The third timeline in Fig. S-1 indicates that the advanced thermal cycle program could proceed to the subsystem development phase during FY 1982 depending on the results of concept feasibility studies, experiments now in progress, and comparative analysis with other thermal conversion techniques. The decision could be to proceed aggressively to subsystem development with one of the concepts currently under study, to generate more support data, or to consider a broader range of thermal options.

Timeline four describes the ocean waves and currents research program. The present plan is to initiate development opportunities annually. Specific wave or current projects possibly could get to a construction phase within FY 1985.

The Solar Energy Research Institute (SERI) and the Oak Ridge National Laboratory (ORNL) are participating in advanced R&D for alternative ocean energy resources. Coordination and integration of the program is accomplished through the Ocean Systems Program Office (OSPO). Subcontracts involved with investigating advanced thermal cycles are being managed by ORNL. Studies of all the other options are funded and managed by SERI.

FY 1980 was the first year that the alternative ocean energy systems effort was integrated into a single program. This consolidation resulted from the necessity to structure project priorities within each program area and then to integrate the areas into a coherent entity. The result is the statement of program goals and strategy presented in this report. Figure S-1 shows the schedule for implementing these strategies within a realistic framework and the available budget. The program objectives are starting to be met, as the following shows:

Management Accomplishments

- Multiyear program plans were developed for each alternative ocean energy resource area.
- A competitive procurement was completed in key Claude cycle technical areas resulting in the signing of four major subcontracts.
- Nine subcontracts were negotiated for the development of innovative alternative ocean energy systems.

- Seventy-five unsolicited proposals were reviewed and processed for further action by either DOE or SERI.

Technical Accomplishments

- Three promising approaches to seawater evaporation in the Claude cycle system were identified and experiments to verify performance were funded.
- A laboratory was constructed at SERI to study heat and mass transfer during evaporation and condensation at low pressures.
- Heat transfer rates of 70,000 W/m^2-K were achieved in a falling turbulent jet evaporator under actual operating conditions.
- Claude cycle turbine research has shown that more small turbine blades are necessary to meet the simultaneous thermodynamic, structural, and dynamic constraints of the cycle. A central box-spar blade design with mass overbalance at the tip is required to suppress flutter.
- Analysis has shown that up to 25% of the air contained in incoming warm water pipes can be disengaged. Experiments have been conducted both at ORNL and by a subcontractor to develop processes and equipment to remove gases with minimum parasitic loss.
- Low surfactant concentrations (20 ppm) were achieved in the foam-lift column experiment. Excessive foam acceleration needs to be solved, and new surfactants need to be derived to further reduce this consumable. Fresh water results have been duplicated in seawater.
- Net work achievement in the mist-lift process has been shown qualitatively in a bench-scale experiment. Supporting transient analysis shows that the system is stable with a variety of boundary condition perturbations.
- Methodology for designing a Dam-Atoll™* Wave Energy Extraction Device has been developed and documented, providing for the development of reduced-scale hardware.
- Preliminary analysis of the Kaimei test data has been completed. Results indicate poorer performance than expected (reportedly due to a mismatch of the barge design to existing sea conditions). Also, uniform data evaluation methods and international cooperation are needed.
- The initial portions of a wave system study have been completed and documented.
- Experiments have been defined to further explore the potential for a wave flap device.
- Testing of a drogue chute for converting ocean current energy has been completed and is presently being evaluated.
- The salinity gradient program results have been reviewed. The main conclusion is that membrane performance and the generation of nonmembrane salinity technology concepts should be studied first, pending funding availability.

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*Dam-Atoll is a patented concept of the Lockheed Missiles and Space Company, Inc.

CONCLUSIONS AND RECOMMENDATIONS

Progress made in FY 1980 promises rapid advances in developing alternative methods for tapping the ocean's energy resource. The program can now accomplish this and simultaneously generate and nurture new concepts that will continue the contribution of ocean energy to the nation's energy supply in future years.

The priorities of the program now are to:

- determine the engineering feasibility of open-cycle OTEC through subsystem test and evaluation;
- make definitive evaluations of advanced thermal, wave, and ocean current energy conversion system concepts by FY 1982; and
- identify and evaluate innovative ocean energy concepts.

Achieving these goals will require mobilizing all the resources required to maintain program momentum, and we recommend that all organizations involved support this goal.

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SECTION 1.0

OCEAN ENERGY CONVERSION SYSTEMS OVERVIEW

B. Shelpuk*

The policy of the U.S. Department of Energy (DOE) Division of Ocean Energy Systems is to pursue projects that might reduce U.S. dependence on oil imports and other exhaustible fuels in accordance with the National Energy Act. Consistent with this policy, research indicates that the potential of useful energy from the sea can be demonstrated with minimal risk by developing a closed-cycle Rankine heat engine system. This engine would use the potential thermal energy inherent in the temperature difference between warm surface water and the colder deeper water occurring in most tropic and semitropic regions. The major engineering effort and the bulk of the budget of the ocean energy program have gone into studies and experiments leading to the construction and testing of a closed-cycle ocean thermal energy conversion (OTEC) pilot plant.

There are alternative ocean energy resources and alternative methods for converting the thermal resource. A significant ongoing research program is identifying and developing those alternatives that are potentially more cost effective or can meet needs supplementary to the closed-cycle OTEC system. This report presents the scope and status of the research being done in this area.

DOE is sponsoring this research with management provided by the Ocean Systems Program Office (OSPO) of the Solar Energy Research Institute (SERI) in cooperation with the Oak Ridge National Laboratory (ORNL).

An additional source of energy from the ocean is in waves, persistant currents usually located on the western edges of oceans and salinity gradients between the sea and fresh water rivers at their estuaries. Work has also been sponsored to evaluate various methods for converting this energy to more useful forms.

To provide a common basis of understanding for the material presented, capsule descriptions of each of the concepts discussed are included in Fig. 1-1. The remainder of the report presents sections on the Claude cycle, alternative thermal cycles, and alternative ocean systems. Each section contains an overview followed by summaries of the various projects being pursued in these three areas.

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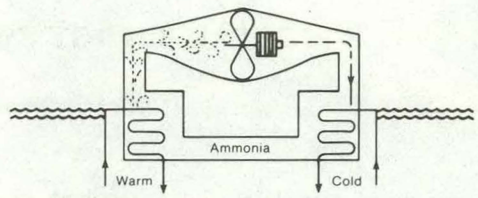
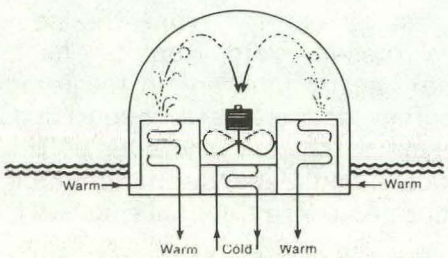
*SERI, Ocean Systems Program Branch.

OCEAN THERMAL ENERGY

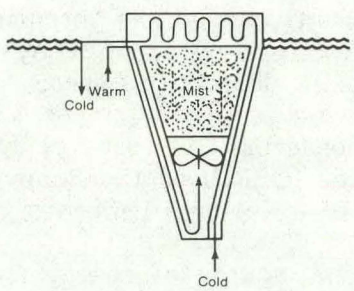
Closed Cycle--Warm ocean surface waters cause a working fluid, such as ammonia, to evaporate. Cold water is pumped from deep waters and is used to condense the ammonia, which is returned to the evaporator to repeat the process in a closed cycle. The work of expansion of the vapor going from the evaporator to condenser is converted to mechanical energy in a turbine. A generator connected to the turbine produces electrical power (Secs. 1.0 and 2.0).



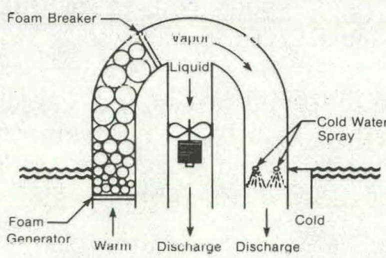
Claude Cycle--This is similar to the closed cycle but does not use ammonia as the working fluid. Steam is produced by flashing the seawater in the evaporator at vacuum conditions. The saturated vapor is expanded through a large low-pressure turbine. The vapor is then condensed by either direct contact or a shell and tube surface condenser, using cold water supplied from the ocean depth as the heat sink. Fresh water is produced as a beneficial by-product when a surface condenser is used. Seawater as the working fluid is continuously supplied to the device in an open-cycle process. Electrical power is produced from the generator connected to the vapor turbine (Secs. 2.1-2.4).



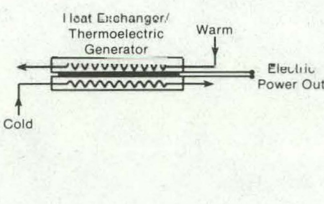
Mist Lift--The ocean's warm surface water is allowed to flow by gravity through a hydraulic turbine. The thermal energy of the water is then used to lift it back to the ocean's surface by means of the lift process. Specifically, a fine mist is created from the warm water entering the bottom of a lift column. The steam fraction of the mist flows in the direction of a condenser located at the top of the column. With efficient two-phase coupling, the work of expansion of the steam is converted to potential energy in the liquid phase. The elevated seawater is then discharged back to the sea in this continuous cycle (Sec. 3.1).



Foam Lift--Similar in thermodynamic principles of operation to the mist lift, this concept uses foam that has a continuous fluid interspersed with vapor bubbles to stabilize the two-phase flow. The surfactant is required: (1) to create an adequate foam to prevent premature rupture in the lift tube, and (2) in the condenser as an antifoaming agent. The liquid carried to height in the process provides the potential energy to drive a hydraulic turbine connected to an electric generator (Sec 3.2).



Thermoelectric OTEC--The ocean temperature gradient is impressed across a semiconductor thermoelectric device that produces electricity by direct conversion using the Seebeck effect (Sec. 4.4).



WAVE ENERGY CONVERSION

Refracted Wave Energy Device--An artificial atoll is used to cause incoming waves to focus, by refraction, toward the center of the atoll. The energy collected from the focused waves is converted into a vortex flow in a standpipe at the central core of the device. The vortex flow drives a hydraulic turbine/generator located at its base (Sec. 4.1.2).

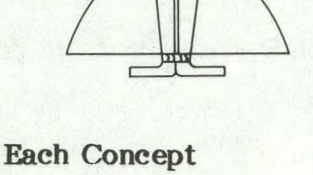
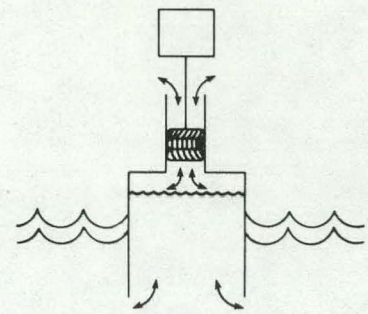
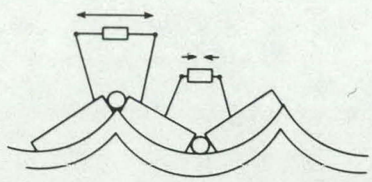


Figure 1-1. Capsule Descriptions of Each Concept

WAVE ENERGY CONVERSION (Continued)

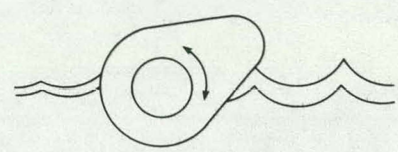
Pneumatic Cavity Resonator—A passing wave causes a water column to resonate in a tuned air cavity, and the pressure variations produced are used to cause an oscillating air flow that drives a pneumatic turbine (Secs. 4.1.4-4.1.6).





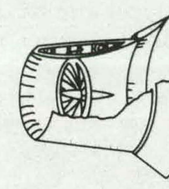
Rafts—A segmented floating surface yields relative motion between the various segments (rafts). This motion can be converted to useful energy by a system of hydraulic pumps and motors (Sec. 4.1.6).

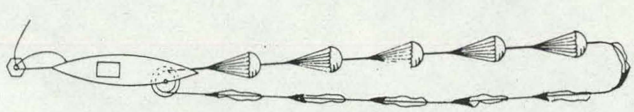
Duck—This device is in the shape of a stubby hydrofoil section that oscillates about a reference axis with a motion matching the orbital motion of the water in the waves approaching its "beak." No new waves are produced astern because of the cylindrical shape on the back side, thereby leading to a high energy capture efficiency (Sec. 4.1.8).



OCEAN CURRENT ENERGY CONVERSION

Axial Flow Turbine—An axial flow turbine configuration is used to convert the ocean current's kinetic energy into mechanical energy. This particular device has two counter-rotating rotors with catenary supported blades mounted within a stationary housing that serves as an augmenting duct. Mechanical energy is converted to electrical energy using generators connected to a friction drive power takeoff at the rotor's rim (Sec. 4.2.1).

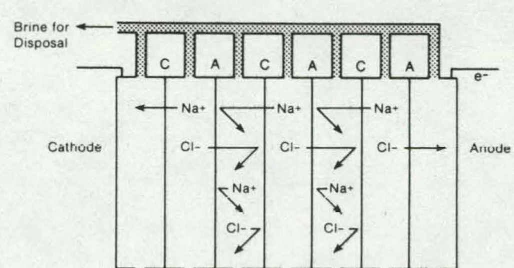


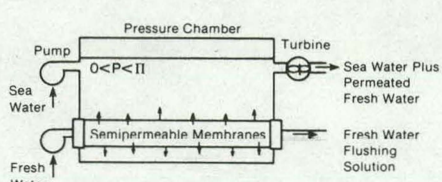


Drogue Chute—The device is composed of some 40 parachutes connected to a continuous loop driven by the ocean current. The loop is connected to the drive shaft of an electric generator. The ocean current fills the parachutes and drives the belt loop. As the chutes reverse direction, they collapse and travel back to the drive shaft (Sec. 4.2.2).

SALINITY GRADIENT ENERGY CONVERSION

Reverse Electrodialysis—Alternating cation-permeable and anion-permeable membranes provide for selective migration of sodium and chlorine ions from the seawater to the fresh water chambers. Each pair of chambers acts as a dialytic battery creating an electrical potential of about 80 mV. Stacking many such chamber pairs results in a practical voltage level (Secs. 4.3 and 4.3.2).





Pressure Retarded Osmosis—Concentration difference causes fresh water to pass through the semipermeable membrane into the high-pressure seawater chamber. The pressure in the seawater chamber is maintained at some energy extraction optimum level, which is less than the osmotic pressure. Net power is provided by directing the seawater plus permeated fresh water through a hydraulic turbine (Secs. 4.3 and 4.3.1).

Figure 1-1. Capsule Descriptions of Each Concept (Concluded)

SECTION 2.0

CLAUDE CYCLE RESEARCH OVERVIEW

T. R. Penney*

INTRODUCTION

Although the engineering emphasis of the U.S. Program in Ocean Energy is directed at demonstrating large-scale OTEC power plants in the open ocean using closed Rankine cycle energy conversion hardware, advanced R&D is being done to develop alternative power cycles that are potentially more cost effective. A 1979 Westinghouse report entitled "100 MW_e OTEC Alternate Power Systems" suggested that a Claude (open) cycle was as cost-effective as other OTEC options. Since Claude cycle designs were basically in an infancy stage, large technical uncertainties surrounded the performance and design of the major subsystem elements: turbine, condenser, evaporator, and the deaeration system.

OBJECTIVE

The long-range objective of the program is to provide a definitive assessment of the potential of open-cycle systems. This will be met by completing two major phases:

- Phase I—Reduce scientific uncertainty in those subsystem technologies critical to the performance of an open-cycle OTEC plant through analysis and laboratory experiment.
- Phase II—Provide complete engineering design and fabrication of experimental subsystem hardware and perform subsystem testing.

Phase I will generate information sufficient to predict subsystem performance, and Phase II will demonstrate these predictions for applications to full-scale systems. Successful completion of these phases will provide the engineering data necessary to assess the potential of open-cycle OTEC systems.

FIVE-YEAR PLAN

The Claude cycle multiyear plan shown in Fig. 2-1 outlines a technology development program that was initiated during FY 1980 in turbomachinery, evaporator, condenser, and deaeration experimental research and analysis. This research will assess the potential of the Claude cycle system with the necessary engineering data for extrapolations to commercially feasible, larger-scale systems by 1985.

Upon completion of the component data base in these areas, a trade-off study and conceptual design will be performed (FY 1982) to establish a new integrated baseline model. Since potable water would be sacrificed if a direct contact condenser were selected, a study must address both the economic and siting issues of the integrated system. The

*SERI, Ocean Systems Program Branch.

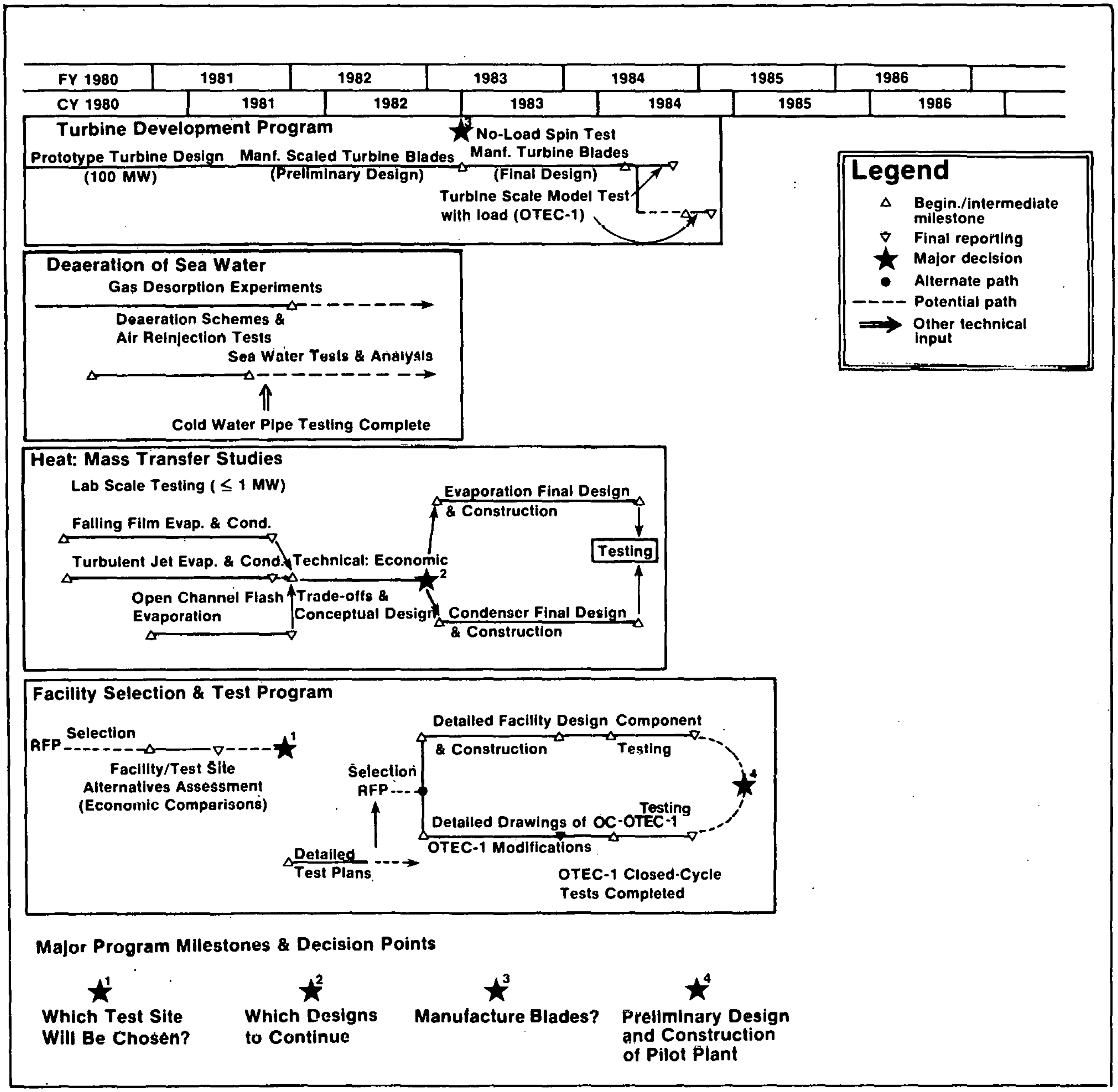


Figure 2-1. Claude Open-Cycle OTEC Multiyear Plan

results of this trade-off will lead to a subscale experimental program that uses the best choices among alternatives. Several milestones must be completed before testing the subsystem components during FY 1984. An assessment of facilities and test sites will be completed in FY 1981. A decision will be made where each of the subsystem components can be tested based on physical requirements, economic considerations, legal and institutional barriers, and other constraints. As indicated in Fig. 2-1, OTEC-1, with certain modifications to accommodate open-cycle components, is a potential test option. Certain subsystem elements may require a new test facility to accommodate larger size scale models that will provide reliable data used for extrapolation to larger scale commercially feasible equipment.

After completing the testing in FY 1984-85, the Ocean Systems Program Branch will have to decide whether or not to escalate the program from the technology development to the engineering development (pilot plant) classification.

SUMMARY OF FY 1980 PROGRESS

Subcontracts were awarded during FY 1980 and their objectives, approach, present status, and expected results are described in each section. The three major research categories and respective subcontractors are:

- Turbomachinery—Westinghouse Electric Corp.;
- Heat and Mass Transfer—Creare Inc., Science Applications, Inc. (SAI), Westinghouse Electric Corp.; and
- Deaeration—Hydronautics, Inc.

The following accomplishments make important contributions as a direct result of subcontracted and national lab research and development during FY 1980.

Turbomachinery

- A thin-shell blade using E-glass fiber tends to twist because of centrifugal movement; changing the chord does not solve the problem.
- A central box-spar design eliminates the twisting but requires mass overbalance at the tip leading edge to suppress flutter.
- Several narrower blades at constant solidity will weigh and cost the least, but upper limits exist because of excessive flexibility and large static droop.

Heat and Mass Transfer

- Calculations have shown that the effective falling film condenser height for a 100-MW_e open-cycle plant ranges from 0.6-1.8 m (2-6 ft) for plate spacing of 2.5-7.6 cm (1-3 in.), respectively.
- Analysis has shown that an effective falling film evaporator for a 100-MW_e open-cycle plant would require a height of only 0.6 m (2 ft) but require a more elaborate distribution system than an open-channel evaporator.

- A heat and mass transfer laboratory was constructed, instrumentation was calibrated, initial checks were performed to achieve heat balance within a few percentage points, and experimental data were taken using normal operating conditions on a falling jet evaporator showing heat transfer coefficients of 70,000 W/m^2 K.

Deaeration

- Experimental laboratory studies using actual operating conditions with fresh water have shown that the percentage of deaeration increases with the velocity. A flow rate of 2 m/s causes about 25% of the gas to evolve naturally.
- Evolution of gas from seawater depends on the nucleation sites available. Literature searches indicate that naturally occurring nucleation sites in surface seawater have a radius of 15-20 μm, which is adequate to support bubble nucleation. Preliminary results in open ocean qualitatively indicate that gas did not evolve from deep water samples.

SUMMARY OF FY 1981 PLANS AND MILESTONES

Results from the subcontracted activities in the three major Claude cycle research areas will be reported according to the milestone schedule shown in Fig. 2-2. A list of deliverables is contained in Table 2-1.

Table 2-1. Data Item Deliverables Log

Deliverable No.	Description	Due Date
1	Subcontract Quarterly Review	F/J/O
2	Test Site Alternatives Report	6/81
3	Annual Research Report	3/81
4	Al Materials Research Report	1/81
5	Initial Prototype Design	2/81
6	Deaeration, E/C Facility Report	2/81
7	Final Prototype Design	6/81
8	Deaeration Final Report	7/81
9	Final Report-Falling Films	9/81
10	OC-OTEC Material Report	10/81
11	Final Report-Turbulent Jets	10/81
12	Claude System Performance Report	10/81
13	OCFE Test Results	1/82

New initiatives for FY 1981 may include:

- detailed site studies for Phase II testing, primarily consisting of a turbine test facility and issues pertaining to environmental constraints;

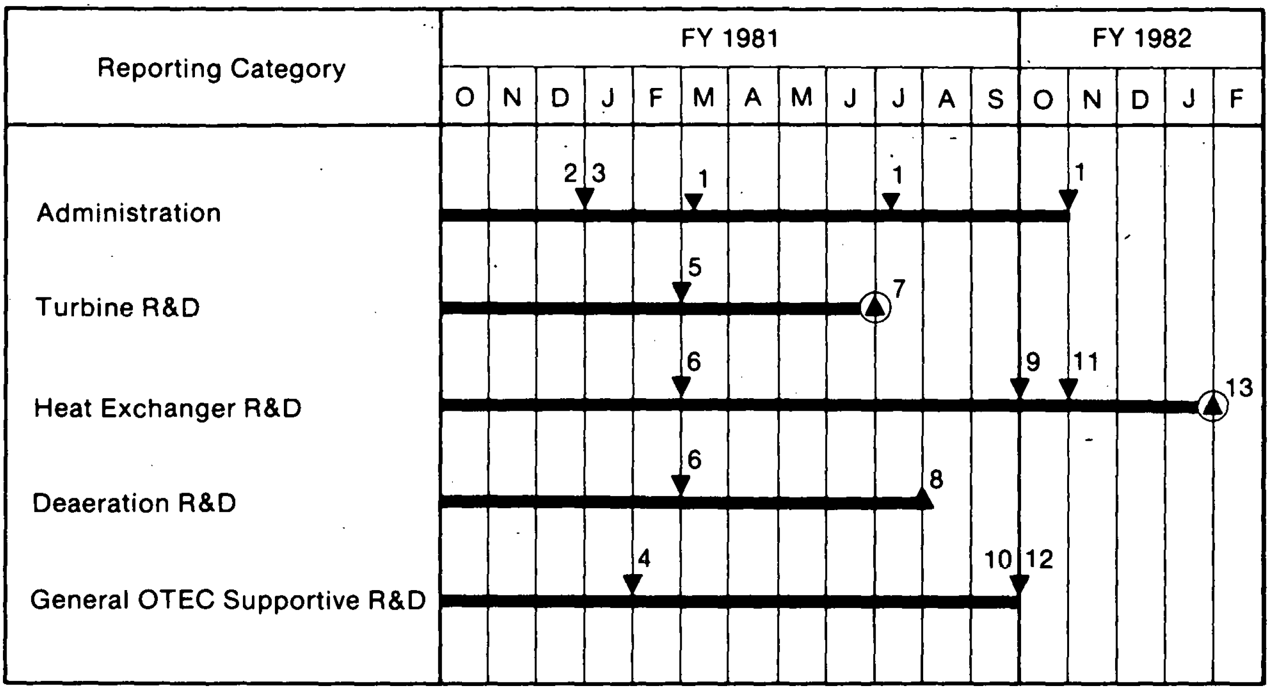


Figure 2-2. Milestone Schedule and Status Report for Claude Cycle Research

- trade-off studies for identifying a new OC-OTEC baseline using a newly developed technical data base on heat exchangers;
- at-sea deaeration experiments relating gas evolution of seawater in static and dynamic testing environments; and
- continued low-pressure turbine development, specifically blade and disc design, fabrication, and scale-model testing.

This FY 1981 program has been structured, with modest and realistic financial constraints, to develop conceptual designs so a trade-off can be performed consistently and rationally with experimental data and design methods reliable for extrapolation to a prototype scale OTEC plant.

2.1 SYSTEM ANALYSIS—Douglas A. Olson*

2.1.1 Objective

The system analysis task is to ascertain how to analyze the thermo-hydrodynamic performance of Claude cycle power plants and apply this to analyzing various Claude cycle systems to determine which performs best. The results will be used by SERI's Ocean Systems Program Office to aid decision making. A secondary objective is to establish at SERI a method, which has been developed elsewhere, to analyze the performance of closed-cycle power plants.

Specific objectives for FY 1980 were to:

- develop a computer program of the Claude cycle system performance algorithm developed in FY 1979;
- develop a computer program of Abelson's closed-cycle system performance algorithm;
- develop performance models of a falling jet evaporator and condenser and a Claude cycle surface condenser; and
- apply the Claude cycle system performance algorithm by comparing a system using a falling jet evaporator and condenser to one with a channel flow evaporator and a surface condenser.

2.1.2 Approach

A Claude cycle computer program was to be developed that would predict the design point performance of a system based on a channel flow evaporator and a direct-contact jet condenser. The computer program was to have each component of the system (evaporator, turbine, condenser, deaerator) as a modular subroutine so that the different components could be analyzed easily. The program was to be verified by studying the deaeration effects.

The closed-cycle performance computer program was developed by acquiring Abelson's (1978) algorithm and programming the algorithm for use on SERI's CDC 7600 computer. The program was to be verified by studying the effect of annual temperature variations on the performance of a closed-cycle system.

The falling jet evaporator and condenser performance models were developed by first finding a method for distributing water to the falling jets. Falling jet heat and mass transfer data would then be used to determine the size of the falling jet evaporator and condenser needed to produce and condense a specified steam mass flow rate. The losses in the full-size water distribution system would then be determined by using experimental data and analytical models. The output would be determined by the size of a falling jet evaporator and condenser based on the specific water distribution required and the losses in the full-size unit. These algorithms would then be programmed as subroutines of the main program.

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*SERI, Solar Thermal Research Branch.

The Claude cycle system comparison looked at the net power output at the common design point of two systems (one using a channel flow evaporator and surface condenser and one using a falling jet evaporator and condenser) sized to produce the same gross power.

2.1.3 Status

The Claude cycle computer program is operational on the SERI CDC 7600 computer and has been used to study the deaeration effects. The results have been published in Lewandowski, Olson, and Johnson (1980) and are shown in Fig. 2-3. Net power is plotted as a function of the temperature distribution through the plant, where R is the temperature drop across the evaporator divided by the temperature drop across the condenser. The results show that deaeration does not improve the performance of this system with the given assumptions regarding component performance. In this simulation, warm water entered at 25° C, cold water entered at 5° C, and the turbine temperature drop was 10° C.

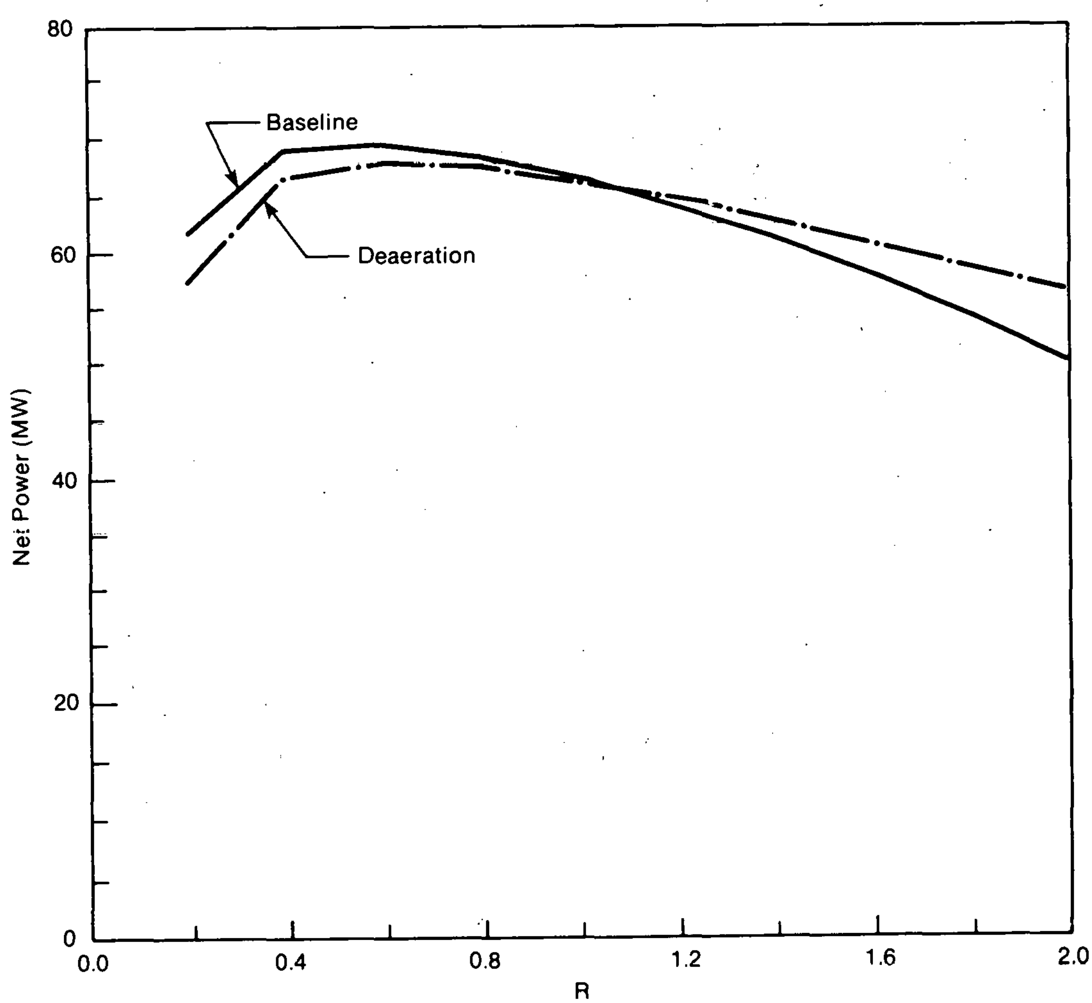

Figure 2-3. Results from Claude Cycle Deaeration Analysis

The closed-cycle algorithm has been programmed into the SERI computer. The annual performance study of the Lockheed PSD-1 design at the Hawaii and Puerto Rico sites has been completed. The performance was very sensitive to the available seawater temperature difference. This algorithm predicts performance at the design point. The annual performance study results must be interpreted with this constraint in mind. At the temperatures Lockheed assumed in developing their design, the algorithm predicted the same performance as Lockheed.

A slotted pipe geometry has been proposed for the falling jet evaporator and condenser. This distribution system significantly reduces the size (25% in plant diameter) over the Westinghouse open-channel evaporator. Analysis and experimentation have been completed on this design's ability to deliver uniform jets. Results indicate that individual sections of slotted pipe must be kept short (1 metre or less) to avoid nonuniformities in the jets. Scaling laws have been developed to determine the optimum length of the slotted pipes for jet uniformity. They also must be kept short to avoid large head losses. Other evaporator and condenser geometries have been proposed. Preliminary calculations indicate a chamber with a slotted floor will eliminate large head losses, deliver uniform jets, and maintain the reduced size of the slotted pipe geometry.

2.1.4 Expected Results/Future Effort

During FY 1981, we intend to:

- develop a conceptual design of the water distribution system for the falling jet evaporator and condenser;
- develop a performance model for the falling jet evaporator and condenser based on the water distribution concept and the falling jet heat and mass transfer data and theory being developed;
- improve the turbine and deaerator models in the system performance algorithm so we can predict off-design performance;
- develop a surface contact condenser model and incorporate models of other evaporators and condensers into the system analysis computer program; and
- compare the performance of various Claude cycle OTEC configurations at their common design point. The comparison will be made in terms of plant size and relative net power production for a specified gross power output.

2.1.5 References

Abelson, H. 1978 (Aug.). OTEC Power System Performance Model. MTR 7924. McLean, VA: Mitre Corp.

Lewandowski, A. A.; Olson, D. A.; Johnson, D. H. 1980 (Sept.). Open Cycle OTEC System Performance Analysis. SERI/TR-631-692. Golden, CO: Solar Energy Research Institute.

2.2 HEAT AND MASS TRANSFER OVERVIEW—David Johnson*

The overall performance of a Claude cycle power plant is strongly influenced by the performance of its evaporator and condenser as measured by their approach to equilibrium and head loss. Seawater flows through these components and steam is either produced by evaporation or quenched by condensation. During evaporation the warm seawater cools down, and during condensation the cold seawater warms up. Maximum use is made of the available energy in the warm seawater if both the cold and warm water approach the temperature of the steam in their respective components. The degree to which this is achieved is called the approach to equilibrium.

These components also have losses resulting from friction, unrecovered kinetic energy of the flowing water, and changes in the height required to produce a flow of water. The total loss in each component may be expressed as a loss in hydraulic head. Usually, a closer approach to equilibrium is achieved at the cost of head loss. A high performance evaporator or condenser will achieve a close approach to equilibrium with little head loss.

Other component design factors include minimizing the transportation of liquid from the evaporator by the steam and using suction to remove noncondensable gases from regions of highest concentration in the condenser.

All of these issues were considered by the French (Claude 1930; Nisolle 1947; Nijery 1954) in their pioneering work on OTEC conducted during the first part of this century and by Westinghouse (1979) in their baseline conceptual design of a Claude cycle power plant. Westinghouse chose a channel-flow evaporator with screen demister and a cross-flow tube condenser with midcondenser noncondensable gas removal. They chose this evaporator because water can be distributed to the channels simply and because there is a great deal of data on the performance of this configuration when used for desalination. Its steam-flow rates were high enough to create a liquid carryover problem, so screen demisters were included. The data extrapolation from desalination to actual operating conditions introduces large uncertainties in the baseline design. Also, if efficient water distribution methods can be devised, other evaporator configurations (e.g., falling jets or films) may perform better. However, data on falling-jet, falling-film, and channel-flow evaporators under actual operating conditions are very scarce. Also, an evaporator could be designed that eliminates liquid carryover.

Westinghouse chose a tube condenser because fresh water is produced as a byproduct. However, for most U.S. applications, obtaining fresh water is not as important as electrical power. If fresh water production is abandoned, the approach to equilibrium in the condenser may be improved without sacrificing head loss by adopting direct contact condensation of the steam on the cold water. However, data on direct contact condensation is limited.

The SERI Claude cycle program investigates alternatives to the Westinghouse baseline design for the reasons just discussed. In the first phase of this program, performance data will be acquired and a design methodology will be developed for each of the alternative candidate evaporators and condensers as well as for the baseline evaporator. Westinghouse will study channel-flow evaporators; Science Applications, Inc. (SAI), will study falling-film evaporators and condensers; and SERI and Creare, Inc., will study

*SERI, Solar Thermal Research Branch.

falling-jet evaporators and condensers. The projected performance of the resulting designs will be compared in a system analysis trade-off study and the most promising component chosen for full-scale construction and testing in the next phase of the program. The following subsections describe the work done so far under the first phase of the program.

References

Claude, G. 1930 (Dec.). "Power From the Tropical Seas." Mechanical Engineering. Vol. 52 (No. 12).

Nisolle, L. 1947. "Utilisation de l'Energie Thermique des Mers: les Problems de Fonctionvement." Societe les Ingeniurs Civils de France. Translated by C. R. Adams. Paris, France.

Nijery, A. 1954 (Mar.). Utilization of the Thermal Potential of the Sea for the Production of Power and Fresh Water. Berkeley, CA: Institute of Engineering Research, University of California.

Westinghouse Electric Corp. 1979 (Mar.). 100 MW_e OTEC Alternate Power Systems. Lester, PA: Westinghouse Electric Corp.

2.2.1 Evaporator/Condenser Performance Task—David Johnson*

2.2.1.1 Objectives

The overall objective is to be able to experimentally and theoretically determine the performance of Claude cycle evaporators and condensers.

The specific objectives for FY 1980 were to construct a heat and mass transfer laboratory capable of gathering data on Claude cycle evaporators and condensers and heat and mass transferred between falling jets of warm and cold water. Another objective was to develop an analytical model to predict the heat and mass transfer between falling jets of warm and cold water.

2.2.1.2 Approach

The laboratory must be able to test sections of full-scale (approximatley 100 MW_e) open-cycle evaporators and condensers and have independent control over the warm and cold water flow rates, inlet temperatures, and the concentration of noncondensables in the condenser. The laboratory also must be instrumented so the heat and mass transfer from an evaporator and to a condenser can be measured separately and accurately within a few percentage points. Finally, it must provide an automated data acquisition system interfaced with and controlled by a computer so that large test matrices can be handled efficiently.

The approach to the falling-jet heat and mass transfer experiments was to design and build falling-jet evaporator and condenser test modules to represent sections of a full-scale evaporator and condenser where the width and height of the falling jets can be varied. A test matrix is to be designed that has as independent parameters:

- the warm and cold water flow rates and inlet temperatures,
- the width and height of the falling jets in the evaporator and condenser, and
- the concentration of noncondensables in the condenser with values spanning the range of typical operating conditions.

Next, measurements are to be taken to fill out the test matrix. Finally, guided by fundamental analysis of the falling-jets, a correlation of the data is to be derived that will allow efficient calculation of the falling-jet performance.

A falling-jet analytical model is to be developed by reviewing existing literature and formulating an approach to modeling the jets. The model equations then are to be developed and programmed for numerical solution by a computer. Next, the model parameters are to be determined and the model predictions verified by comparing the numerical solutions with the experiment. Finally, a parametric study of the jet behavior is to be performed and simple functions fitted to the results for interpolation between data points by the performance model.

*SERI, Solar Thermal Research Branch.

2.2.1.3 Status

The heat and mass transfer laboratory has been constructed, operational procedures have been established, and the laboratory's performance has been verified. The basic temperature, flow rate, and mass transfer instrumentation has been calibrated and installed and is operating correctly. A description of the laboratory has been published in Kreith (1980). Figure 2-4 shows a schematic of the laboratory.

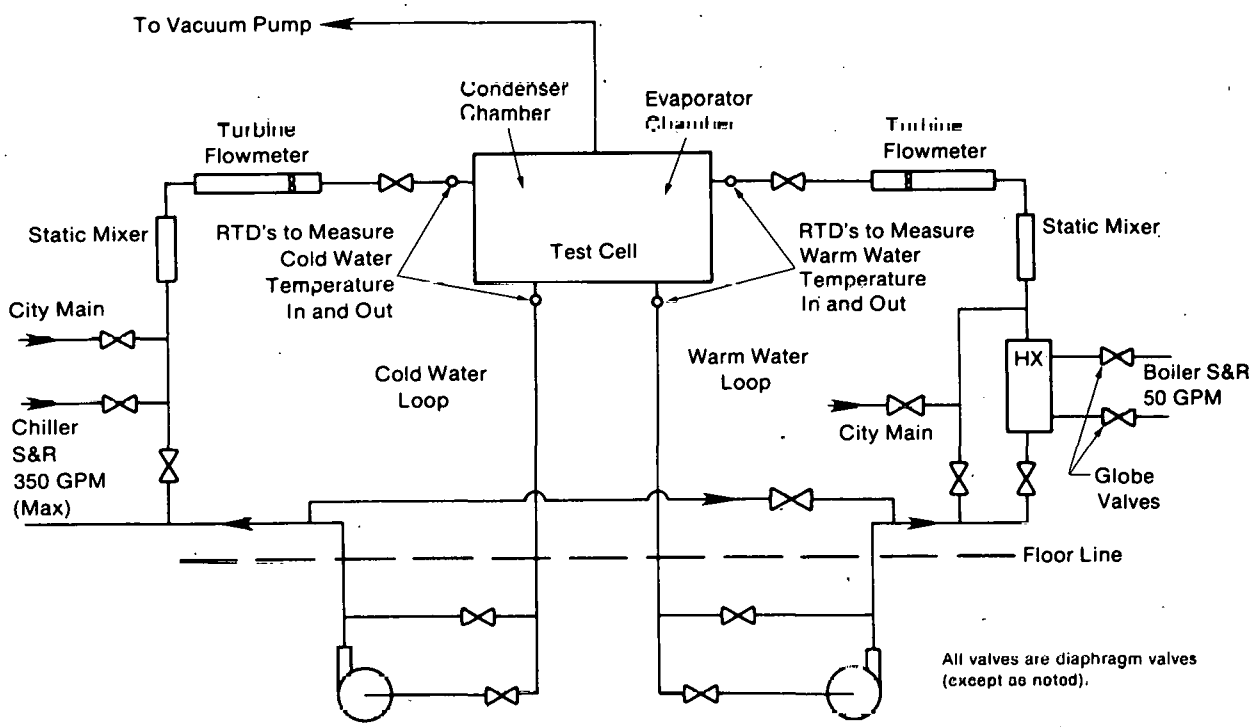

Figure 2-4. Piping Schematic of Heat and Mass Transfer Laboratory

The falling-jet evaporator and condenser test modules have been designed and built. The falling-jet width will be varied by exchanging slotted pipes of various widths (already built), and height will be varied by using a false floor (designed but not yet built). Preliminary heat and mass transfer measurements have been obtained during the laboratory shakedown. The falling-jet evaporator and condenser and preliminary data on their performance are described in Kogan et al. (1980).

A literature search has been completed using the government's computerized literature files. Eleven papers were found on condensation of turbulent jets, no papers on evaporation from turbulent jets, and three papers on mass transfer into turbulent jets. From these papers an approach to modeling the falling jets has been formulated. This approach has the vapor flowing in a channel between the jets, uses the turbulence models found in the mass transfer papers to determine the heat transfer in the jets after an appeal to the Reynolds analogy, and includes the effect of noncondensables on the condenser.

2.2.1.4 Expected Results/Future Effort

The objectives for FY 1981 will be to finish acquiring data and developing an analytical model to describe the heat and mass transfer between falling jets of warm and cold water.

Specific objectives are to:

- install equipment capable of injecting controlled amounts of noncondensable gases into the test cell and measuring the concentration of noncondensables at various locations in the condenser;
- develop an automated data acquisition system;
- design the falling-jet test matrix;
- carry out the measurements to fill out the test matrix;
- formulate the falling-jet model equations and program them for numerical solution by a computer;
- compare the theoretical and experimental results to determine model parameters and verify the predictions of the theory; and
- perform parametric studies of the falling-jet behavior using the theoretical model and extracting interpolation functions from the results.

2.2.1.5 References

Kreith, Frank. 1980 (July). An Overview of SERI Solar Thermal Research Facilities. SERI/SP-631-750. Golden, CO: Solar Energy Research Institute.

Kogan, A.; Johnson, D. H.; Green, H. J.; Olson, D. H. 1980. Open Cycle OTEC System with Falling Jet Evaporator and Condenser. Presented at Seventh Ocean Energy Conference, Washington, DC, 2-5 June 1980. Washington, DC: U.S. Department of Energy.

2.2.2 Falling-Film Evaporator/Condenser—A. T. Wassel*

2.2.2.1 Objective

The economic feasibility of an open-cycle approach to the OTEC power plant design largely depends on three major system factors: (1) the operating characteristics of the evaporator and the condenser; (2) the need for deaeration; and (3) innovative turbomachinery designs (Boot and McGowan 1974; Brown and Wechsler 1975; Sciubba 1978; Shelpuk and Lewandowski 1979; Watt, Mathews, and Hathaway 1977). The SAI program will develop the design methodology and experimental data base for open-cycle evaporators/condensers with specific emphasis on the direct contact, falling-film configuration.

The SAI research program involves fundamental heat and mass transfer analysis, supporting laboratory experiments, and implementation of the developed technology in the design of an experimental validation program on a prototype system.

2.2.2.2 Approach

Analytical performance models for falling-film evaporators/condensers are being developed that combine basic considerations of heat and mass transfer processes in seawater with the practical considerations and constraints of actual hardware systems. A parallel laboratory experimental effort is being carried out to confirm modeling approaches using geometries and flow conditions analogous to an ultimate full-scale system. The validated performance models will provide key data for preliminary subsystem conceptual designs and will establish a detailed test plan for full-scale evaluations of falling-film evaporator/condenser designs.

2.2.2.3 Status

Analyses describing heat and mass transfer processes in falling-film systems (based on existing data bases) are nearing completion. Subsystem performance code development is well underway, and check-out parametric investigations of evaporator/condenser performance have been carried out. The design of the laboratory test facility (shown in Fig. 2-5) and instrumentation selection is under way.

2.2.2.4 Expected Results/Future Effort

The SAI research and development (shown in Fig. 2-6) will provide the validated design methodology for falling-film evaporators/condensers required to support economic assessments of alternative approaches to the OTEC power plant design. The current phase of the program will lead to the design, fabrication, and testing of 1-MW_e subsystems.

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*Science Applications, Inc.

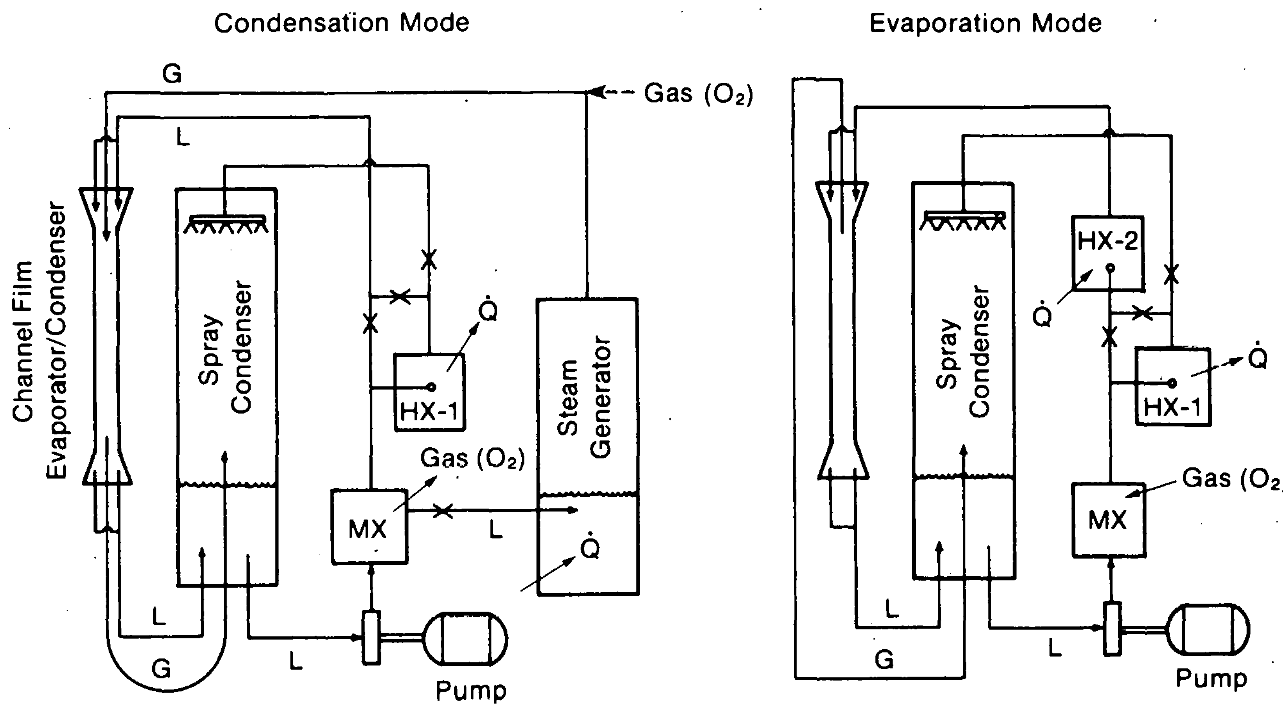


Figure 2-5. Schematic of Falling-Film Evaporator/Condenser Laboratory Experiment

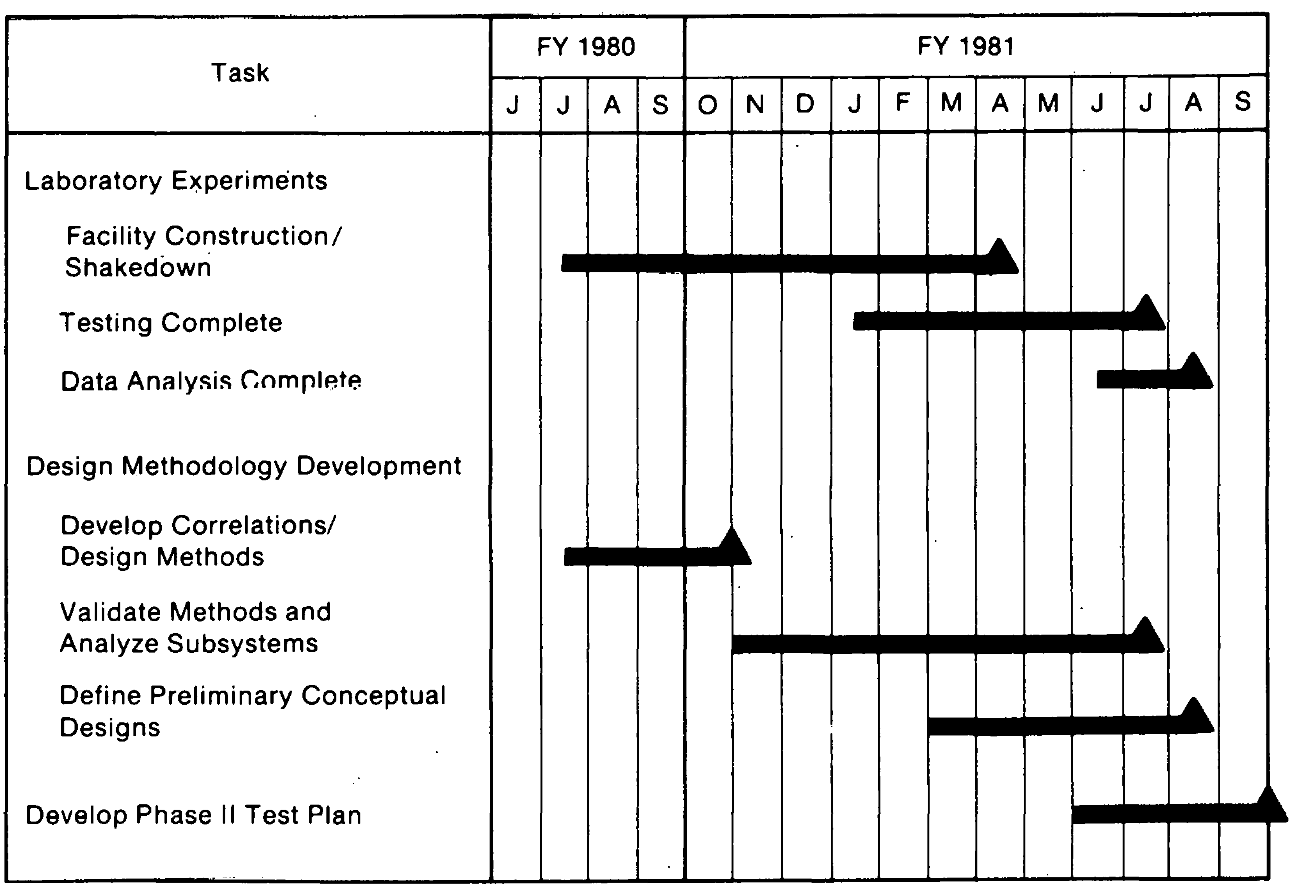


Figure 2-6. Schedule and Program Milestones for Falling-Film Evaporator/Condenser Performance/Configuration Evaluation

2.2.2.5 References

Boot, J. L.; McGowan, J. G. 1974 (Aug.). Feasibility Study of a 100 Megawatt Open Cycle Ocean Thermal Difference Power Plant. NSF/RANN/SE/GI-34979/TR/74/3. Amherst, MA: University of Massachusetts.

Brown, C. E.; Wechsler, L. 1975 (May). "Engineering and Open Cycle Power Plant for Extracting Solar Energy from the Sea." Proceedings of the Seventh Offshore Technology Conference. OTC 2254. Houston, TX.

Sciubba, C. 1978 (Dec.). "Project Summary: 100 MW_e OTEC Alternate Power Systems Study." Proceedings of the OTEC Alternate Cycles Contractors' Information Exchange Meeting. Washington, DC: Westinghouse Corporation.

Shelpuk, B.; Lewandowski, A. A. 1979. Alternate Cycle Applied to Ocean Thermal Energy Conversion. Presented at the Eleventh Offshore Technology Conference, No. 3589. Houston, TX; 30 April - 3 May 1979.

Watt, A. D.; Mathews, F. S.; Hathaway, R. E. 1977 (Dec.). Open Cycle Ocean Thermal Energy Conversion: A Preliminary Engineering. ALO/3723-76/3. Golden, CO: Colorado School of Mines, Engineering Physics Department.

2.2.3 Open-Channel Flash Evaporator/Demister–Paul D. Ritland and Noam Lior*

2.2.3.1 Objective

The objective is to develop a data base on open-channel flash evaporators relating to open-cycle OTEC systems. The specific objectives are to study the approach to equilibrium, pressure drop, hydrodynamics, desorption (deaeration), and other dissolved gas effects as a function of flow geometry, flow rate, flashing aperture (e.g., orifices and nozzles), and influence of surfactants. This research includes studying methods to enhance the approach to equilibrium and gas desorption. A more limited objective is to study the need for demisters and their efficiency and pressure drop as a function of steam flow rate and geometry. The tests will also show whether an evaporator of sufficient height requires a demister at all. If not, parasitic losses in the system could then be eliminated.

2.2.3.2 Approach

A small and versatile test facility will be designed and constructed, and a parametric experimental study will be conducted. In flash evaporation studies, the primary unknowns are the evaporation rate, approach to equilibrium, and steam pressure drop; in gas desorption studies, the primary unknowns are the concentration of gas in the seawater before and after flashing; and in demisting studies, the primary unknowns are the need for a demister and its efficiency and pressure drop.

The results will be correlated in a manner that provides the necessary information to design, construct, and test the larger OTEC flash evaporator model planned for Phase II of the open-cycle OTEC program.

2.2.3.3 Status

Presently, there is no quantitative information on flash evaporation and gas desorption (deaeration) and insufficient information on optimal demisting of the emanating steam during flash evaporation in the range of parameters (temperature, pressure, flow rate) relevant to open-cycle OTEC systems. The proposed study should throw light on these phenomena and provide design information for the open-cycle OTEC program.

2.2.3.4 Expected Results/Future Effort

The following results are expected:

- the development of a quantitative relationship among flash evaporation rate, approach to equilibrium of fresh and saline water, and stream pressure drop as a function of flow rate, depth, stage length, temperature, and flash-down temperature difference;

*Westinghouse Electric Corporation and University of Pennsylvania, Department of Mechanical Engineering, respectively.

- the development of a quantitative relationship between the gas desorption rate from the flashing stream and the flow rate, depth, stage length, temperature, flash-down temperature difference, and original gas concentration;
- the determination of the rate of demisting as a function of stage height, if no demister is used and demister effectiveness and pressure drop for two to three common demister types with demister installed; and
- a better understanding of the fundamental phenomena associated with flash evaporation and desorption in the range of parameters pertinent to open-cycle OTEC systems.

These results are to provide design tools for the Phase II OTEC subsystem tests.

2.2.3.5 References

Lior, N.; Greif, R. 1976 (May). "Heat Transfer and Evaporation in the Horizontal Flash Evaporator." Proceedings of the Fifth International Symposium on Fresh Water from the Sea. Porto Conte, Sardinia, Italy.

Lior, N.; Greif, R. 1979. "A System for the Experimental Study of Flash Evaporation." Desalination. Vol. 30: pp. 87-99.

Westinghouse Electric Corporation. 1979 (Mar.). 100 MW OTEC Alternate Power Systems. Lester, PA: Power Generator Division.

2.2.4 Direct-Contact Evaporators and Condensers—Bharatan R. Patel*

2.2.4.1 Objective

The objective is to develop a heat and mass transfer data base and a method for designing and evaluating direct contact evaporators (falling turbulent jet) and condensers (falling turbulent jet and film) suitable for open-cycle OTEC application.

The evaporator and condenser are two subsystems critical to the performance of the open-cycle OTEC plant. Direct contact evaporators and condensers appear to be best suited for this application and would eliminate the problems of high cost, biofouling, etc., that occur in conventional heat exchangers. Although these direct contact heat exchangers have demonstrated advantages, the available application data base is inadequate for use in open-cycle OTEC plant design. Further, adequate design and optimization methods have not yet been developed.

2.2.4.2 Approach

The project consists of three major activities: (1) obtaining heat and mass transfer data, (2) developing data correlations, and (3) developing a design method.

The heat and mass transfer data for selected direct contact evaporator and condenser configurations will be obtained over a range of prototypical open-cycle OTEC plant conditions. A test facility that provides the required range of conditions and test geometries will be designed, constructed, and instrumented. A series of scoping tests will then be performed to determine the important parameters affecting the performance of the direct-contact evaporator and condenser. Based on the results of these scoping tests, the Phase I tests will be performed where the important parameters are systematically varied over the appropriate range. These tests (including the scoping tests) will provide the required heat and mass transfer data base.

Correlations will be developed to present the heat and mass transfer data in a form easily implemented in a design method. An in-depth review of available correlations will be performed to determine if they are adequate. Then, these correlations will be refined or new ones developed as appropriate.

A method will be developed that can be used to design and evaluate the performance of the direct-contact evaporator and condenser selected. The design method will use the previously developed data correlation.

Specifically, the major project involves:

- a preconstruction report containing specifications and milestone charts for facility construction, instrumentation, installation, and total facility shakedown accomplishments;
- an interim report documenting scoping test results and formulating the test matrix for the Phase I evaporator and condenser tests;

*Creare, Inc.

- an interim report documenting the results of the Phase I evaporator and condenser test results; and
- a final report documenting the data correlations and design methodologies and recommendations.

2.2.4.3 Status

The project schedule is shown in Figs. 2-7, 2-8, and 2-9. The project was initiated 1 June 1980 with a partial funding of $50,000 for FY 1980. This partial funding allowed the initiation of facility and instrumentation design to identify and place orders for long lead-time items. The preliminary facility and instrumentation design will be completed and orders for long-leadtime items placed by the end of October 1980.

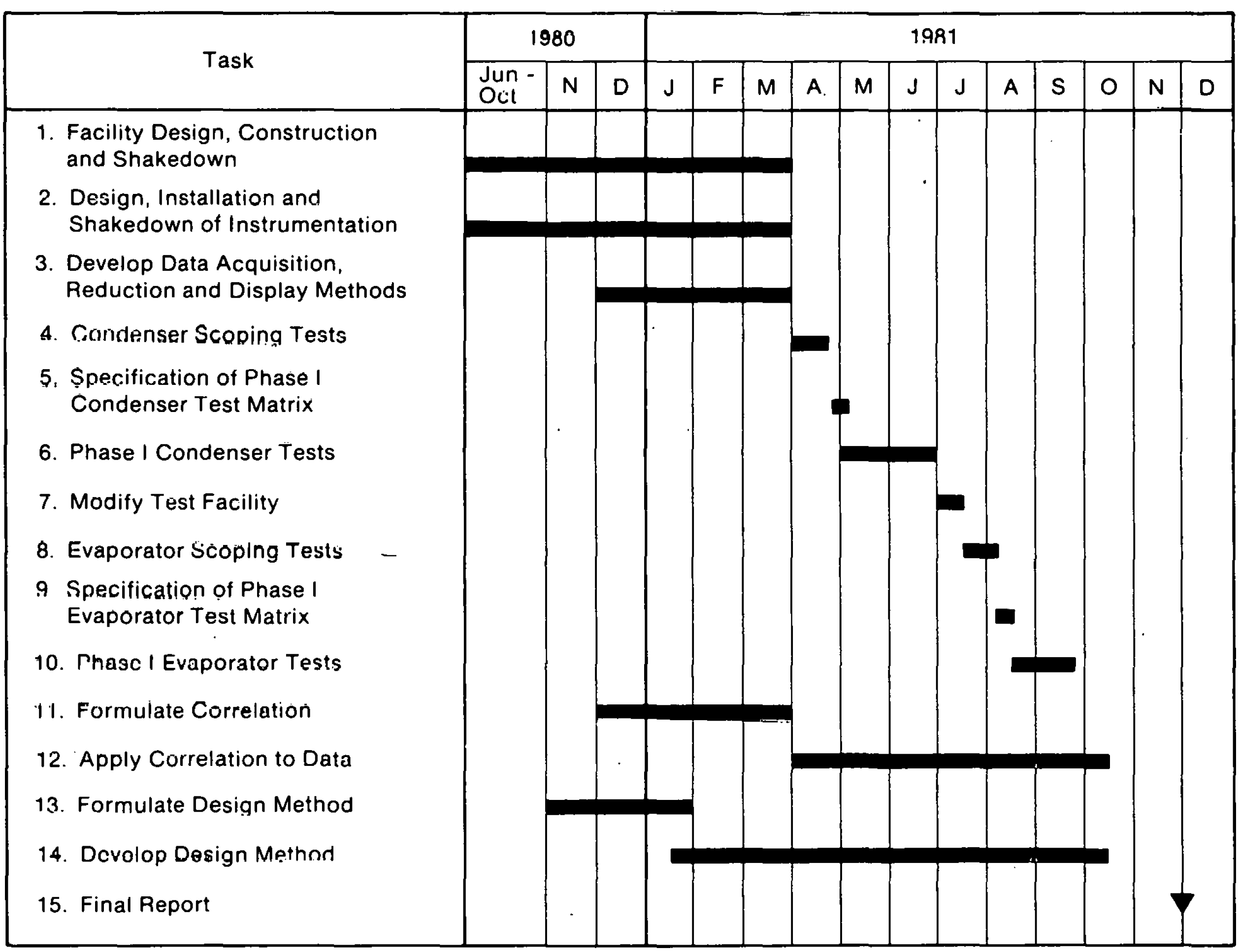
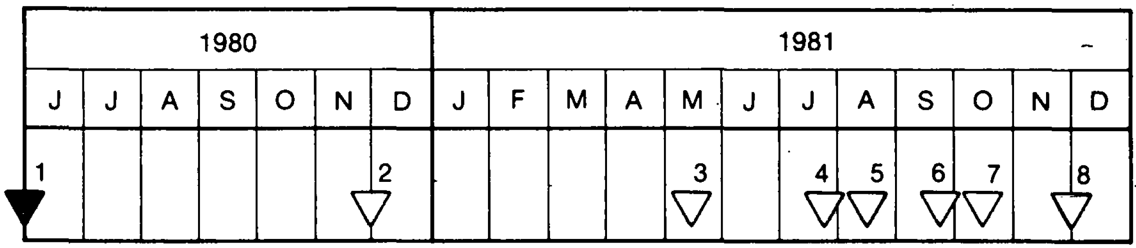
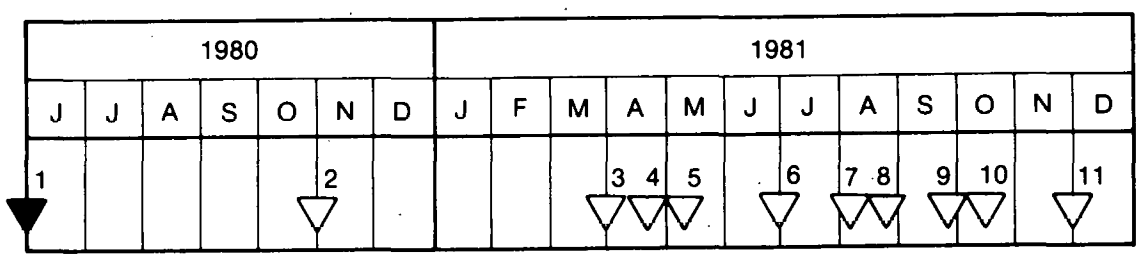


Figure 2-7. Condenser and Evaporator Program—Phase I Schedule



1 Project Initiated - Contract Executed
2 Facility and Instrumentation Design Report
3 Condenser Scoping Tests - Quick Look Report
4 Condenser Phase I Tests - Quick Look Report
5 Evaporator Scoping Tests - Quick Look Report
6 Phase II Program Plan
7 Evaporator Phase I Tests - Quick Look Report
8 Project Final Report Draft

Figure 2-8. Condenser and Evaporator Program—Phase I Major Deliverables



1 Project Initiated (Partially funded)
2 Facility and Instrumentation Design Completed
3 Facility, Instrumentation and Data Acquisition System Shakedown Completed
4 Condenser Scoping Tests Completed
5 Phase I Condenser Test Matrix Selected and Phase I Condenser Tests Initiated
6 Phase I Condenser Tests Completed
7 Evaporator Scoping Tests Completed
8 Phase I Evaporator Test Matrix Selected and Phase I Evaporator Tests Initiated
9 Phase I Evaporator Test Completed
10 Data Correlations and Design Method Completed
11 Project Completed - Final Report Draft Issued

Figure 2-9. Condenser and Evaporator Program—Phase I Major Milestones

Also, tests have been performed to determine the nozzle geometry for producing falling turbulent jets and films. A nozzle geometry that produces continuously over the desired range of jet or film thicknesses and initial velocities has been obtained.

2.2.4.4 Expected Results/Future Effort

In addition to the data base, correlations, and design methodologies, recommendations will be developed regarding the following optimum design parameters:

- number of jet or film units;
- jet or film spacing;
- liquid and vapor flow rates per jet or film; and
- overall dimensions.

These items will form the required technical data base that will allow subsequent engineering assessments of the direct contact evaporator and condenser and will result in selecting the optimum evaporator and condenser subsystems for open-cycle OTEC applications.

2.2.4.5 References

Solar Energy Research Institute. 1979 (Feb.). "Testing and Analysis of Direct Contact Condensers and Turbulent Jet Evaporators," Addendum to Creare Proposal P-547. 15 February 1979.

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2.3 OC-OTEC LOW PRESSURE TURBINE DEVELOPMENT—Paul D. Ritland*

2.3.1 Objective

The objective of this project is to develop a data base through analysis and subsystem testing that will assess the potential of open-cycle OTEC systems.

The specific objectives are to:

- establish a 100-MW_e open-cycle prototype turbine design;
- develop scale model test parameters; and
- develop a turbine off-design and transient computer program to support blade design.

The key is to determine the practicality of the extremely large single-stage turbine required. This project will supply the design, manufacturability, and cost information to determine whether a cost-effective system is possible and competitive with other renewable energy systems. It will provide for meaningful testing of small-scale models of the prototype and provide a method for interpreting the results. Also, it will provide the tools to develop control strategies and evaluate turbine design adequacy for a range of heat exchanger models.

2.3.2 Approach

The size and operating characteristics of the baseline 100-MW_e turbine require using materials with high specific strength and superior fatigue properties. The choice of fiber-reinforced epoxy resin composites not only provides a means of obtaining these characteristics but allows freedom in turbine blade design not available in the design of homogeneous blades. The knowledge gained from the commercial application of materials and design concepts to helicopter rotors and turboprop propellers is being drawn upon for this project. The thermodynamic aspects draw upon longstanding low-pressure steam turbine design practice.

The primary deliverables are as follows:

- the thermodynamic design of the prototype turbine including a complete definition of the blade section geometry as a function of radius and complete thermodynamic performance data at the design point;
- analysis using physical similarities to determine the minimum scale at which an open-cycle OTEC turbine can be demonstrated and results extrapolated with high confidence to full scale;
- the turbine mechanical design including aeroelastic and structural dynamics analyses, general design specifications, and blade and stator materials assessments;
- turbine manufacturability analysis; and
- off-design and transient analysis including a computer code providing for additional heat exchanger models.

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*Westinghouse Electric Corporation.

Successful completion of each task will resolve the key technical issues; i.e., suppression of static and dynamic instabilities due to aeroelastic and structural dynamic effects, selection of materials, overspeed control strategies, thermodynamic efficiency, manufacturability, and cost (see Fig. 2-10).

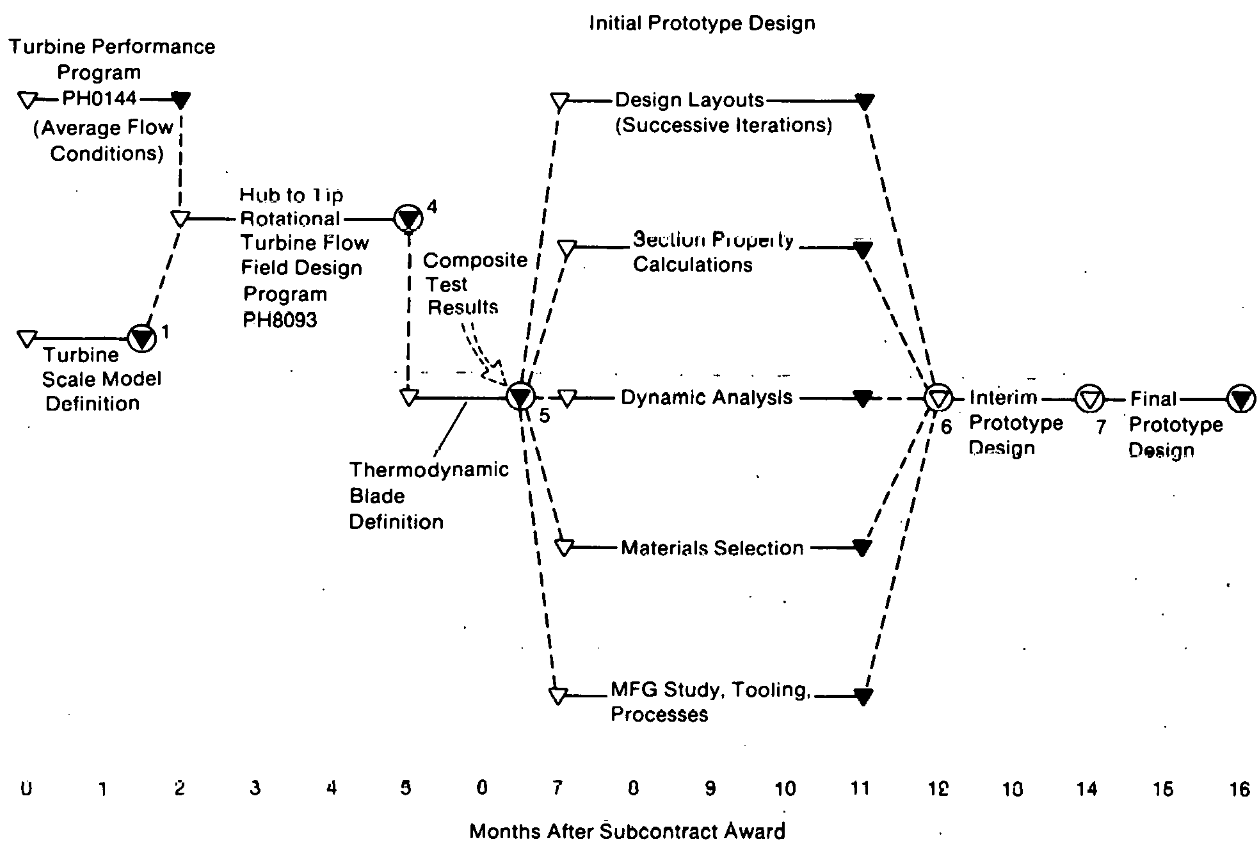

Figure 2-10. Milestone Schedule of Low-Pressure Turbine Development

2.3.3 Status

At the end of FY 1980, several items had been completed. Analytic tools for aeroelastic and structural dynamics had been developed and used on a provisional blade design. A basic computer model for off-design and transient analysis had been developed and used. Scale model similarities and preliminary turbine disc-strut designs had been studied. Material assessment had been completed as well as a turbine flowfield design for a 110-blade design and work on a 220-blade design was continuing.

As a result, we know that a thin shell blade using E-glass fiber tends to twist due to centrifugal movement (tennis racket effect) and that changing the chord doesn't solve the problem. Excessive twisting is eliminated by a central box-spar blade design with lightweight leading and trailing edge. This requires overbalance mass weights at the tip leading edge to suppress flutter.

A further evolution to a canted spar blade design minimizes mass weights by slanting the spar toward the leading edge at the tip (so that the spar structure itself provides most of the forward mass requirement) while the large box-spar fits inside the thick part of the rooted air foil at mid-chord. A considerable range of blade aspect ratios will be feasible regarding structural dynamics and aeroelastic behaviors with the canted spar design. In general, a larger number of narrower blades (at constant solidity) will provide the least total blade weight and cost, but upper limits exist because of excessive flexibility and large static droop stresses.

The materials assessment showed that oriented E-glass filaments with epoxy resin are adequate in the low-pressure saturated open-cycle environment and that the structural properties are adequate for the bulk of the blade. More development is needed to define the disc and blade root.

The details and effectiveness of the control system or the response of the system to various heat exchanger types are not known.

The scale relationships and confidence bands have been determined. Needed are the top level requirements of a system test. Questions such as: What are the test objectives? Must a 100-MW_e prototype be modeled? What are the site characteristics? need to be answered before proceeding to Phase II.

2.4 SEAWATER DEAERATION OVERVIEW—F. C. Chen*

In OTEC open-cycle power systems, warm seawater is the working fluid. Low-pressure (subatmospheric) steam generated through the flashing process is used either to run a vapor turbine in a Claude-cycle system or to lift water in various lifting cycle concepts for power generation. Natural seawater contains many different dissolved gases. Nitrogen and oxygen constitute the bulk of the dissolved gases, but measurable amounts of argon and free carbon dioxide are also present. These gases are released during the flashing process. If these noncondensable gases are not removed from the condenser, they will accumulate there, build up the condenser pressure, reduce the system pressure gradient, and affect the power generation rate.

To maintain a stable power generation rate, the noncondensable gases evolved from seawater must be removed continuously from the power system by deaeration. Two deaeration options have been proposed in the previous open-cycle system studies. G. Claude employed a predeaeration process in his open-cycle plant in which dissolved gases were removed from the warm seawater stream before entering the flash evaporator. In the Colorado School of Mines open-cycle power system study (Watt, Mathews, Hathaway 1977), a post-deaeration process was proposed in which the dissolved gases that evolved during the flashing process were removed at the condenser together with any other system air leaks.

The advantage of the predeaeration process is that the deaeration occurs above the saturation vapor pressure of the seawater. Less pumping power is required to eject the noncondensable gases to the atmosphere; but additional system components are needed, such as deaerators and compressors. Additional hydraulic head is also needed to operate the deaerators. In the postdeaeration system, the deaeration occurs at the condenser where the system pressure is the lowest. More parasitic power is required to remove the noncondensable gases. Although the deaerator is not needed in the postdeaeration system, more heat transfer surface area is required to compensate for the noncondensable gas effect on the condensation phenomena.

Results of a preliminary economic analysis based on conceptual designs of the two deaeration options were compared in a recent open-cycle power system design study by Westinghouse; the results are shown in Table 2-2. The capital cost is less for the predeaeration option, but the parasitic power loss is more than that of the postdeaeration option.

In the conceptual design analysis, a commercially available packed column vacuum deaerator was selected for the predeaeration system. It was designed to operate at 6.89 kPa (1 psi) with a 0.80 stage effectiveness packed with 1.22 m (4 ft) of 5.1-cm (2-in.) Raschig rings and required an operating head of 2.71 m (8.9 ft). At a designed warm seawater flow rate of 4.54×10^8 kg/hr (1.0×10^9 lb/hr), the deaerator hydraulic power loss would be 4.68 MW. That represented 63% of the total operating power requirement of the predeaeration process.

In an open-cycle power system, deaeration is necessary to avoid excessive condenser pressure build-up. A high efficiency predeaeration process is desirable but not critical for OTEC power generation. In desalination applications, highly effective predeaeration is essential to avoid corrosion and scale build-up (capable of removing 99.93% of the oxygen and 99% of the carbon dioxide); a deaerator design capable of removing 80% of each was found sufficient in the Westinghouse study.

*Oak Ridge National Laboratory

Table 2-2. Comparison of OTEC Deaerator Cost and Power

	Option 1: Predeaeration			Option 2: Postdeaeration		
	Flows and Ratios kg/h (lb/h)	Cost (in million $)	MW	Flows and Ratios kg/h (lb/h)	Cost (in million $)	MW
Vacuum Deaerator p = 6.89 kPa (1 psi) 80% efficiency		2.84	4.68			
Air Removed	6.03×10^3 (13.3×10^3)					
Steam Removed	3.63×10^3 (8.0×10^3)					
Steam-Air Ratio	0.6					
Air Removal Equipment		2.17	1.3			
Air to Condenser [add 1.8×10^3 kg/h (4000 lb/h) leakage]	3.58×10^3 (7.9×10^3)			9.8×10^3 (21.6×10^3)		
Condenser Air Removal Equipment		3.51	1.49		9.6	4.1
Condenser Inlet Steam-Air Ratio	547			200		
Condenser Area Increase (%)	40			48		
					0.98	
Total		8.52	7.47		10.58	4.1

Conditions: Open-Cycle Power System
Warm Seawater Flow = 4.53×10^8 kg/h (1.0×10^9 lb/h)
Surface Condenser
Axial Compressors
Condenser Exit Steam-Air Ratio—4.0
Condenser Saturation Temperature—4.45° C (40° F)
Condenser Cost—12.26×10^6

Although low head-loss deaerators are not readily available, many state-of-the-art vacuum deaeration concepts could conceivably be developed to fit particular needs where low operating power is more critical than the high stage efficiency. Shallow packings, rotating disk sprays, and tilt tray type with turbulent promoters are among the advanced vacuum deaeration concepts that could be applicable. Using the seawater intake pipe for predeaeration is another option. Although this was proposed in the original Claude open-cycle power plant design, the effectiveness has not been investigated.

Pumping power required to eject noncondensables to surroundings represents a parasitic loss to an OTEC power plant. Intercooler condensers are presently proposed to be employed with staged compressors for ejecting the noncondensables to the atmosphere. By condensing part of the water vapor from noncondensable gas stream through intercooling, the compressor pumping power is reduced. However, disposing of noncondensables through the entrainment in the warm seawater or cold seawater exhaust stream, which further reduces parasitic power, is another alternative. This alternative not only promises pumping power reduction in the noncondensables disposal but also alleviates the environmental impact of discharging a large quantity of deoxygenated seawater.

The objective of the seawater deaeration study is to obtain technical data so that a more cost-effective deaeration and noncondensables disposal subsystem can be designed. This will include investigating the deaeration effectiveness of seawater barometric intake pipes, the technical feasibility of various design concepts of vacuum deaeration, and the disposal of noncondensables through entrainment in exhaust seawater streams. Various aspects of seawater deaeration are being pursued by ORNL, Hydronautics, Inc., and Carnegie-Mellon University.

Reference

Watt, A. D.; Mathews, F. S.; Hathaway, R. E. 1977 (Dec.). Open Cycle Ocean Thermal Energy Conversion: A Preliminary. ALO/3723-76/3. Golden, CO: Colorado School of Mines, Engineering Physics Department.

2.4.1 Gas Desorption Experiments—F. C. Chen and A. Golshani*

2.4.1.1 Objective

Seawater deaeration is a process affecting almost all of the proposed OTEC open-cycle power systems. If the noncondensable dissolved air is not removed from a power system, it will accumulate in the condenser, reduce the effectiveness of condensation, and result in system performance deterioration. A gas desorption study is being conducted at ORNL to mitigate these effects. The vacuum deaeration process will be investigated analytically and experimentally for actual operating conditions where conventional steam stripping deaeration may not be applicable.

2.4.1.2 Approach

The approach included designing and fabricating the gas desorption test loop, OTEC barometric intake configuration, and air reinjection system and conducting the proper experiments.

The gas desorption test loop consists of a water storage tank, gas removal system, liquid recirculating system, and a desorption test section. A schematic of the gas desorption system is shown in Fig. 2-11. Deaeration takes place in the section labeled desorption column. This column, shown in Fig. 2-12, will be filled with different types and sizes of packing. Different packing has different mass transfer characteristics. In the first series of tests, the column was filled with 3.8-cm (1.5-in.) Raschig rings in an effort to verify system performance. We will use 1.6-, 2.5-, and 3.8-cm (5/8-, 1-, and 1.5-in.) plastic Pall rings to find the information on height-of-transfer unit (HTU) for these types of packings.

The OTEC barometric intake configuration has been fabricated with a 9.1-m (30-ft) long, 5-cm (2-in.) diameter vertical, transparent, plastic pipe. The method was to determine the deaeration feasibility via barometric leg. Test periods were usually three hours during which the water temperature was held constant to within 1° C. Water velocity varied from 0.6-1.8 m/s (2-6 ft/s) in an effort to simulate OTEC conditions. The OTEC barometric intake configuration and air reinjection system can be seen in Fig. 2-13.

OTEC air reinjection is fabricated with a 12.2-m (40-ft) long, 5-cm (2-in.) diameter vertical, transparent, plastic pipe. This system will be employed to test the feasibility of air reinjection. Single-needle, multiple-needle, and porous stone injections will be used to test the air entrainment effectiveness in an exhaust water stream.

2.4.1.3 Status

Vacuum deaeration in a column packed with 3.8-cm (1.5-in.) Raschig rings has been completed, as has the barometric leg intake degassing tests. Tests of the various Pall ring packings are in progress, and the air reinjection test will follow.

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*Oak Ridge National Laboratory

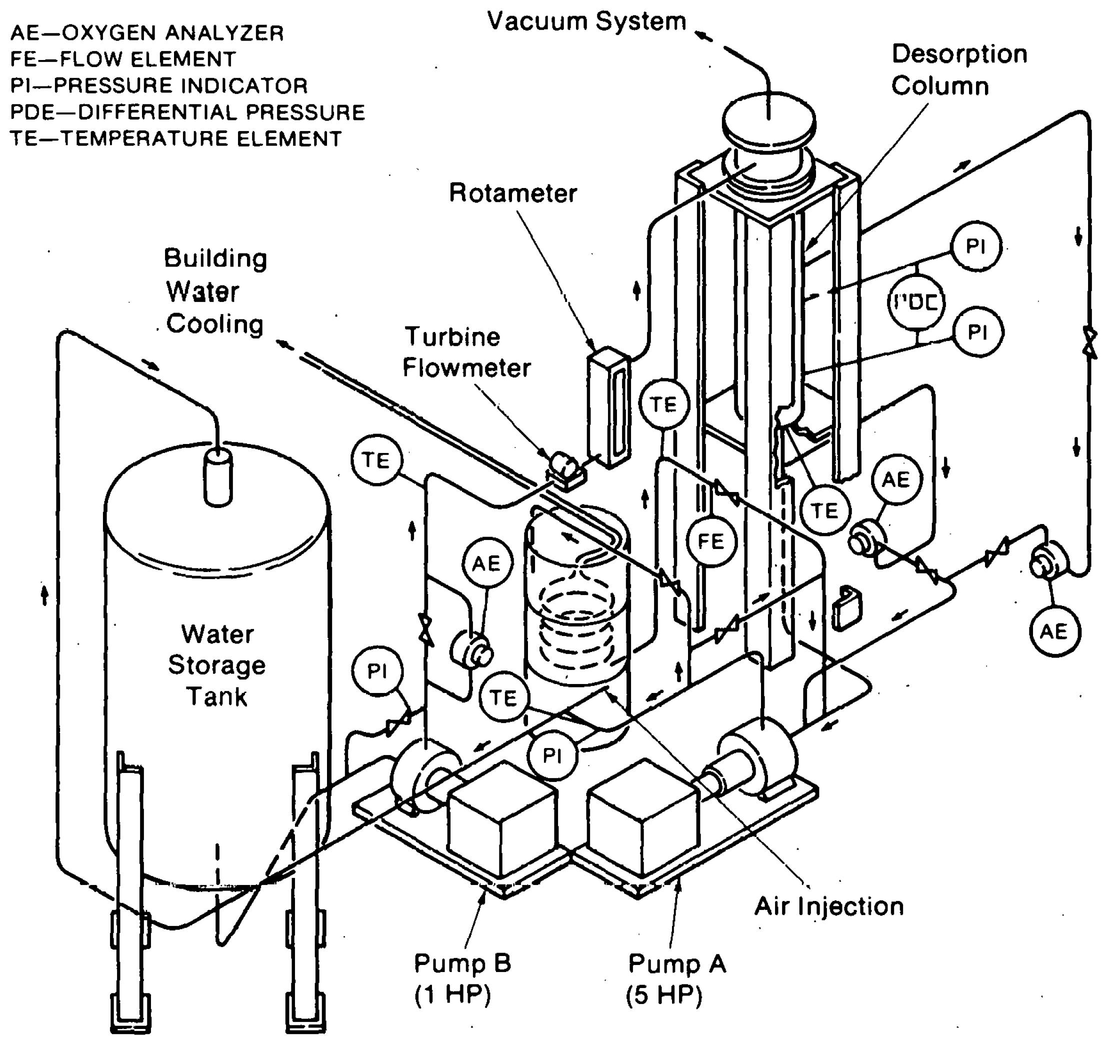

Figure 2-11. Gas Desorption Test Facility

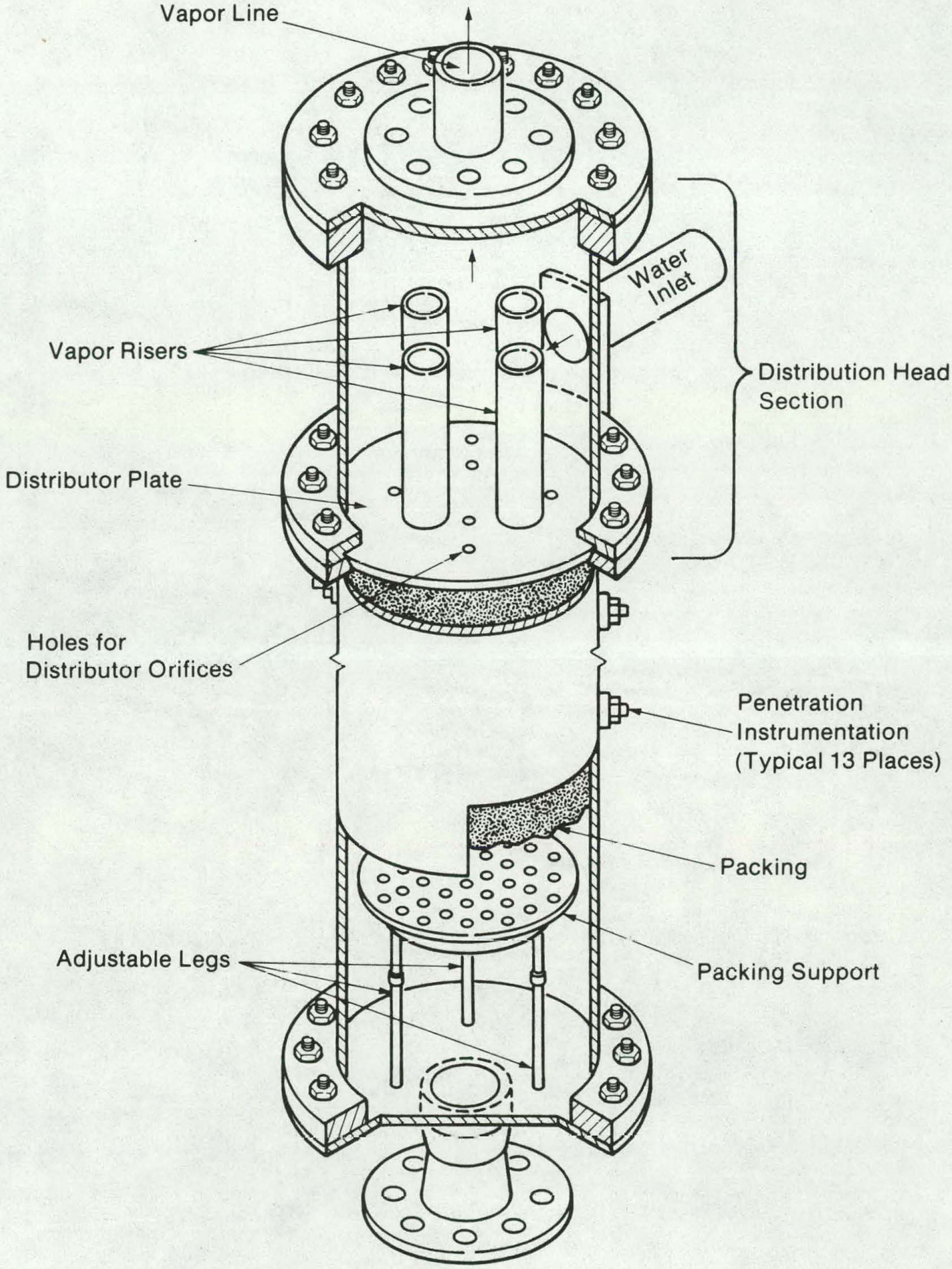

Figure 2-12. Desorber Test Section

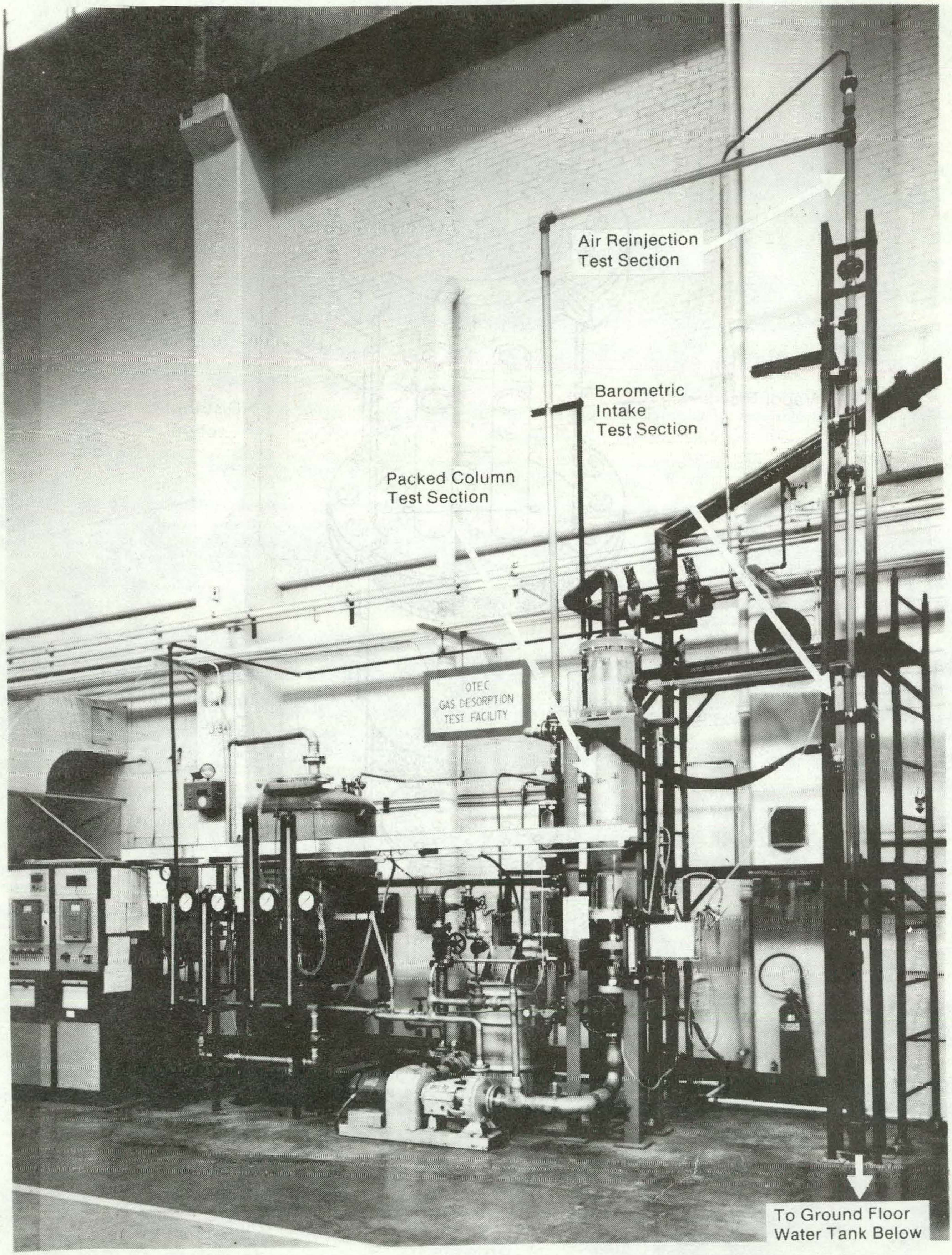

Figure 2-13. OTEC Gas Desorption, Barometric Intake, and Air Reinjection Facility

The packed column carries out mass transfer between gas and liquid when the two fluids pass countercurrent to each other. Earlier, the column was packed with a 3.8-cm (1.5-in.) Raschig ring to verify the test loop performance. The HTU in this study was found to be somewhat greater than reported by earlier investigations. Thus, from the present experiment at 25° C, HTU for air desorption from water on 3.8-cm (1.5-in.) Raschig rings can be expressed as a function of water flow rate by:

$$HTU = 4.93L^{0.25} \quad (2\text{-}1)$$

where HTU is the height of transfer unit in centimeters; and L is the liquid flow rate, in kg/h-m^2. This is shown as line M' in Fig. 2-14.

In contrast, the Sherwood and Holloway results (line M, Fig. 2-15) for oxygen, hydrogen, and carbon dioxide desorption from water at 25° C on 3.8-m (1.5-in.) Raschig rings is described by:

$$HTU = 5.38L^{0.22} \quad (2\text{-}2)$$

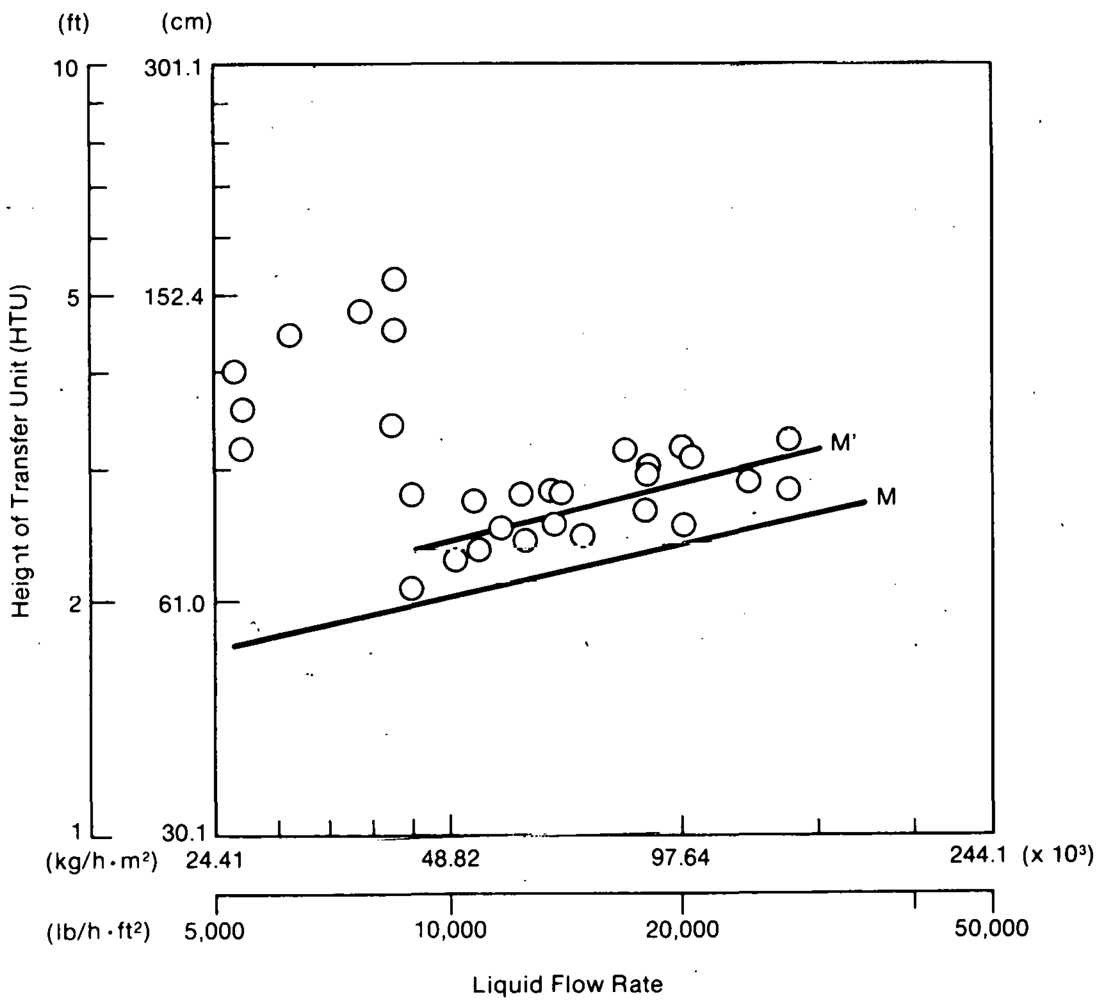

Figure 2-14. Comparison of Test Data with Results of Sherwood and Holloway

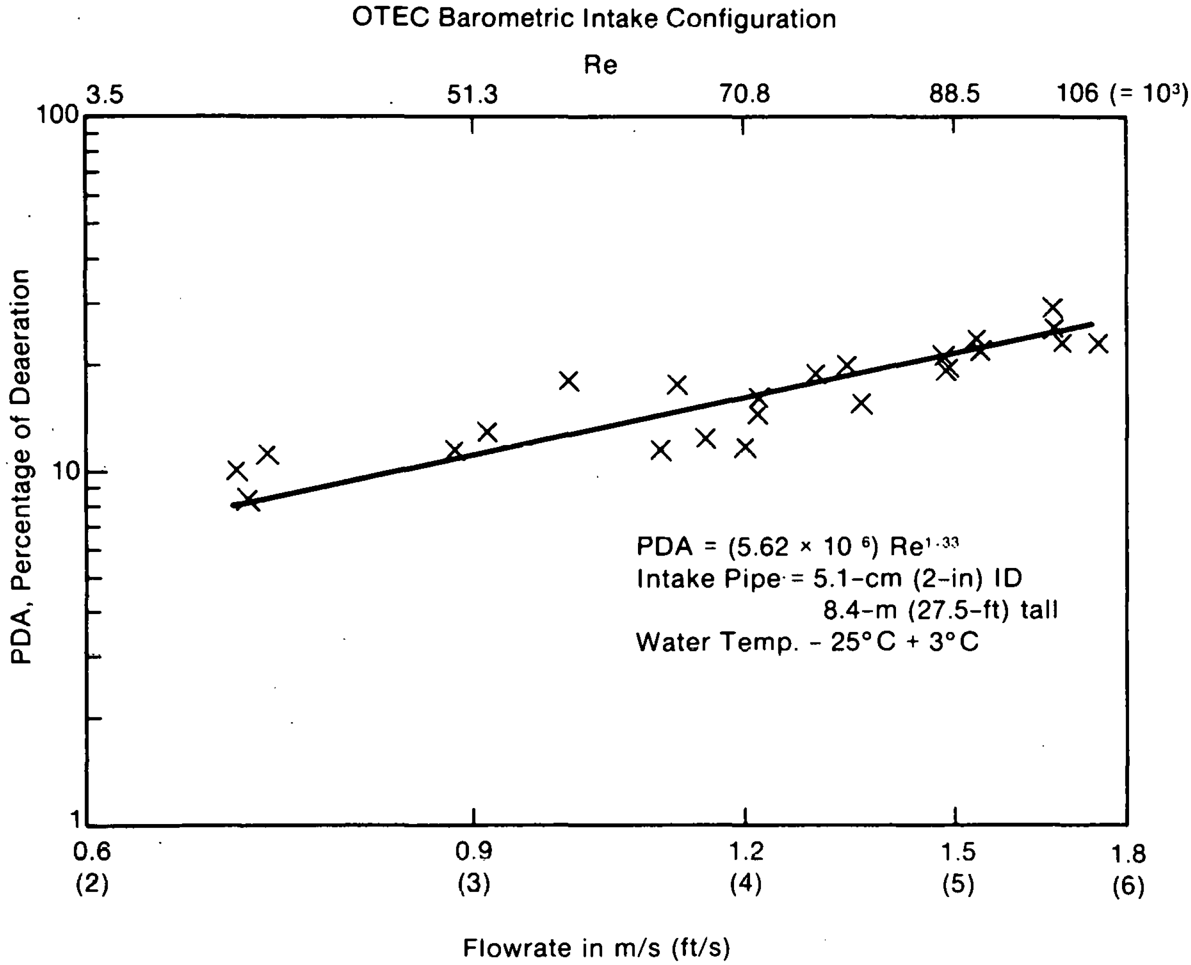

Figure 2-15. Relationship Between Water Flow Rate and Percentage of Deaeration

The observed discrepancy may be due to differences in end effects and in vacuum versus atmospheric pressure operation.

The concept of barometric intake configuration is not new, yet no previous investigation on the feasibility of the barometric leg deaeration has been done. Our experimental assessments indicate that for a barometric leg of 8.4 m (27.5 ft), the percentage of deaeration (PDA) via barometric leg corresponds to Fig. 2-15 and can be expressed as:

$$PDA = 2.51v^{1.33} \qquad (2\text{-}3)$$

The water flow rate ranged from 0.6-1.8 m/s (2-6 ft/s) at 25° C±3° C.

Tests are in progress that will give information on HTU for a column packed with a plastic Pall ring, since there is no data in the literature regarding them. This study is interesting because

- the plastic rings cost $141/m^3 ($4/ft^3) compared with $353/m^3 ($10/ft^3) for ceramic packings; and
- the mass velocity of 292,000 kg/hr-m^2 (60,000 lb/hr-ft^2) of plastic rings is higher compared with 146,000 kg/hr-m^2 (30,000 lb/hr-ft^2) of ceramic rings.

This packing was not considered by previous investigations because the HTU liquid rate design was not available.

2.4.1.4 Expected Results/Future Effort

Tests on various sizes of plastic Pall ring packings will continue into next year. Experiments on an air reinjection system will start after packed column data are obtained. Also, work on an intake configuration will continue that includes using a hydrogen generation system for enhanced deaeration.

2.4.1.5 References

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Golshani, A.; Chen, F. C. 1980 (Oct.). OTEC Gas Desorption Study Report-Design of Experiments. ORNL/TM-7438. Oak Ridge, TN: Oak Ridge National Laboratory.

2.4.2 Deaeration and Air Reinjection Studies—William T. Lindenmuth*

2.4.2.1 Objective

The objective is to provide design data that will be used in assessing deaerator performance and to provide data for systems that reinject scavenged air into exhaust water streams.

Dissolved noncondensable gases are present in seawater. The warm surface layers are nearly saturated with air, and cold water feedstreams may have comparable concentrations of dissolved gas. The pressure (or head) in the warm and cold water feedstreams is reduced as these fluids rise above the ocean surface to the evaporator and condenser sections of an open-cycle OTEC system. The gases begin to evolve where the local static pressure falls below the partial pressures of the dissolved gases in each stream; i.e., when the pressure is below the saturation level.

The design and performance of the condenser will be closely tied to the amount of noncondensable (free) gas that must be removed. Subsystems that remove gases from the warm water before reaching the evaporator and from the cold water before entering the condenser may reduce the condenser's gas load significantly, which improves its effectiveness and increases the power plant's efficiency. However, gases that evolve in the evaporator and condenser or that leak through turbine seals, etc., must still be pumped from the condenser.

The size of the compression system for handling the gases scavenged from the condenser and deaerators can be reduced by reinjecting gas into the exhaust water streams. The load on the plant's main circulating pumps would necessarily be increased to account for the work of compression and head loss due to buoyancy.

2.4.2.2 Approach

Design data specific to deaeration and air reinjection subsystems are being developed through a program of laboratory experiments and analyses. Experiments will be conducted in a new 10.7-m (35-ft) tall flow loop (shown in Fig. 2-16). Feedwater flowing up the loop's riser pipe will have the same velocity and pressure gradient as those found in a full-scale prototype to simulate the mass transfer of gas into bubbles with realistic time scales. Similarly, gas reinjection can be modeled in the downcomer side of the test loop.

Phase I is composed of five tasks:

1. design and construction of apparatus,
2. nucleation studies,
3. shakedown and scoping tests,
4. deaeration tests and analysis, and
5. air reintroduction tests and analysis.

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*Hydronautics, Inc.

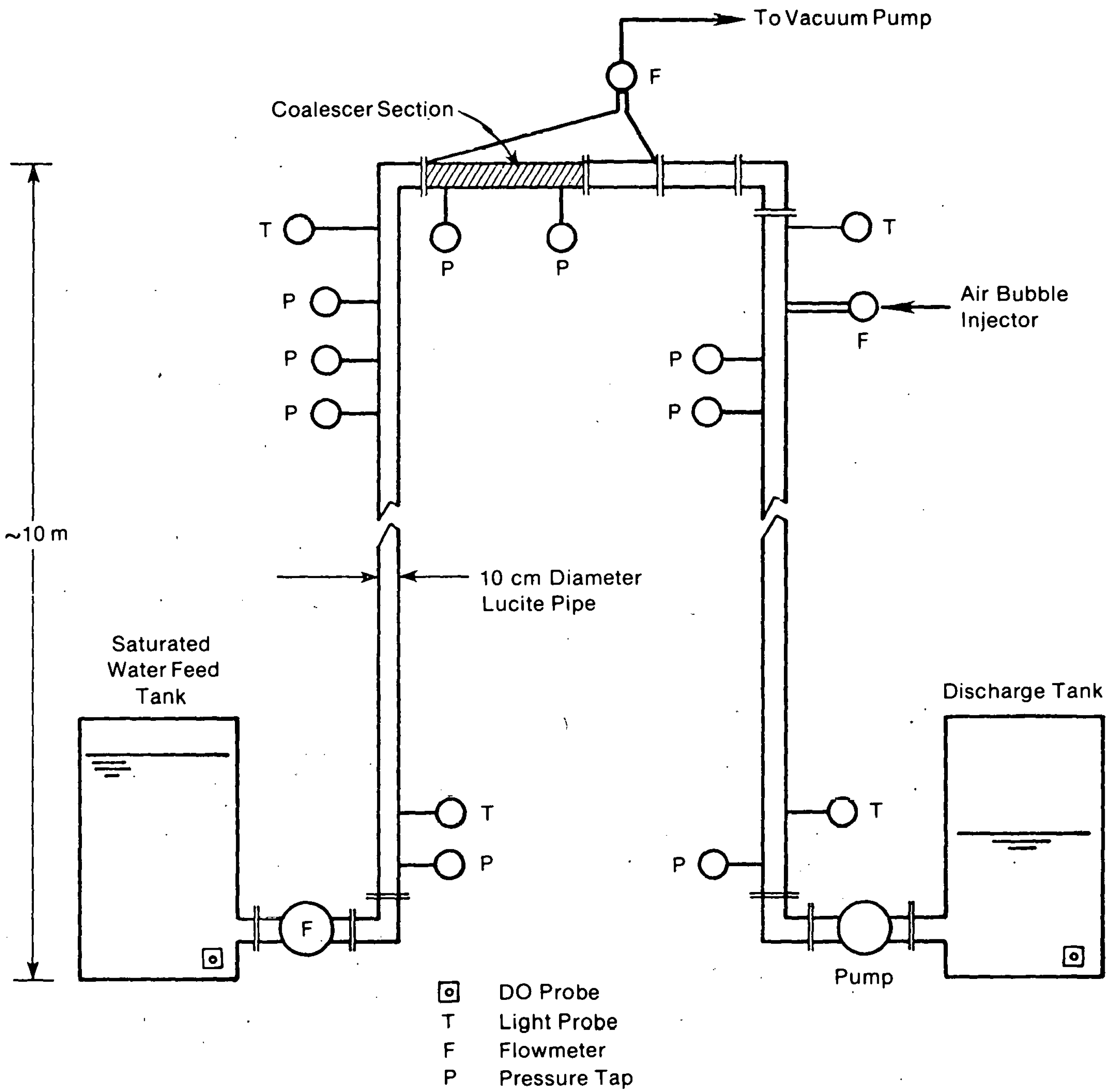

Figure 2-16. Schematic of Test Loop for Deaeration and Air Reinjection Studies

The project deliverables include:

- a preliminary facility specification and milestone chart for construction and shakedown;
- an instrumentation specification and milestone chart for installation and shakedown;
- samples of raw data formats;
- scoping test plans (Task 3);
- scoping test results (Task 3);
- test plan (Tasks 4 and 5);
- test results (Tasks 4 and 5); and
- final report.

Criteria for the evaluation of the project's experimental and analytical work includes:

- freedom from scale effects and other ambiguities;
- general applicability and relevance to desired system design trade-offs; and
- accuracy, consistency, and clarity in reports.

2.4.2.3 Status

The experimental flow loop design has been completed and its construction is well under way. The first major milestone, completion of the test apparatus, is expected by 31 October 1980. This will be followed by operational checks and a complete shakedown of the loop's instrumentation and capabilities.

2.4.2.4 Expected Results/Future Effort

The most fundamental parameter to be studied is the diffusiveness that governs the rate of gas evolution in the riser pipe. The rate will depend on the initial gas concentration, bubble nuclei population, and flow velocity. Bubble resorption for gas reinjected in the downward exhaust flow (and for any small bubbles that pass through the deaerator section) will be governed by analogous processes having comparable diffusion coefficients. However, rates will be lower owing to the smaller relative driving pressure ratios.

The removal of free gas bubbles from the feedstreams should be done in the flow loop's test section, the horizontal leg at the upper end of the loop. Deaeration effectiveness, efficiency, and associated head losses will be investigated. The test data and analysis of results should enable engineering design trade-offs to be made for preliminary system design and for Phase II subsystem design efforts, with regard to deaeration and reinjection.

2.4.2.5 References

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2.4.3 Deaeration by Entrainment—Tomlinson Fort, Jr. and Clarence Zener*

2.4.3.1 Objective

The long-range objective of the Carnegie-Mellon University (CMU) OTEC work is to develop a viable open-cycle OTEC system based on the physical properties of a foam. The rationale is that eliminating heat exchangers greatly reduces the open-cycle system's cost and that the extremely low density of the foam will enable the small difference in vapor pressure at the surface and in the deep ocean water to lift the foamed surface water at least several hundred feet. A major problem in this system is removing the noncondensables from the condenser; otherwise, the air pressure buildup will block the operation of the power system. Deaeration by entrainment is a possible low-cost solution to this problem. As the cold water spray impinges upon the condenser pool, it automatically entrains some of the surrounding gas. The entrained air is then carried by the pool, via a barometric leg, out of the system into the ambient environment.

2.4.3.2 Approach

A simple system has been built that simulates an actual condenser. Here, a single jet impinges on a pool contained in a column approximately 2.54 cm (1 in.) in diameter and approximately 12.2 m (40 ft) high. The jet flow is sufficient to carry the water down this barometric column at a velocity higher than the velocity at which the entrained air bubbles rise. The chamber above this pool is enclosed except for the entering water jet and a controlled air bleed (see Fig. 2-17). A flow meter monitors the air flux into the chamber. Simultaneously, a manometer measures the total gas pressure in the chamber. This gas pressure, minus the vapor pressure of the water, gives the air partial pressure within the chamber. From this air partial pressure and the measured air bleed rate, the volumetric air entrainment rate can be calculated. The single criterion for judging the efficacy of deaeration by entrainment is the Volumetric Entrainment Ratio (VER): expressed as

$$\text{VER} = \frac{\text{Volumetric entrainment rate of air}}{\text{Volume flow rate of jet}} \qquad (2\text{-}4)$$

In particular, VER must be measured as a function of the air partial pressure. It must be sufficiently high at the allowable partial pressure to remove air at the same rate as the air entering the chamber. As an example, suppose the warm water input to the foam OTEC system was saturated with air at 1 atmospheric pressure; suppose all this air came out of the water during the foam lift process; and finally, suppose the cold water spray flow was three times the warm water flow rate. Then, in a steady state

$$\text{VER} = \frac{101.4 \text{ kPa } (4.7 \text{ psi})}{P_{air}} \times \frac{0.018}{3} \qquad (2\text{-}5)$$

*Carnegie-Mellon University

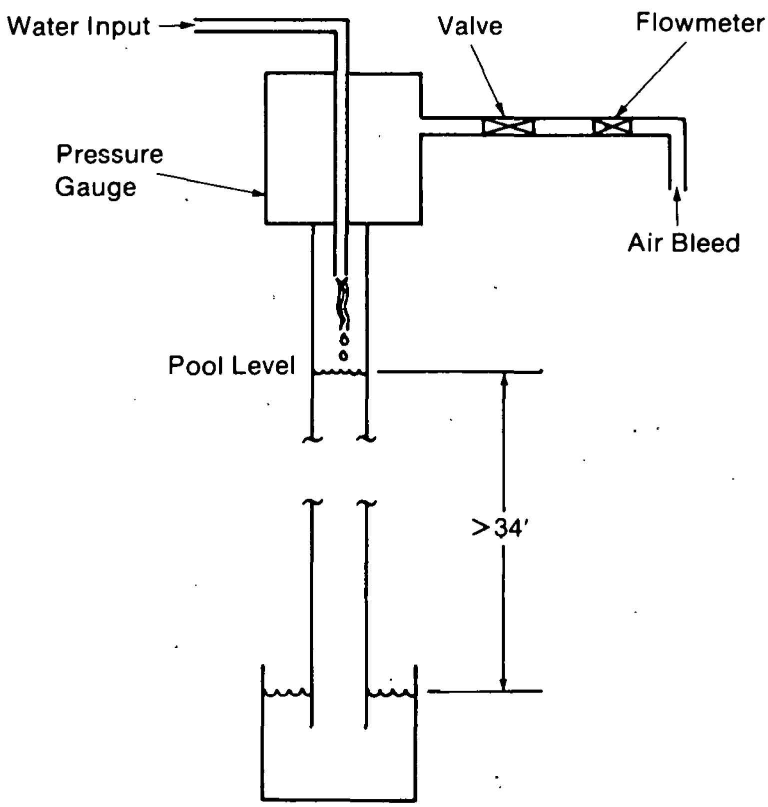

Figure 2-17. Schematic of Apparatus to Measure Volumetric Entrainment Ratio (VER)

The steady-state air pressure just above the pool would then be

$$P_{air} = \frac{0.607 \text{ kPa } (0.088 \text{ psi})}{\text{VER}} \tag{2-6}$$

In a practical system, P_{air} must be small compared with the saturation vapor pressure. This is 1.23 kPa (0.178 psi) as shown using Eq. 2-6 having a 10°C condensing temperature. Thus, VER should be greater than unity. Therefore, VER provides a single criterion for judging the success of this project.

2.4.3.3 Status

Our experiments definitely have shown that VER is nearly unity when P_{air} exceeds P_{H_2O}, the saturation vapor pressure of water. Also, VER rises rapidly as P_{air} is lowered below P_{H_2O}. This second result is highly significant, because the efficiency of our power system requires that P_{air} be small compared with P_{sat}. To summarize, it is definitely known that

$$VER = \begin{cases} \simeq 1 & \text{when } P_{air} > P_{sat} \\ > 1 & \text{when } P_{air} < P_{sat} \end{cases} \quad (2\text{-}7)$$

It is not known precisely how VER increases as P_{air} is lowered below P_{sat} because it is not known how much of the air originally dissolved in the water escapes from the falling jet into the condenser chamber. If all the originally dissolved air escapes, VER would rise above 6. To remove all ambiguity, equipment is being constructed for deaerating the water prior to jet formation. The function VER (P_{air}/P_{H_2O}); i.e., the dependence of VER on the ratio P_{air}/P_{H_2O}, in the range where P_{air} P_{H_2O}, gives the minimum knowledge necessary to decide whether to abandon the entrainment concept or start a condenser development project using entrainment as the minimum cost method of maintaining a low condenser air pressure.

2.4.3.4 Expected Results/Future Effort

It is expected that

$$VER > 2, \text{ when } P_{air} < 0.5\, P_{H_2O}$$

If that is true, then a cost-effective project for handling air in open-cycle OTEC systems could be defined in which the anticipated result would be essential. Here, the major fraction of the dissolved air in the incoming warm water will be removed prior to foaming. The residual air coming from the warm water, as well as from other sources, would be exhausted through entrainment. The greater the VER becomes at low P_{air}/P_{H_2O} ratios, the smaller the necessary air removal prior to the water entering the system will be. The removal of all the air from the incoming water would not be cost-effective. A cost-effective method of removing a major part of the air prior to injection into the system is currently being developed.

In addition, verifying this would create a better understanding of the detailed mechanism of entrainment itself. All the interpretations heretofore presented predict a VER independent of the gas composition. If the results are verified, they will show that VER is a marked function of the ratio of the noncondensable partial pressure to the condensable pressure. Presumably during the entrainment process, condensation of one component allows more entrainment of the noncondensable component.

2.4.3.5 References

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SERI

SECTION 3.0

ALTERNATIVE THERMAL CYCLES RESEARCH OVERVIEW

T. R. Penney and F. C. Chen*

INTRODUCTION

Although the emphasis in the Alternative Thermal Cycle Program is on the Claude cycle, other promising concepts are in earlier stages of development. The advanced thermal cycles, typically mist-lift and foam-lift, have undergone continuous evaluation and remain viable options. Since the theoretical thermodynamic analysis has shown that energy conversion potential using the lift-cycle concept is vast, government supported work was begun on foam-lift in 1976 and on mist-lift in 1977.

OBJECTIVE

The objective of the Alternative Thermal Cycle Program is to develop systems and technologies that extract renewable energy from the ocean in a reliable, environmentally acceptable, cost-effective manner. Power cycles are reviewed in the early conceptual evaluation stage if they are technically sound and potentially economical. Uncertainty about these areas is then reduced with each succeeding research phase. The power cycles also are constantly being reevaluated as to their potential when compared with other innovative designs.

FIVE-YEAR PLAN AND FY 1980 STRATEGY

Within the Alternative Thermal Cycle Program is a range of options that extends from ideas in the earliest stage of development to more advanced conceptual designs where successful experiments have produced quantitative scientific data bases and viable first-order economic projections. During FY 1980, foam- and mist-lift power-cycle experiments and supporting analysis helped strengthen the data base necessary to quantify the technical unknowns.

Foam-lift systems development has been carried out by the Carnegie-Mellon University (CMU) complemented by seawater experiments at the University of Puerto Rico (UPR). Mist-lift development is being done by R&D Associates with the University of California at Los Angeles (UCLA) and Dynamics Technology performing experiments. In support of the experimental work, Dartmouth and SERI performed transient and steady-state analysis to develop an understanding of the fluid mechanics of the mist-lift process.

During FY 1981, accomplishments and cycle competitive viability will be reviewed. Justification for continued support will be based on rational and evaluative criteria. An outline defining the immediate research priorities and current economic goals with associated uncertainties will be discussed. It is intended that the program allow the innovation and selection process to be continuously active, considering the schedule and budget realities of the Ocean Systems Program.

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*SERI, Ocean Systems Program Branch and ORNL, respectively.

Figure 3-1 shows a possible near-term development plan for lift-cycle systems that will lead to the proof-of-concept pilot power system demonstration that includes subsystem development, conceptual design, and integrated systems studies. As events and breakthroughs dictate, either the objective or the preferred option can change. Regular review and public scrutiny of the process will ensure its integrity.

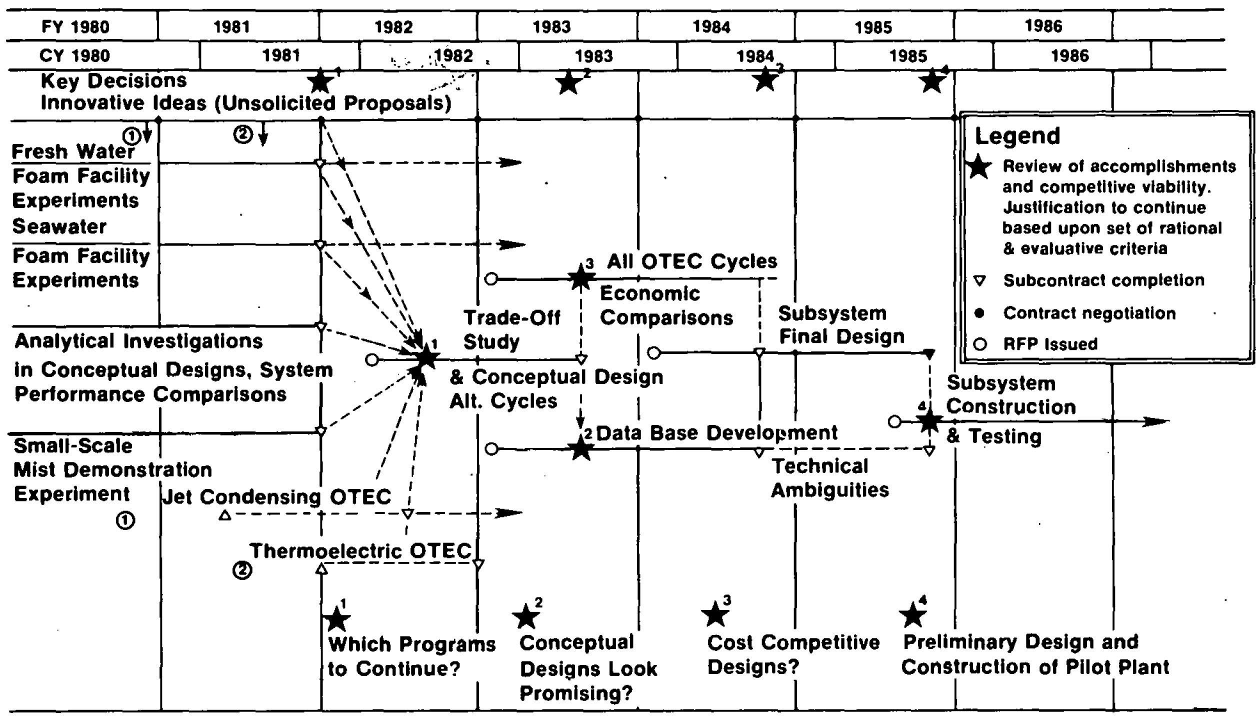

Figure 3-1. Alternative Thermal Cycles Multiyear Plan

SUMMARY OF FY 1980 PROGRESS

Subcontracts were awarded during FY 1980 and the following subsections describe their objectives, approach, present status, and expected results. The major research categories and respective subcontractors are:

- Mist-Lift Power Cycles—R&D Associates, UCLA, Dartmouth, SERI; and
- Foam-Lift Power Cycles—CMU, University of Puerto Rico.

The following accomplishments show important contributions as a direct result of subcontracted and national lab research and development during FY 1980.

Mist-Lift Power-Cycle Development

- A complete thermodynamic and preliminary engineering analysis both in steady-state and transient modes of operation has been completed.
- A short-term vertical mist flow in the UCLA 7-m mist-lift test facility was achieved.

- A gas phase stationary experiment indicates that adequate gas droplet coupling and mist density are achievable.
- A bench scale experiment, 4-m tall, with a 898-cm^2 cross-section area, showed qualitatively that mist lift can be maintained continuously in a stable mode of operation at OTEC conditions. Extrapolated calculations indicate that coupling between the water vapor and the water droplets can be maintained long enough to lift the droplets 50 m or more against gravity at a reasonable mechanical efficiency.
- Analytical calculations have shown that a mist-lift system responds stably to perturbations in boundary conditions that are not sufficiently extreme to lead to column collapse, rainout, or unattainable steady states.

Foam-Lift Power-Cycle Development

- Laboratory-scale foam lift has been demonstrated with a range of surfactant down to concentrations of 20 ppm.
- Analytical work indicates a large, variable-area foam column could operate with even lower surfactant concentrations than presently achieved. Furthermore, newly developed surfactants with different molecular structures can maintain stability at lower, more economically attractive concentrations.
- A Neodol-produced foam in seawater seems stiffer than in fresh water as experimental comparisons at UPR and CMU have shown.
- The suitability of a surfactant for a foam-lift OTEC system is critically dependent on the charge group that juts above the water surface.

SUMMARY OF FY 1981 PLANS AND MILESTONES

Results from the subcontracted activities in foam- and mist-lift power cycles will be completed and reported in a major design review in February 1981, as shown on the milestone schedule in Fig. 3-2. Reports on mist-lift and foam-lift cycles will detail the accomplishments and recommendations for the most critical areas and for continued research. Other advanced thermal cycles that constitute new and innovative design concepts will be reviewed as required throughout the year.

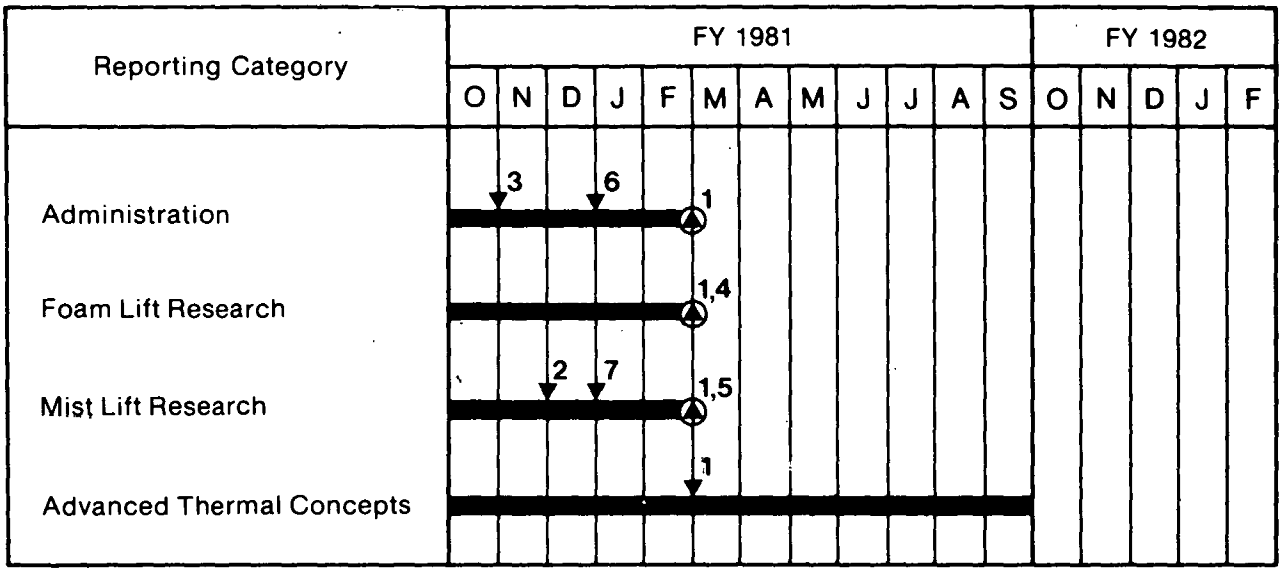

Figure 3-2. Milestone Schedule and Status Report for Foam- and Mist-Lift Power Cycles

3.1 MIST-LIFT POWER CYCLES

3.1.1 Mist-Lift Experiments—S. L. Ridgway*

3.1.1.1 Objective

The objective is to determine the feasibility of the mist-lift ocean thermal energy process by developing and testing the essential components of the system. The fluid dynamics of the two-phase flow that takes place in the lift tube should be understood sufficiently to reasonably project the operating characteristics and the possible capital costs of a mist-flow ocean thermal energy plant. The influence of mist parameters (droplet size, droplet size distribution) and transport parameters (pressure gradient, duct profile, and velocity schedule) on the lift effectiveness of the two-phase flow is to be determined.

3.1.1.2 Approach

The three successive steps in the mist-flow process are mist generation, mist transport, and mist collection. The mist collection process, in which the vapor is condensed and the liquid collected to return to the ocean, is an engineering problem for which several alternative solutions exist and is not now a major issue. The major technical issues are in the mist transport process and the mist generation process. The breakup of the injected water and the formation of the transporting vapor by flashing in the mist generator happen as conceptualized. The issue in the mist generation process is whether the injector can supply the mist transport stage with a sufficient uniform mist so that coalescence effects are manageable.

An analysis was conducted of the two-phase flow in the mist transport assuming either complete coupling or a strong coupling of the vapor to the droplets (which would be the actual case in the absence of droplet coalescence). The analysis predicts that under these assumptions the mist transport can be accomplished stably and efficiently. Droplet coalescence is the major unresolved issue. As the droplets collide and grow, the aerodynamic drag forces diminish relative to the droplet weight, and, therefore, the slip velocity between the two phases must increase to support the droplets.

3.1.1.3 Status

A new experimental apparatus has been designed and constructed for studying the mist transport process under vapor velocity conditions similar to those expected in mist-flow OTEC plants and for studying droplet coalescence and breakup effects as the slip velocity of the vapor relative to the liquid is varied. The test section is a transparent rectangular duct 23 cm x 36 cm (9 in. x 14 in.) and 3.7 m (12 ft) in height. Liquid injection velocities between 3 and 30 m/s will be available, and vapor during the condenser capacity for a vapor velocity of 60 m/s is available. This equipment is now entering its shakedown phase, and preliminary results should be available soon.

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*R&D Associates.

One experiment (the vapor stationary experiment) was conducted in which a mist falls downward through a stationary volume of air. This experiment was done at a higher mist density than is expected in a full-scale OTEC power plant. The experiment also demonstrated that momentum equivalent to 25 m of lift could be transferred to the droplets in 0.7 seconds without excessive droplet coalescence.

The flow in a mist-flow plant and the flow in the vapor stationary experiment have several differences. In the mist-flow plant, the mist that flows into the top of the vapor volume element is aged (i.e., some coalescence has occured) whereas in the vapor stationary experiment, fresh uncollided mist is injected into the top of the volume element. Using air instead of water vapor for the gas phase substantially increases the Reynolds number of the droplet drift through the gas, which should influence the results quantitatively. The coalescence probability will be decreased in air relative to water vapor since the air film between colliding drops can hinder coalescence.

The mist generator was a 0.25-mm (0.010-in.) thick stainless steel plate with 0.10-mm (0.004-in.) diameter holes electron-beam punched on a 1.8-mm (0.072-in.) square pitch. The plate dimensions were 22.9 cm x 25.4 cm (9 in. x 10 in.). The droplets were injected at 3 m/s, which was the minimum velocity at which the mist generator could satisfactorily operate. At lower velocities, water covered the plate and dripped from it in large drops. The plate was supported only at its edges, which was sufficient at the low pressures involved. The duct was attached and sealed to the mist generator at the top, and at the bottom was watersealed. After the flow was initiated, photos were taken, and the mist front was filmed as it advanced.

In air, the mist decelerates quickly from its injection velocity to its terminal velocity. Eventually, the mist front becomes nonuniform, and part of it advances faster than the rest.

In Fig. 3-3, the positions of the leading part and the trailing part of the front are averaged and plotted as a function of time. The momentum per gram of the mist at the end of the duct is estimated as the average velocity of the leading and the trailing parts, which is 1.5 m/s.

The momentum-per-gram input to the mist is 3 m/s injected plus a gravity contribution of 0.7 s x 9.8 m/s^2 or 6.86 m/s for a total of 9.86 m/s. Deducting the output momentum per gram of 1.5 m/s determines the average amount of momentum transferred, which is 8.36 m/s. This vapor-liquid coupling in a mist-flow power plant with a mean transport velocity of 30 m/s would represent work done by the vapor at 0.25 J/g, which corresponds to a lift of 25 m.

Although coalescence cannot be excluded in this experiment, it is of substantial consequence in the mist-flow OTEC plant. The average mist density in this experiment is 5 to 10 times greater than the expected mist density in the operating power plant. This difference will accentuate the effects of coalescence in the experiment. Air, however, retards coalescence, and water vapor does not, but the relative importance of air and water on coalescence is not known.

3.1.1.4 Reference

Ridgway, S. L.; Hammond, R. P.; Lee, C. K. 1980 (Apr.). Mist Flow Ocean Thermal Energy Process. RDA-TR-110901-001. Marina del Ray, CA: R&D Associates.

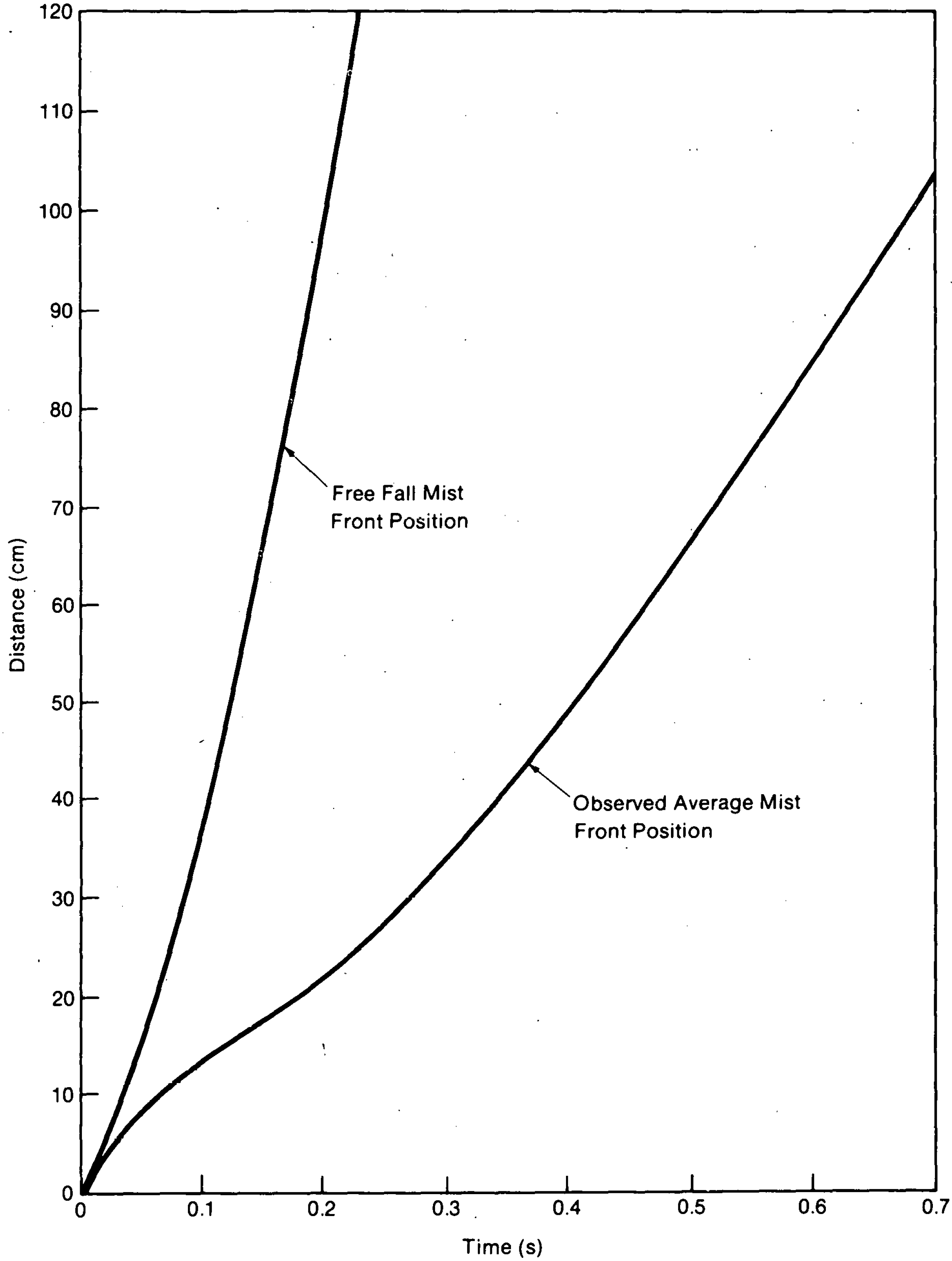

Figure 3-3. Time Dependence on Mist Front Position

3.1.2 Mist-Lift Analysis—A. F. Charwat*

3.1.2.1 Objective

The objectives are to identify the unit process of a mist-lift OTEC cycle, to assess the pertinent technical and scientific background, and to operate a test facility that can generate design data for developing key system components and can demonstrate the overall feasibility of the mist-lift cycle.

A numerical solution to the vertical mist transport problem was successfully developed that can model the collisions among drops using Monte-Carlo simulation, including transverse scattering, variable coalescence efficiencies, and wall deposition. Wall deposition analysis lends credibility to the experimental result. The last phase of the theoretical work, analyzing the dissipation growth of transverse disturbances, is in progress.

3.1.2.2 Reference

Charwat, A. F.; Lee, J. Y. 1979 (Dec.). Numerical Studies of the One-Dimensional Collisionless Vertical Mist Transport. Report UCLA-ENG-8048. Los Angeles, CA: University of California.

*University of California, Los Angeles.

3.1.3 Mist-Lift Analysis—Roger Davenport*

3.1.3.1 Objectives

This section explores the feasibility of proposed open-cycle alternatives to the Claude cycle. The specific objectives for FY 1980 were to:

- develop a one-dimensional, steady-state, multisize drop model of the mist-lift process;
- perform exploratory analysis of new concepts such as
  - steam-boosted mist-lift,
  - jet condenser, and
  - two-phase nozzle flow; and
- assess the performance of an open-cycle OTEC system based on the mist-lift process.

3.1.3.2 Approach

Prof. Graham Wallis of Dartmouth was asked to develop a one-dimensional, steady-state, single-size drop model of the mist-lift process. SERI personnel would then expand this model to include interacting drops of different sizes, first considering drops interacting only by coalescence and then considering drops breaking up as well as coalescing. At each step, this model would analyze the sensitivity of the mist-lift process to parameter variations to identify possible problems.

Exploratory analysis was adapted to each new concept. The steam-boosted mist-lift concept involves injecting steam at the base of the mist-lift tube to boost the mist and prevent rain-out. This concept was to be evaluated by modifying the single-size drop model to include steam injection at the bottom of the lift tube and to use the modified model in a parametric study on the effect of steam boosting on mist-lift performance. The jet condenser concept was first developed for geothermal power sources and involves condensing a mist created by expanding warm water through a converging/diverging nozzle on a jet of cold water and using the increased kinetic energy of the jet to eject itself from the expansion chamber. Preliminary evaluation of this concept involved a thermodynamic analysis of the jet condenser power cycle as applied to OTEC conditions. The flow of warm water at OTEC conditions through a converging/diverging nozzle is interesting for the jet condenser power cycle and is an alternative to generating the mist for the mist-lift cycle. Exploring the feasibility of this generation method involved a literature search on 2-phase nozzle flows and an attempt to describe such a flow under OTEC conditions.

The performance of an open-cycle OTEC system based on the mist-lift process was assessed by incorporating the single-size drop model into the open-cycle system performance analysis algorithm. This involved developing a hydraulic turbine model.

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*SERI, Solar Thermal Research Branch.

3.1.3.3 Status

The single-size drop model has been developed by Prof. Wallis and is described in Wallis, Richter, and Bharathan (1979). The multisize drop, coalescence interaction model has been developed at SERI. This model and the results of parametric studies with both models are reported in Davenport (1980). Figure 3-4 shows the results of these studies. Lift height is plotted versus inlet mass flow rate for two different inlet pressures (before the oriface plate). Both curves are characterized by significant lift height over a very narrow range (10%) of inlet flow rate. At low flow rates, not enough steam is generated to lift the drops, and rain-out occurs. At higher flow rates, the warm water reaches the condenser temperature immediately after entering the mist-lift tube. Rain-out might be prevented by injecting steam at the bottom of the tube.

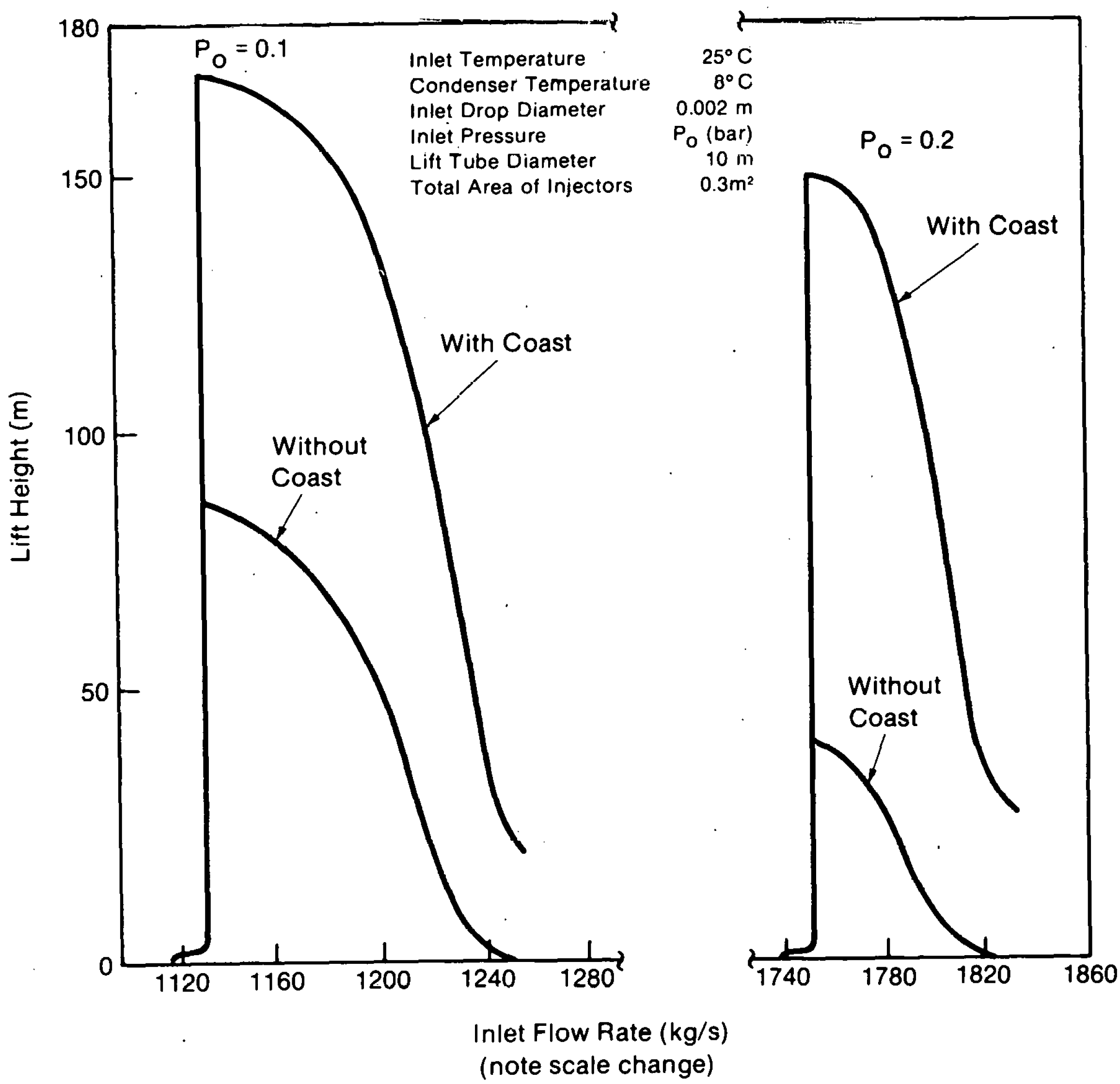


Figure 3-4. Dependence of Lift on Flow Rate With and Without a Coast Phase at the Condenser Inlet

The exploratory analysis of new concepts has been completed and informally reported, and the steam-boosted mist-lift concept appears promising. Rain-out is delayed by injecting steam and can be completely prevented if the injected steam mass flow rate is high enough. The thermodynamic analysis of the jet condenser showed that the concept is feasible under OTEC conditions. This concept is attractive because of its simplicity and further study may be warranted.

The literature search for a description of a two-phase flow through a converging/diverging nozzle failed to turn up any data at normal operating conditions (much data exist for higher temperatures and pressures). The solution to this problem is important to many alternative thermal cycles, so a qualitative experiment that observes liquid dispersion would be useful.

Assessing an open-cycle OTEC system based on the mist-lift process was not done during FY 1980 because more important work needed to be done on the Claude cycle system performance analysis and because problems were encountered in developing a model of the mist-lift process that included coalescence and breakup of the drops as they interact. This assessment will be rescheduled to fit the overall objectives of the Alternative Thermal Cycle Program.

3.1.3.4 Expected Results/Future Effort

During FY 1981, we intend to do the following:

- complete the development of a model of the mist-lift process that includes coalescence and breakup of the drops as they interact;
- acquire the transient mist-lift model developed at Dartmouth during FY 1980;
- perform parametric studies of these models and report potential problems with the mist-lift concept and suggest procedures for resolving them; and
- perform qualitative experimental studies of the liquid phase distribution after the critical flow of water through a converging/diverging nozzle.

3.1.3.5 References

Davenport, Roger. 1980 (Sept.). Mist Lift Analysis Summary Report. SERI/TR-631-627. Golden, CO: Solar Energy Research Institute.

Wallis, G. B.; Richter, H. J.; Bharathan, D. 1979 (Sept.). Analysis of the OTEC Mist Lift Process. SERI/8317-1. Golden, CO: Solar Energy Research Institute.

3.1.4 Mist-Lift Analysis—G. B. Wallis and H. J. Richter*

3.1.4.1 Objective

The objective is to obtain theoretical models that can evaluate the performance of a mist-lift OTEC system. The major short-range objective is to construct a computer model for the transient response of the mist-lift column to changes in boundary conditions at the droplet generator and the condenser. Secondary objectives include considering and analyzing concepts for improving performance.

3.1.4.2 Approach

Various computations for integrating the basic one-dimensional transient equations describing droplet suspension are being developed and evaluated. Projects include computer programs and operating instructions. Criteria for success are the ability to track the transient readjustment of the system from one steady-state operation to another and to indicate conditions under which operating difficulties might be experienced. The results should also prove a basis for more thorough long-term system simulation.

3.1.4.3 Status

Several computations have been developed and tested (see Fig. 3-5). Although some of these were unsuccessful, at least two approaches have yielded good results. These are being refined and the effects of parameters such as the order of the difference, the number of nodes, the interaction methods, and the integration routine on computational accuracy and efficiency are being evaluated.

3.1.4.4 Expected Results/Future Efforts

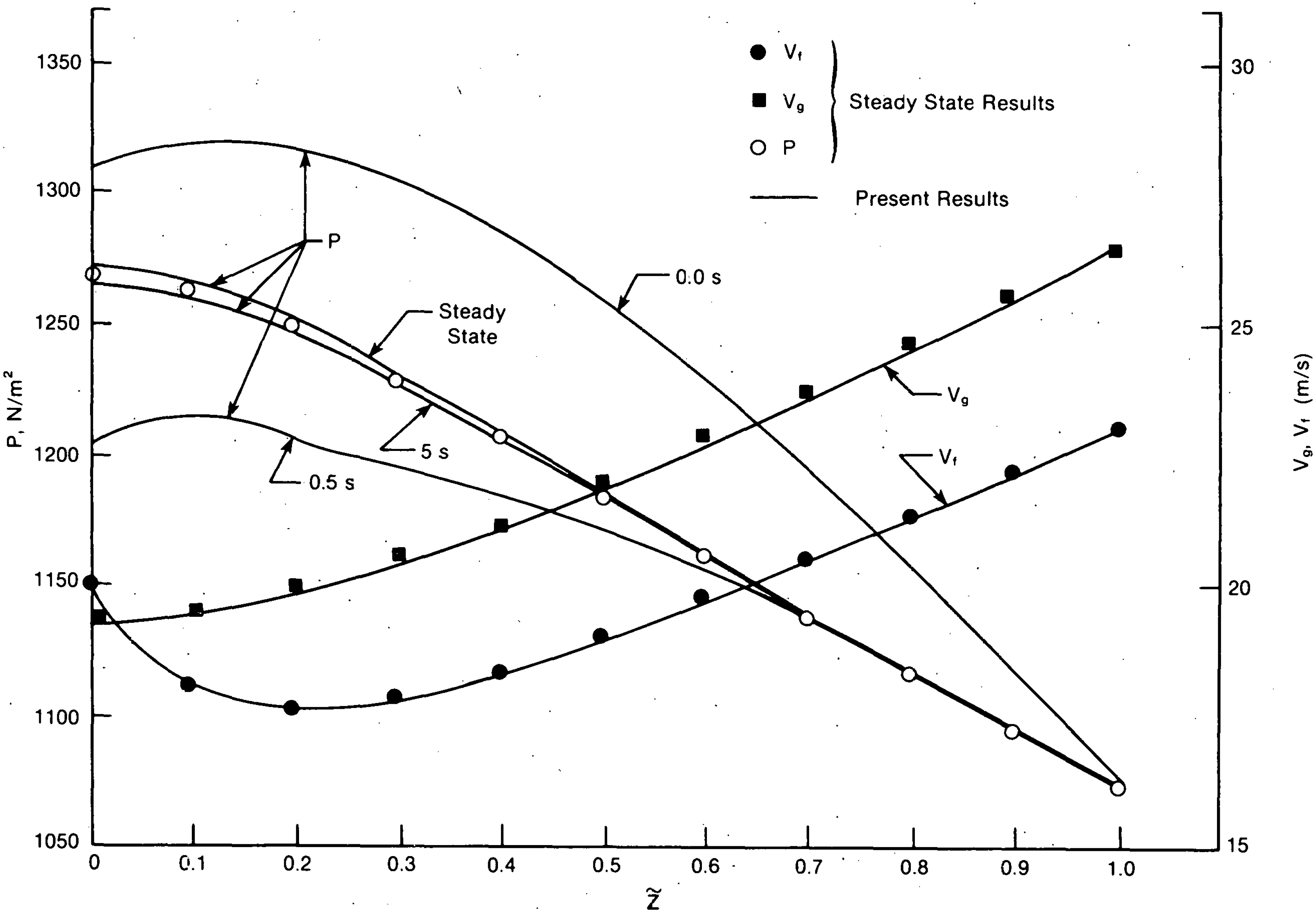
Several typical mist-lift transients will be simulated and tools will be available for evaluating further transients, as desired, and for incorporation into a more comprehensive system model that could include the condenser and turbine.

3.1.4.5 References

Wallis, G. B.; Richter, H. J.; Bharathan, D. 1979 (Sept.). Analysis of the OTEC Mist Lift Process. SERI/8317-1. Golden, CO: Solar Energy Research Institute.

Wallis, G. B.; Richter, H. J.; Bharathan, D. 1980 (Jan.). "A Computer Model of the Mist Lift Process in an OTEC Open Cycle System." Proceedings of the Eleventh Annual Pittsburgh Conference on Modeling and Simulation. Pittsburgh, PA; January 1980, University of Pittsburgh.

*Thayer School of Engineering, Dartmouth College.



Source: Wallis et al. 1979.

Figure 3-5. Pressure Profiles at Different Times

3.2 FOAM-LIFT POWER CYCLES

3.2.1 Foam Experiments—Tomlinson Fort, Jr. and Clarence Zener*

3.2.1.1 Objective

The current goal is to understand the detailed mechanism of foam growth and use this understanding to significantly reduce the required surfactant concentration, which will aid in establishing the economic feasibility of the foam OTEC system.

3.2.1.2 Approach

CMU constructed and operated a complete foam-lift system on a laboratory scale using a 10-cm-(4-in.-) diameter, 9.1-m-(30-ft-) high column to investigate the foam-lift phenomena. This system consisted of foam generation, foam lift, foam breaking, liquid and vapor separation, and, finally, segregating liquid into a standing pipe and condensing vapor by cold water spray. A schematic is shown in Fig. 3-6.

In this laboratory system, an upward flux density comparable to that anticipated for a commercial-size system was used. This flux density of approximately 1 g/cm^2/s would give a net power of approximately 11 kW/m^2. The law governing the rise of this OTEC foam was also developed, which simply states that the foam behaves as a viscous fluid. This was unexpected because the literature reported more complicated behavior for foam flow. Presumably the critical difference between the behavior of the OTEC foam and foam behavior reported in the literature lies in the rapid foam expansion immediately following foam generation. This expansion narrows all drainage paths thereby retarding drainage.

The viscosity of the OTEC foam is high, approximately 40 centipose, versus the 1 centipose of water. The Reynolds number for the flow is correspondingly low, approximately 40; therefore, the flow is laminar. This laminar flow will increase its diameter by a factor of 10. Thus, the laminar flow for columns up to 0.9 m (3 ft) in diameter can be extrapolated.

The Bernoulli equation with only one arbitrary constant describes the rise of the foam. Normally the condenser fixes the final foam temperature; therefore, the bottom foam temperature is indeterminant. When in the 9.1-m column $\dot{m}$ (mass flux) exceeds 0.2 g/cm^2/s, the foam temperature reaches the 25°C of the incoming water. With this flow rate the foam cannot expand until a critical height is reached. When $\dot{m}$ is less than 0.2 g/cm^2/s, the foam temperature is lower than the 25°C at the foam bottom and, therefore, the incoming water is warmer (superheated) than the first layer of foam cells. A foam generator was designed to take advantage of this superheat.

*Carnegie-Mellon University.

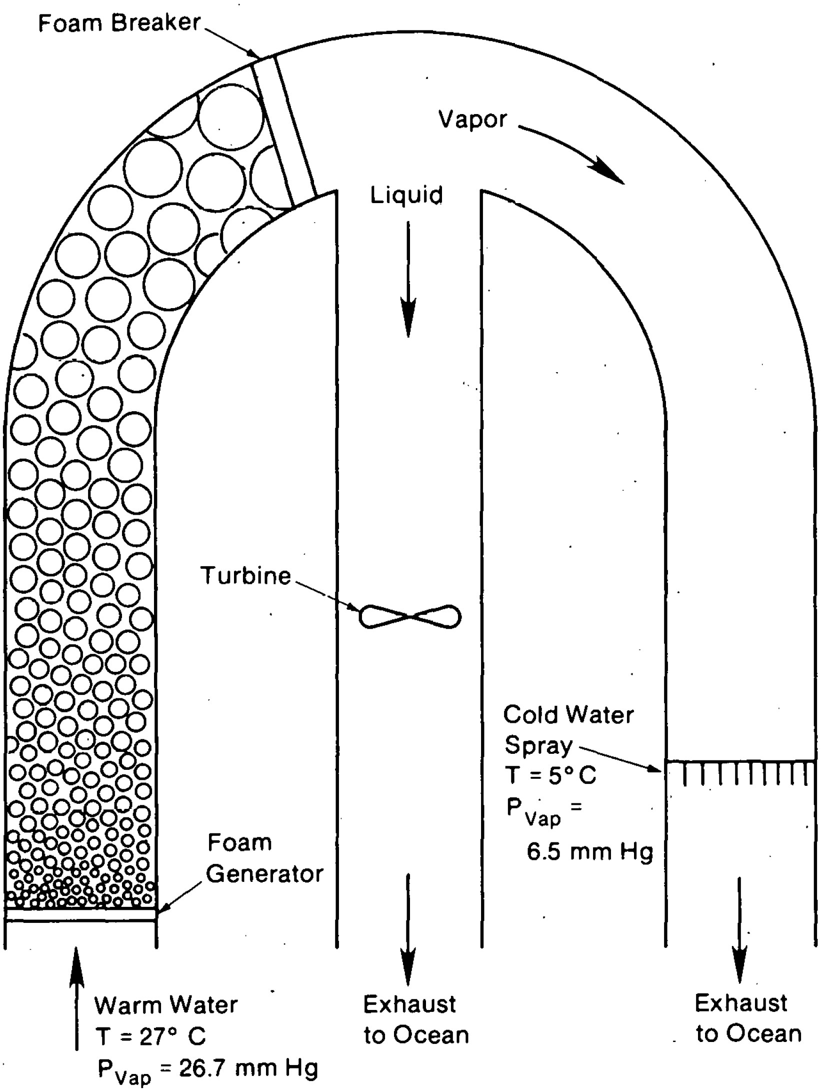


Figure 3-6. Schematic of the Foam OTEC Concept

3.2.1.3 Status

Foam Stability and Wall-to-Edge Drainage. Previously, surfactant concentrations of at least several hundred particles per minute were used to avoid foam rupture at the top of the column. What caused this rupture?

Gibbs recognized more than 100 years ago that the foam of a single component fluid would spontaneously fall apart. The foam edges, now called the plateau borders, are bounded by convex surfaces. The capillary tension of these convex surfaces lowers the pressure within the edges to below the pressure within the foam walls; thus, the walls are spontaneously sucked into the edges. Gibbs, as well as his contemporary Marangoni, also recognized that surfactants retard the fluid flow from the walls to the edges. The gas-like mutual repulsion of these surface molecules prevent the molecules from concentrating in the edges, effectively making the surface incompressible. The fluid can flow from the high pressure walls to the low pressure edges only between rigid surfaces.

A foam model was constructed that estimates the time required for the capillary-induced drainage to destroy the foam walls. In this model, wedge-shaped edges overlay the structure of a foam with uniformly thick walls. The calculated wall-to-edge drainage rate is two orders of magnitude too small to account for the observed foam rupture; therefore, an alternative cause of foam rupture was sought.

Foam Stability and Acceleration. Surfactants also can prevent foam failure by gravity. An identical argument shows how surfactants protect a foam from failure by acceleration, provided the concentration is sufficiently high.

Gravity drainage induces a higher surfactant concentration in the lower part of a cell interior than in the upper part. Under steady-state conditions this concentration exerts an upward surface force that exactly balances the downward force of gravity. The required surfactant concentration to counteract the gravity drag can be calculated. Using 200 as a typical surfactant molecular weight, 5.5 ppm is required.

Concerning the foam behavior, an upward acceleration of G has exactly the same effect as increasing gravity by G. Therefore, the foam acceleration in the column was studied, and it was found that this acceleration increases cataclysmicly as the foam approaches the top of the column. The acceleration rises as an exponential of the height. A 20°C temperature drop in the 10-cm-diameter column would cause an acceleration of 2000 G, if the foam maintained its integrity.

Realizing this disastrous effect of rapid acceleration, past experimental data were analyzed and found to be completely consistent with the calculations. Next, experiments were performed in which accelerations were reduced by elevating the operation temperature from 5°-10°C. As shown in Fig. 3-7, nearly an order of magnitude reduction in required surfactant was achieved. Refining the foam generator should bring the required surfactant down to 10 ppm, the theoretical value required for an upward acceleration of one G.

Replacement of Air Injection by Vapor Injection in Foam Generator. Previously, air was injected into a foam generator to form the required bubbles. This injected air has been the main source to the condenser. A new foam generating system has been built that replaces air injection with vapor injection.

In this system, now being tested, the problem of injecting water vapor with a higher pressure than the pressure of the incoming water had to be solved. This additional pressure must overcome the vapor pressure of the warm water, the retarding capillary pressure of the bubble being injected, and the pressure drops in the manifold. This problem was solved by adjusting the flow parameter rate so the foam column produces an "under pressure" at the bottom of the column. This under pressure is referred to as superheat with 1.86 millibars relating to 1°C of superheat. Thus, to overcome capillary pressure to nucleate 1-mm-diameter bubbles requires an extra pressure of 2.8 millibars, and a superheat of 1.5°C.

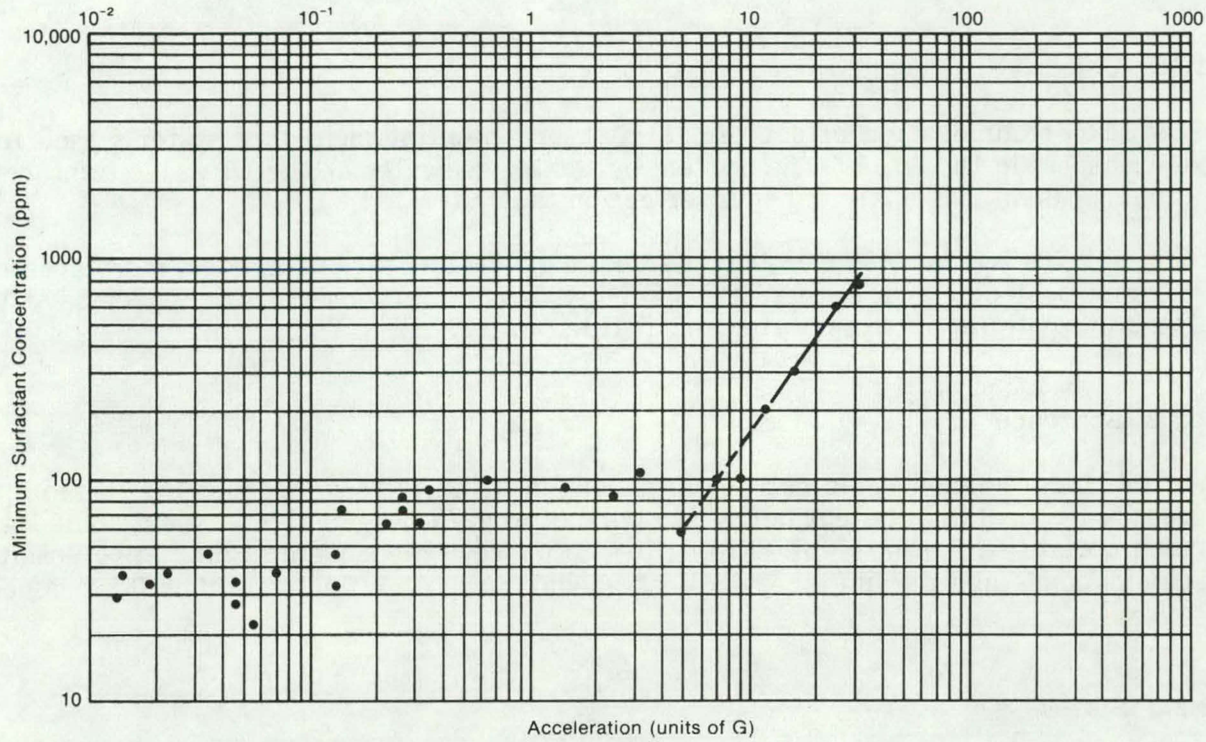


Figure 3-7. Minimum Surfactant Concentration vs. Upward Acceleration

3.2.1.4 Expected Results/Future Effort

The first scale-up will be constructed from a 10-cm (4-in.) to a 30-cm (1-ft) nominal diameter, 9.1-m-high column. The incoming warm water will be largely deaerated. The foam generator will use vapor injection, an atomized surfactant spray breaking the foam. The cold water spray will keep the condenser's air partial pressure within acceptable limits. The required surfactant concentration for this system will be very similar to that for commercial systems.

3.2.1.5 References

Molini, A. E. et al. 1979. "Design of Land-Based, Foam OTEC Plants for Bottoming Cycles." Proceedings of the Sixth OTEC Conference. CONF-790631/1. Washington, DC; 19-22 June 1979. Laurel, MD: The Johns Hopkins University, Applied Physics Laboratory.

Zener, C. et al. 1979. "Recent Development in the Foam OTEC System." Proceedings of the Sixth OTEC Conference. CONF-790631/1. Washington, DC; 19-22 June 1979. Laurel, MD: The Johns Hopkins University, Applied Physics Laboratory.

3.2.2 Foam Experiments—M. I. Kay*

3.2.2.1 Objective

This section examines the effect of seawater on potential surfactant systems used for mass transport in the foam OTEC system by testing seawater and fresh water transport, reproducing them, and analyzing their effect on the system.

Projected goals for FY 1980 were to construct a generator; to build a safer, more accessible tower scaffold; and to find the minimum surfactant concentration necessary to maintain mass transport in seawater and distilled water.

3.2.2.2 Approach

Since the foam column could not be permanent in its early form because the surfactant concentration could not be cut below 250 ppm, a program was instigated that would survey appropriate surfactants while attempting to improve the system. Eliminating unsuitable compounds and parameter guidelines should result. A final report will be issued later.

3.2.2.3 Status

All leaks have been sealed in the column; two foam generators have been used; and the scaffolding and a ladder have been constructed. Initial experiments have brought the Neodol 25-3A and 91-6 concentrations down to about 250 ppm. Using the CMU results announced at the Seventh OTEC Conference, the 25-3A surfactant concentration was further reduced to below 75 ppm in July 1980. A degasser has been constructed that reduces air concentration to about 25% of saturation at flows below 500 cm^3/min.

Thus far, at the high concentration used and high concentration resolution, there has been no quantifiable difference in the minimum concentration needed to transport distilled water and seawater nor much in molar concentrations of different Neodol surfactants.

The main experiment has been to simply dilute the surfactant solution until it will no longer transport water. Initially this was done by a factor of two dilutions. A peristaltic pump is now available that was installed after the minimum surfactant concentration dropped below 100 ppm in the reduced column. The most interesting result is that for fairly good surfactants no differences in minimum concentration between transported seawater and deionized water have been measured under similar conditions. The results are given in Tables 3-1 and 3-2.

The calculated acceleration forces for all of the above runs are small ($< G$). The calculation based on the measured temperature drop essentially begins meters above the foam generator in the 9.1-m column [see Zener et al. (1979)]. The bottom of the column is flooded with a turbulent air-driven foam. Since the column of water exists, $\dot{m}$ in the upper half of the column may not be totally commensurate with the incoming water flow.

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*University of Puerto Rico.

Table 3-1. Transport Results with a 9.1-m Column[a]

Surfactant Concentrations[d]	Transport (in ppm)			
	Good	Poor[b]		No
Ionic				
Neodol 25-3A	500	250	6×10^{-7}	125
3S	500	250	6×10^{-7}	125
Nonionic				
TRITON X-100	1000	500	8×10^{-7}	250
Neodol 91-6	500	250	6×10^{-7}	125
25-7[c]				

[a]Distilled water and seawater (ΔT about 8° ± 2° C)
[b]Second column expressed as moles/cm^3
[c]Very poor transport and expansion
[d]Surfactant chemistry

Neodol-25 $C_{12}H_{25}OH$ to $C_{15}H_{31}OH$ (mostly straight chain alcohols)

⟨MW = 203⟩

Neodol-91 $C_9C_{10}C_{11}$ alcohols (20%/40%/40%)

⟨MW = 160⟩

TRITON X-100
$$CH_3-\underset{CH_3}{\overset{CH_3}{\underset{|}{\overset{|}{C}}}}-CH_2-\underset{CH_3}{\overset{CH_3}{\underset{|}{\overset{|}{C}}}}-\Phi-(OCH_2CH_2CH_2)_{9.5}OH$$

where 9.5 denotes a peak in a poison distribution

$$\Phi = C_6H_4$$

Neodol:

25-3A, 3S: Was examined. These are ammonium and sodium salts of ethoxy sulfates. The 3 denotes the number of ethoxy groups. In salt water solution these will effectively be the sodium salt.

25-7: $(OCH_2CH_3)_7$ OH

91-6: $(OCH_2CH_2)_6$ OH

It is encouraging to note that the smaller chains are as effective or more so than the longer ones.

Table 3-2. Results with 6.1-m Column

Temperatures	Transport	No Transport	Liquid Transported
T_o = 35° C	75	37	Seawater Distilled Water
T_o = 30° C	150	75	Distilled Water Seawater
ΔT = 4° C			
T_o = 28° C	75	55	Seawater

The original 9.1-m column was reduced to 6.1 m and has been much easier to control. A picture of the test column is shown in Fig. 3-8.

Results will be observed carefully for differences in temperature distribution. Finally, the concentration resolution used was quite coarse. Differences below a factor of 2 could not be seen. The experiment as operated with the surfactant pump can probably be developed to about 10% to 20% of the concentration levels.

Most Center for Energy and Environment Research (CEER) data were collected using ambient water for input (29° ± 2° C). Operating at 35° C showed a drop in the friction coefficient from about 0.012 $\dot{m}$ to 0.006 $\dot{m}$ as predicted in Noriega and Zener (1980). Currently, all measurements indicate that dynamic effects are totally overwhelming chemical differences in appropriate surfactant systems. It is assumed that as the surfactant concentration decreases and the precision of the measurements increases, differences will appear.

3.2.2.4 Expected Results/Future Effort

Work will be continued at lower concentration levels using a 3- to 6.1-m (10- to 20-ft) column. At levels below 75 ppm, concentrations needed for minimum transport will be established more precisely ($\Delta T(z)$ regime) and/or single surfactant systems will be investigated.

The amount and effect of suspended particulates in seawater on the surfactant solutions will be established by extracting and checking surface tension as a function of particulate addition.

The column will be rebuilt so that larger expansions may be achieved, preferably with more uniform acceleration.

It would probably be useful to reduce the column by about another metre or work at a slightly higher ΔT to reduce or eliminate the ill-defined spherical region completely. At $\dot{m}$ = 0.3 g/cm^2/s, the bottom of the column is still in the spherical region for small ΔT.) At ΔT = 6° C the foam spends 83 s in the spherical region and 38 s as a polyhedral foam under the above assumptions.

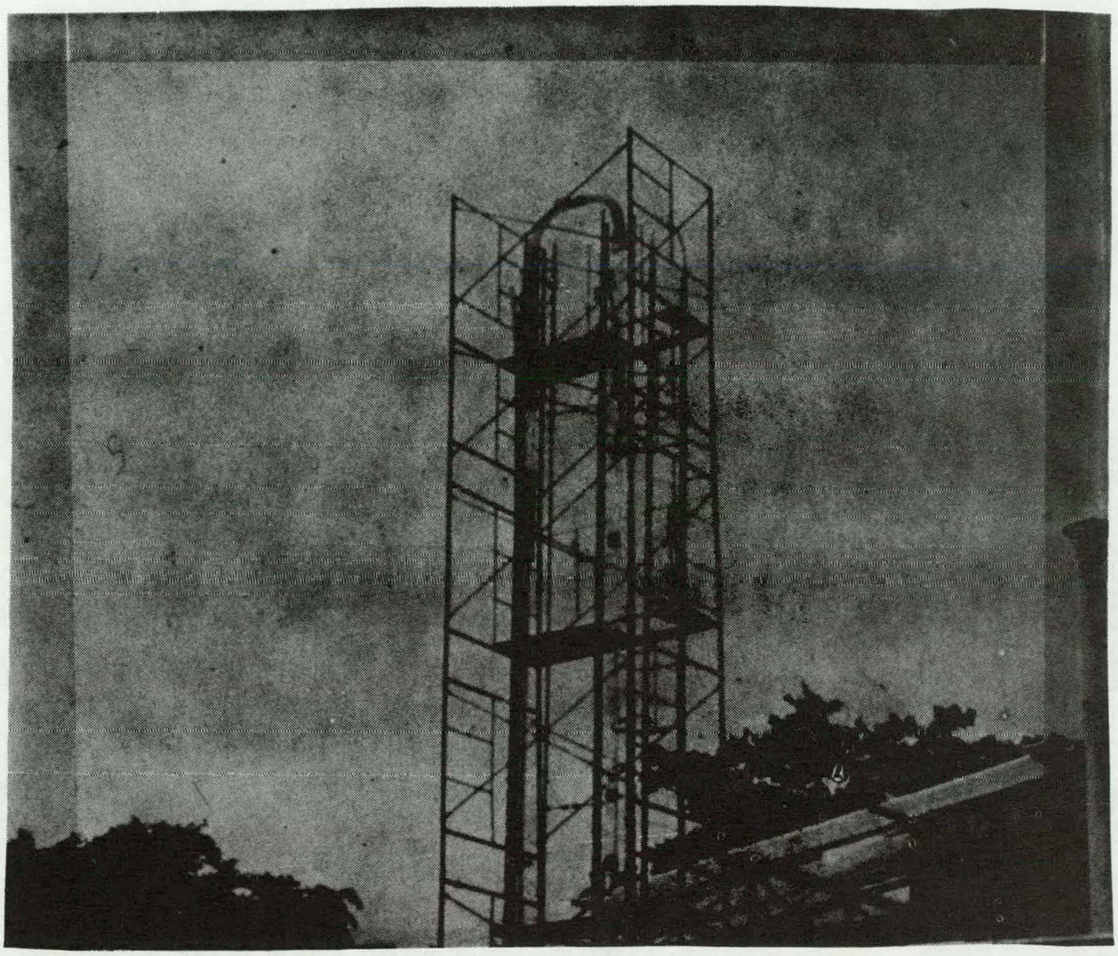

Figure 3-8. The Foam-Lift Test Column

3.2.2.5 References

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Noriega, J.; Zener, C. 1980 (June). VII OTEC Conference (Oral presentation).

Zener, C.; Molini, A.; Fort, T.; Fetkovich, J.; Greenstein, M. 1979 (June). Paper 9.2, Proceedings of Fifth OTEC Conference, Washington, DC.

SECTION 4.0

ALTERNATIVE OCEAN SYSTEMS OVERVIEW—Peter H. Davidoff*

4.1 SERI'S ALTERNATIVE OCEAN SYSTEMS PROGRAM

The Alternative Ocean Systems Program began in 1975 as R&D spinoffs of DOE's [then called Energy Research and Development Administration (ERDA)] OTEC program. The program became part of the DOE Ocean Systems Branch when DOE was formed (Sherwood et al. n.d.). The early phase of the program emphasized:

- evaluating unsolicited proposals;
- supporting selected devices to establish their engineering feasibility;
- participating in International Wave Energy Programs via the International Energy Agency (IEA); and
- organizing activities that would generate an initial data base on wave and current energy (Sherwood et al. n.d.).

On 1 October 1979, the responsibility for the Alternative Ocean Systems Program was transferred to SERI. SERI's specific role is defined as the assessment and development of those ocean energy technologies considered alternatives to the DOE baseline program, closed-cycle OTEC. These alternatives presently include:

- alternative thermal cycles,
- ocean wave energy,
- ocean current energy, and
- salinity gradient energy.

The SERI role is to manage subcontracted research that supports these technologies.

The specific goals of the SERI Alternative Ocean Systems Program were developed to support the DOE mission. The overall program goal is to investigate and accelerate the technical, commercial, and economic viability of Alternative Ocean Energy Systems.

To support these goals, SERI has defined initial objectives, in part, adopting and continuing the original DOE objectives. These objectives are to:

- develop and assess an alternative ocean energy data base that consists of
  - gathering alternative ocean energy resource statistics and scenarios,
  - determining ocean engineering requirements pertaining to wave and current devices,
  - specifying applicable markets and market needs,
  - determining institutional requirements,
  - deriving alternative ocean energy system economics, and
  - classifying, investigating, and setting priorities of wave energy devices;

*SERI, Ocean Systems Program Branch

- support specific promising ocean wave and ocean current device development; and
- generate a theoretical and analytical basis for the design of specific wave energy devices.

The alternative ocean systems program comes under the Advanced R&D Program and is divided into four areas of research plus administration. This breakdown is shown in Fig. 4-1.

Discussions of the work performed under Wave Energy Research and Ocean Current Research are presented in Secs. 4.1 and 4.2, respectively. Work performed under Other Technology Research is presently limited to salinity gradient and thermoelectric OTEC. The following sections present an overview of the Wave Energy Program, its five-year plan, FY 1980 progress, and FY 1981 plans. Similar sections are presented on the Ocean Current Program followed by accounts of the limited work in salinity gradients and thermoelectric studies.

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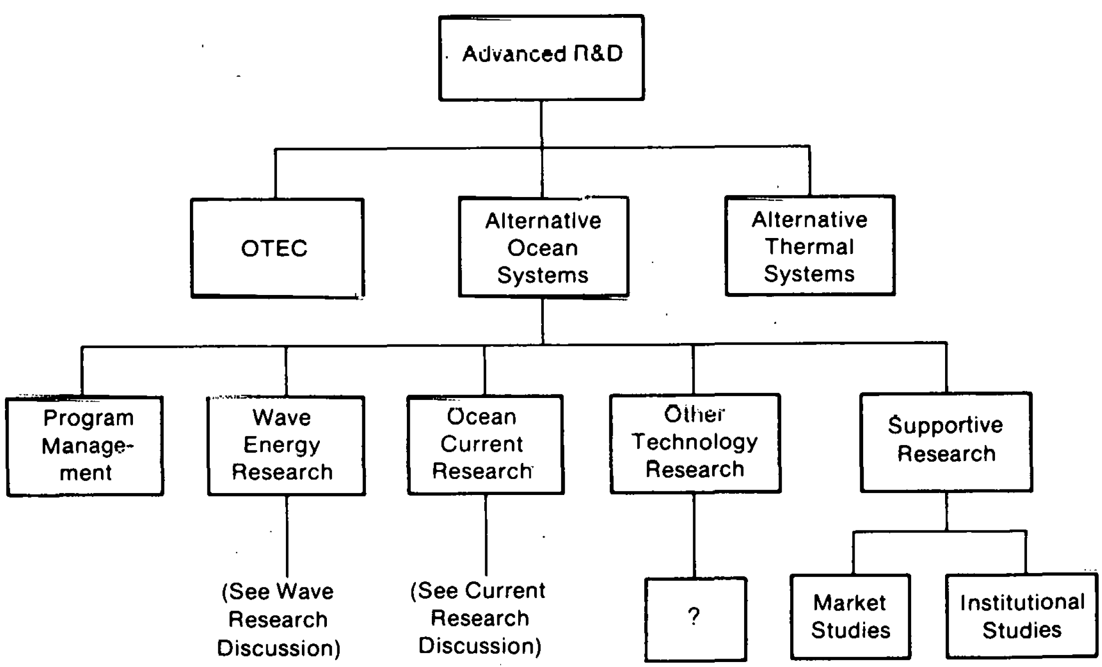

Figure 4-1. Breakdown of Advanced R&D Program at SERI

4.1 WAVE ENERGY PROGRAM OVERVIEW—Peter H. Davidoff*

The U.S. Wave Energy Program is in a period of growth and change. It focuses on those innovative and promising device and system concepts that presently are not being adequately pursued in ongoing international programs. It acts as a liaison with these ongoing programs and complements them. Further, the program is built around the potentially more cost-effective offshore power generation systems. Emphasis is on the total system as opposed to individual device or subsystem concepts. Thus, the technologies pursued are determined by their potential cost-effectiveness and readiness for commercialization. And finally, while the main thrust of the program will be in specific initiatives arising out of system design and application studies, it will be the program's policy to continue soliciting and encouraging innovative ideas not currently within the program.

The wave program organizational structure is shown in Fig. 4-2. There are six areas of program thrust: power system research, head sea devices, beam sea devices, wave focusing devices, internal liaison, and support.

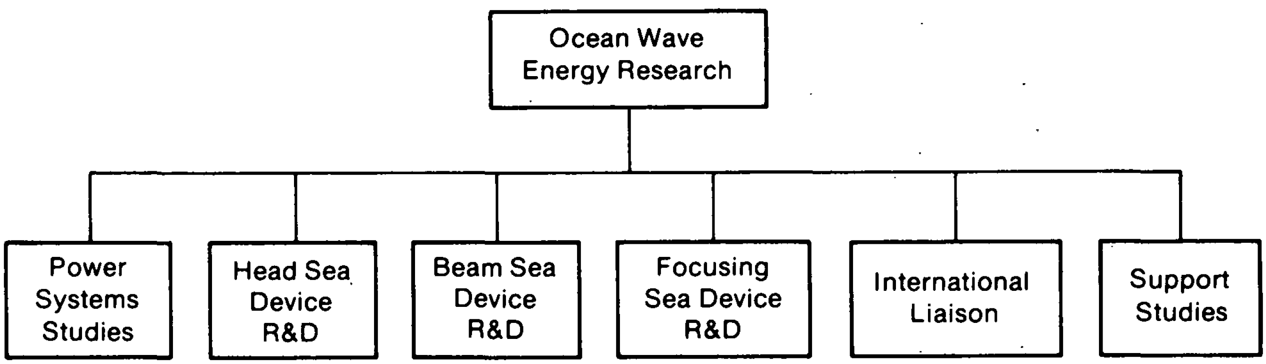

Figure 4-2. Wave Energy Program Organizational Structure

<u>**Progress in FY 1980**</u>

The wave program has initiated some new studies and continued DOE-originated studies; specifically,

- Power System Studies
  - a wave energy systems study was initiated to evaluate wave devices and systems from an engineering/cost perspective, and
  - the CUNY wave resource study was continued.

*SERI.

- Head Sea Devices
  - Numerical analyses were done and are continuing to aid the understanding of the hydrodynamics of wave interaction with devices similar to the Kaimei barge and the Hagen-Cockerell raft. These analyses show the potential for improving device energy extraction efficiency and reducing mooring forces.
  - Construction and fabrication are near completion for a full-scale head sea device, the 125-kW_e pneumatic turbine designed for use on the Kaimei barge. Furthermore, a detailed test plan was developed for this oscillating flow turbine. Methods for using this laboratory test data to predict the sea performance of the air turbine were formulated.
  - Analysis of the data from the second sea trial of the Kaimei was initiated and plans were formulated for international cooperation in this effort.
- Beam Sea Devices
  - Support for the development of a tuned, tandem-flap wave device was initiated.
  - Evaluation of a large number of unsolicited proposals, mostly dealing with beam sea devices, is in progress. Funding possibilities are being explored.
- Wave Focusing Devices
  - An investigation of the potential for refractive wave systems (Dam-Atoll[tm]*) was initiated. The preliminary analysis and mathematical modeling that will lead to construction and testing of a scale model have been completed.

The deliverables for FY 1980 included parts of the systems study: a bibliography, a work breakdown structure, and a top-level-requirements document. The numerical studies in head sea devices produced two reports: "Head Sea Diffraction by a Slender Raft with Application to Wave Power Absorption" and "Rafts for Absorbing Wave Power." Another report pertaining to head sea devices was the Sea of Japan, Wave Energy Conversion Data Analysis. Other projects were started in mid- and late FY 1980, and the deliverables for these projects are scheduled for receipt throughout FY 1981.

Plans for FY 1981

Many FY 1980 initiatives will be continued in FY 1981. These continuations plus new activities follow:

- The wave systems study will continue with deliverables that include performance estimates for the nine generic wave energy extraction/conversion concepts, and the synthesis and preliminary engineering/cost evaluation of power systems built around these concepts.
- A wave systems priority study will be conducted that will provide insight into the weakest areas of the data base. It will also rank the various wave systems with a multiple criteria framework consisting of performance, cost, survivability, and environmental considerations.
- Hydrodynamic analysis will emphasize head sea devices and be directed to support the laboratory testing of the oscillating flow pneumatic turbine, as well as being supportive of any possible U.S. participation in future Kaimei deployments.

- A new device initiative is planned, soliciting new ideas in all areas of wave energy. This effort will build on the unsolicited proposals currently on hand.
- The refractive wave device (Dam-Atoll) will enter its model testing phase around mid-1981.
- The prototype air turbine wave energy converter will have completed its testing program. These steady-state test results plus some hydrodynamic analysis will be employed in a dynamic performance modeling of the turbine and its attached generator.
- A concept development and model testing program for the tandem-flap beam sea device will be implemented during FY 1981.
- Analysis of the data from the second sea trial of the Kaimei will continue.

Five-Year Plan

Figure 4-3 presents the SERI 5-year plan for the wave program. Line 1 indicates new technology assessment. Seed Request for Proposals (RFPs) will be issued, at most, on an annual basis and will call for innovative concepts to be forwarded to SERI for potential funding.

Line 2 indicates the first level of funding—Device Development, Phase I—which involves mathematical modeling and feasibility studies. Should the concept evaluation warrant continued funding, it moves into the system R&D phase requiring device development and testing (Line 3).

Lines 4, 5, 6, and 7 show the plans for more generic activities of the system study, experimental program, critical component development, and numerical analysis. The system study will help define areas common to wave devices that require experimental investigations and will be reviewed annually and updated. The program provides continual feedback between analyses and experimental programs. The City University of New York (CUNY) is providing a general wave energy resource assessment (Line 8). As systems are developed and prototype application studies identify preferred deployment scenarios, site-specific studies will be required.

Deployment of major at-sea experiments will require planning through commercial and institutional studies concurrent with the technical studies. Some of the institutional studies will be performed by SERI's internal research group (Line 10).

The configuration studies (Line 11) are part of the power system study (Line 4). The intent of these studies is to detail large-scale applications of wave devices raising technical as well as institutional issues. Wave energy devices may apply to several immediate small-scale applications. Line 12 identifies these applications and shows the eventual deployment and testing of wave devices needed.

The program intends to maintain a dialogue among the nations participating in the development of wave energy (Line 13).

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*Dam-Atoll is a patented concept of the Lockheed Missiles and Space Company, Inc.

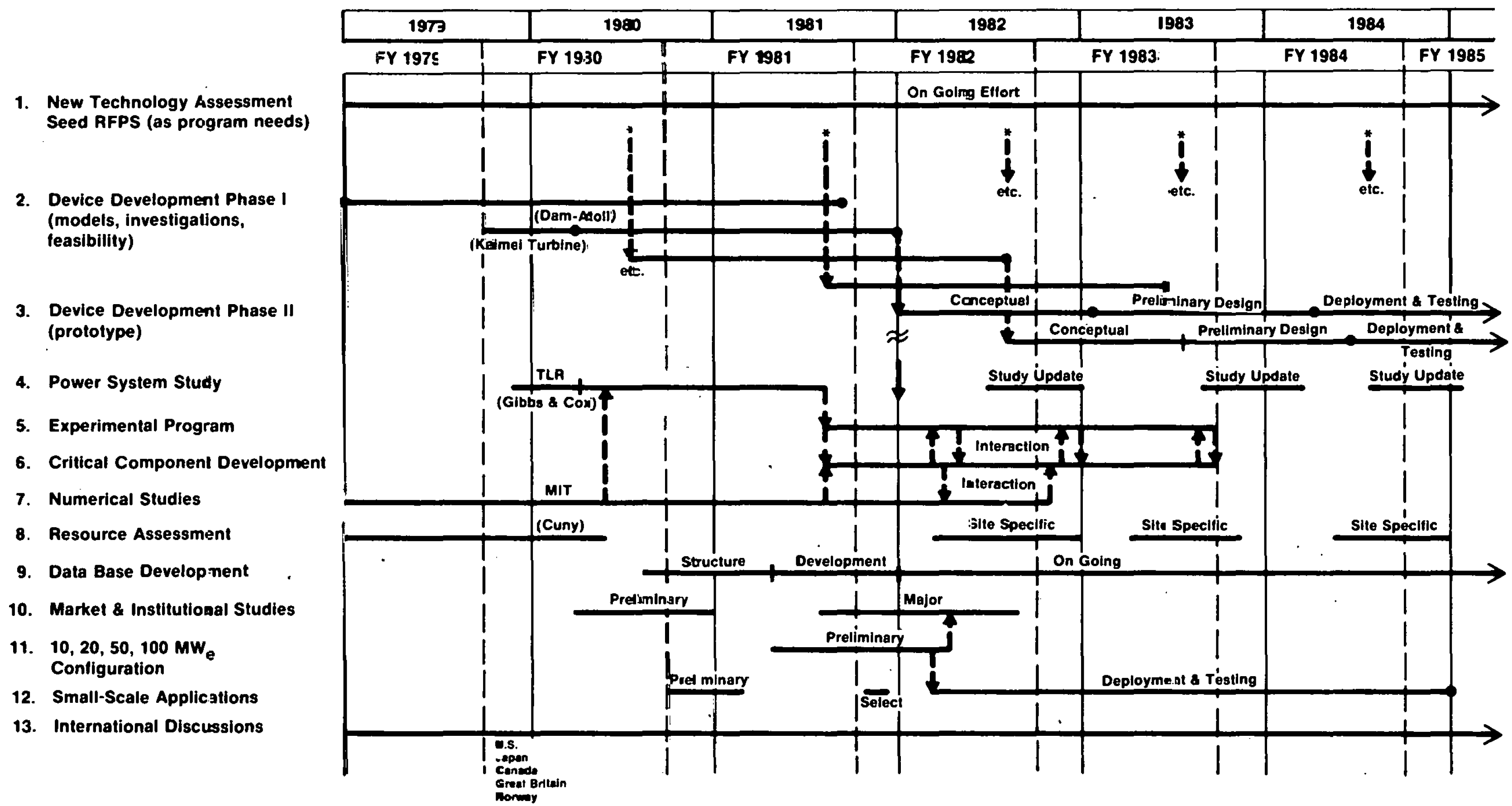

Figure 4-3. Five-Year Plan Wave Energy Program

4.1.1 Wave Resource Study—Peter H. Davidoff*

4.1.1.1 Objectives

This study will prepare a climatology of available wave power for selected locations and will provide a wave and wind climatology for four potential OTEC sites. These results will be based on Wave Hindcasts prepared by the Fleet Numerical Weather Central, presently archived at the David Taylor Naval Ship Research and Development Command. This climatology will be used to select a set of grid points for the North Atlantic and North Pacific oceans.

4.1.1.2 Approach

The Fleet Numerical Ocean Center (FNOC) produced a wave climatology based on the historical data for the meteorological fields over the Northern Hemisphere oceans. With about 1250 grid points for the Spectral Ocean Wave Model (SOWM),** 365 days in a year, and 4 spectra per day, the climatology consists of approximately 36 million spectra. Since each spectrum needs to be described by about 180 numbers, the total numbers involved are about 6.5 billion.

The first task was to obtain a manageable subset for wave power and OTEC climatology studies from this data. This was done by producing master data tapes for the 10 years of available data and for selected grid points in the North Atlantic Ocean, Gulf of Mexico, and North Pacific Ocean. Originally the FNOC spectra were compressed by omitting very low values, whereas the master data tapes were expanded to be more useful.

The Gulf of Mexico has five locations. The North Atlantic has 19 locations—5 across the trade-wind belt, 3 around Puerto Rico, and 11 off the east coast of the United States. The North Pacific has 33 locations—7 off the west coast of the United States, 6 around Hawaii, 8 west of Hawaii, and the remainder in the Gulf of Alaska. This subset of spectra is contained on less than 60 magnetic tapes and can be used for purposes other than this study.

In general, the grid points of SOWM are too far offshore to represent the waves that would occur at a potential wave power installation within 20 km of a coastal target city. Programs were developed to convert the SOWM spectra at the grid points to spectra representative of a location closer to the coast for a number of target points. These included computing the local wind sea for offshore winds, detecting those spectral frequency-direction bands with offshore propagation directions, and correcting for island shadowing effects.

A first order correction for the effect of wave refraction was also made for target points in shallow water, assuming the device for extracting the power from the waves would be a linear array approximately 10 km long. For straight parallel depth contours, the

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*SERI, Ocean Systems Program Branch

**Developed by Dr. Willard Pierson, the SOWM specifications and forecasts are produced on a grid of points laid out on twenty triangles that form an icosohedron. It uses 20 years of meteorological data and provides directional wave spectrum for the specified grid points.

available power is reduced by the angle of the wave crests in deep water made with the wave power array as aligned with the depth contours.

The wave spectra with ft^2 units after integration over a 30-degree direction band and the appropriate range of frequencies, can be converted to true wave power spectra by dividing each element of the 180 value array by the central frequency of the spectral band, and multiplying the result by 0.724. The number that results is the wave power in kilowatts/metre, or megawatts/kilometre, if all the kinetic and potential energy in the waves for that range of frequencies and directions could be extracted with 100% efficiency.

Any frequency-dependent system can be studied in terms of these true wave power spectra, but for this study the optimum orientation of a linear array 100% efficient at all frequencies is used, and the available wave power is found from each six-hour spectrum in the master data file.

The available data on the wave power for each target location will be processed to show the cumulative histogram of the number of times the wave power was less than a given value for that six-hour spectrum for each month of each year. Also, the number of consecutive hours the power exceeded various threshold values will be given. When stratified by month, the average monthly value for the wave power will be found and the variability for the same month of the year from one year to another will be shown. The statistics will make it possible to carry out preliminary design calculations as if the target point were a candidate for a wave power installation.

4.1.1.3 Status

No progress has been made in the program since June 1980. At that time the authorization to use the Naval Research Computer (NRL) (but not the funds available) expired. The lapse of the program at ORNL plus its transfer to Chicago and then to SERI created delays.

To date, the program design is complete and the data base of 54 reels of magnetic tape containing the raw SOWM spectra is compiled. But the program must be run to produce the desired output.

4.1.1.4 Expected Results/Future Effort

SERI is arranging with NRL for CUNY to use NRL facilities to do a final run of the program and data. This will form the final report.

4.1.2 Dam-Atoll Device—J. Frier*

4.1.2.1 Objective

The long-range objective is to design, fabricate, install, and operate a large-scale example of the Dam-Atoll Wave Energy Device to demonstrate production of usable electrical energy from ocean waves and, ultimately, to produce full-scale commercial systems. It is estimated that each full-scale unit will produce 1-2 MW of electrical power.

The Dam-Atoll program at Lockheed Missiles & Space Company (LMSC) Ocean Systems, presently under contract to SERI, has the engineering design studies and small-scale model tests necessary to provide data that directly support the subsequent large- and full-scale development. This project will define the detailed data base and methodology necessary to develop each of the technical areas and the total system.

4.1.2.2 Approach

The Dam-Atoll device is basically an artificial atoll that causes incoming waves to focus toward the center of the atoll (see Fig. 4-4). The energy collected from the breaking waves is concentrated into a vortex flow created in the central core of the device and drives a turbine and generator. Analytical and design methods and design parameters must be established to develop the Dam-Atoll device.

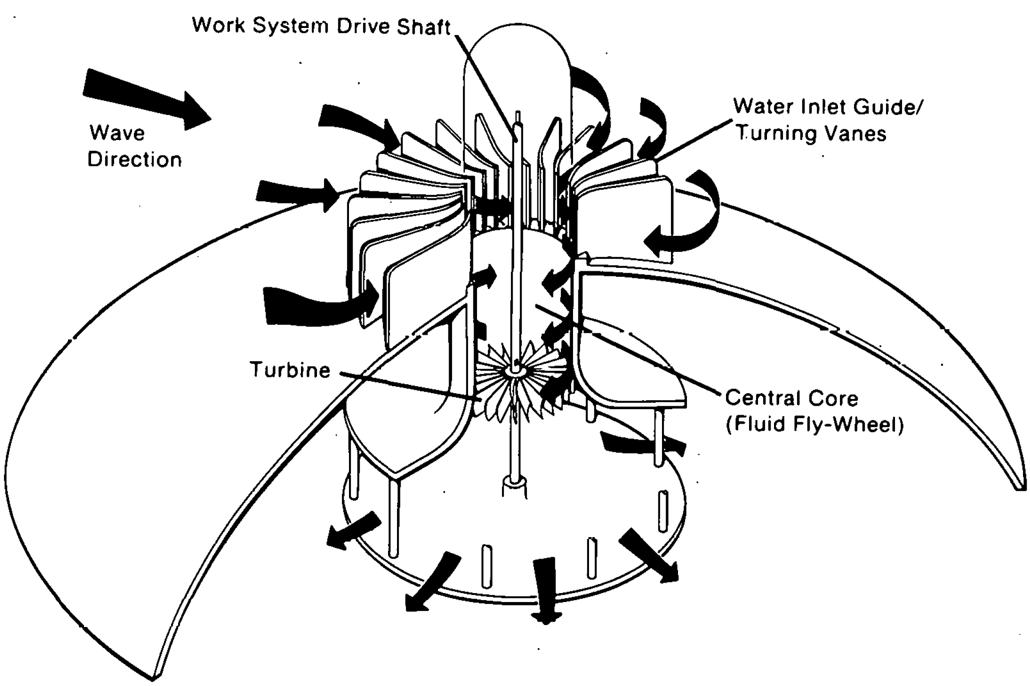
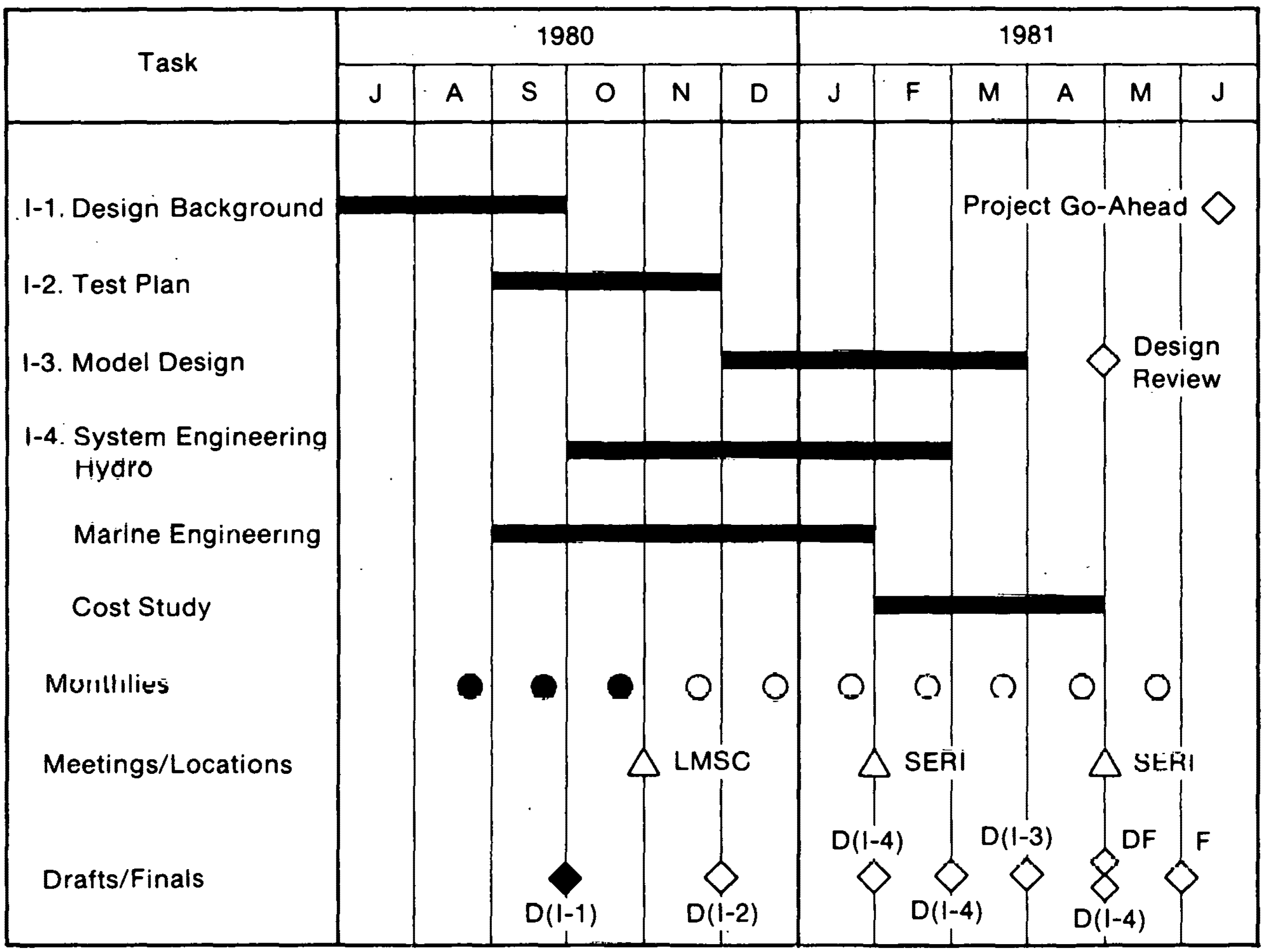


Figure 4-4. The Dam-Atoll Conversion Device

*Lockheed Missiles and Space Company, Inc., Ocean Systems.

The LMSC program has two one-year phases. The tasks and schedules are contained in Figs. 4-5 and 4-6.

Phase I will (1) define the analytical methodology and data necessary for model design and subsequent system development; (2) develop a preliminary model test plan; (3) execute a model design (1/50th scale); and (4) accomplish a systems engineering investigation in the areas of hydrodynamics, marine engineering, and costs. A report will be written for each of these tasks. Phase II will commence when SERI approves these progress reports, conducts a major project review, and approves going ahead.



D - Draft DF - Draft Final F - Final

Figure 4-5. Dam-Atoll Wave Energy Extraction Device SERI/LMSC Contract—Phase I

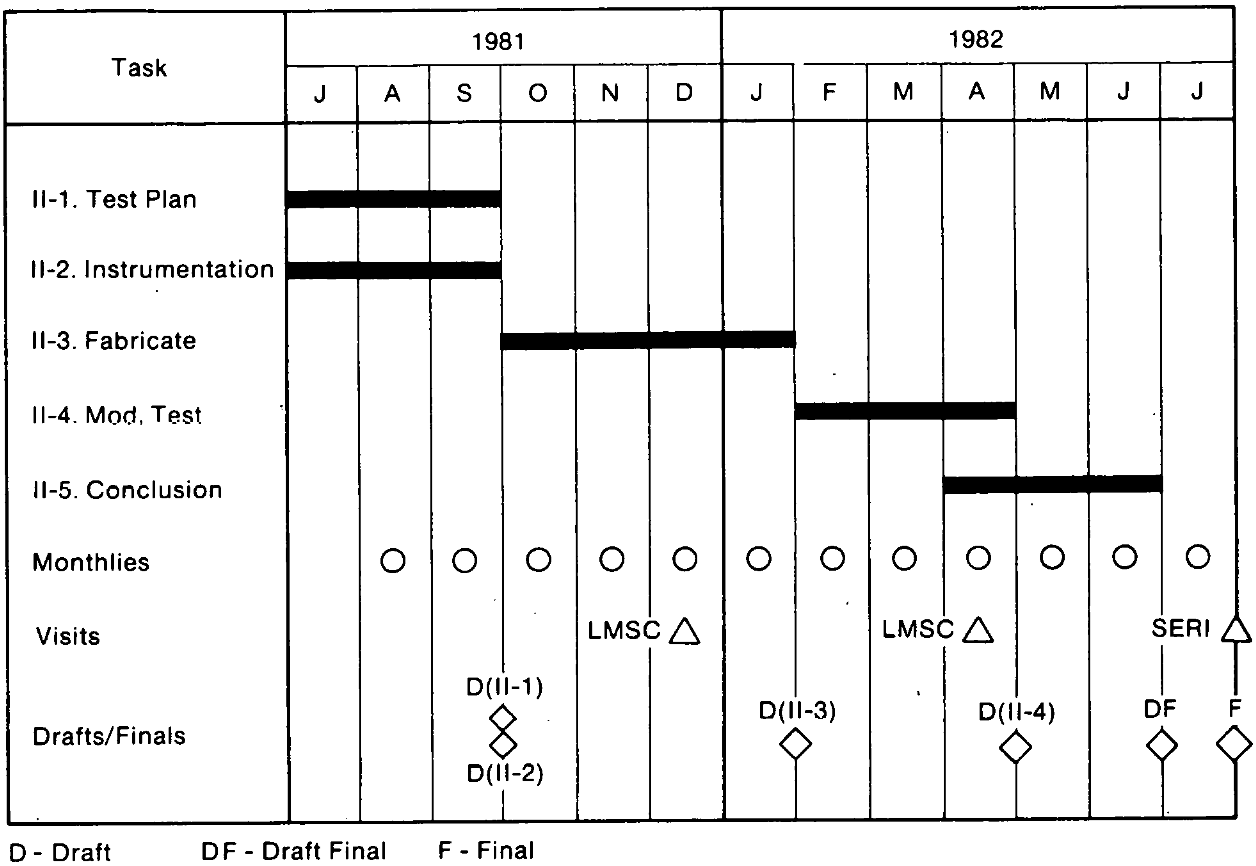


Figure 4-6. Dam-Atoll Wave Energy Extraction Device SERI/LMSC Contract—Phase II

The preliminary model test plan generated during Phase I will be revised during the first three months of Phase II. An instrumentation plan will also be generated. Models will be fabricated over a four-month period and tested during the three months following fabrication. A final report will be delivered that summarizes all Phase I and II tasks and results, conclusions, and recommendations for the Dam-Atoll Program. Theoretical studies, formulation of methodologies, design, and test of the model will be evaluated against several criteria that may include agreement between theory and test results, optimization of components and the system, and treatment of scaling factors. Overall, the results of Phases I and II are to reflect the development and refinement of data and techniques directed to maximizing development of large- and full-scale Dam-Atoll systems.

4.1.2.3 Status

The first task was initiated with a contract awarded on 30 June 1980. Task I-1 was completed on 30 September 1980 as scheduled and a draft report was delivered to SERI. The model test plan task, the hydrodynamics portion of the systems engineering, and marine engineering have been initiated.

The design background task compiled and documented the wave refraction methodology developed during early feasibility studies and included modifications and improvements that provide flexible designs for subsequent component and system design and optimization studies. Tests of computations and correlation of the different values and computer graphic printouts confirm program readiness for use during future investigations.

Early tests of a Lockheed small model have proven that the device operates; however, it is only proof of concept using qualitative data. Design and optimization of components and of the total system still need to be accomplished. The Lockheed program will provide the quantitative data necessary for further development. Useful quantitative information is yet to be obtained by calculation or test for the internal flow in the central (vortex) core, turbine design, installation and operation, the power system, manufacturing, and costs.

All the engineering investigations of the first 12 months of the program will provide information to support the decision to proceed with Phase II. It is not anticipated that any results of technical studies in Phase I will affect that adversely, even if some technical questions exist in an individual area. The decision to develop a large-scale Dam-Atoll system for demonstration in the ocean depends on the cumulative results of Phases I and II.

4.1.2.4 Expected Results/Future Effort

Completion of Phases I and II of the program now under contract will provide the methodology for study and design of the Dam-Atoll system, and improved knowledge of the device based on application of results of engineering studies and tests of the 1/50th scale model. The next step probably will be tests and analyses of a larger scale model in a controlled facility followed by the design, development, and installation of a large-scale device in a selected coastal region to obtain measurable power, determine efficiencies, and obtain operational experience. The next phase will be to develop a full-scale Dam-Atoll system and operate it in the ocean to obtain data on power output, efficiencies, reliability, and operating procedures over a period of time and evaluate how the power can be used by the utilities. The full-scale ocean installation will provide the ultimate measure of Dam-Atoll in providing electricity from ocean waves.

4.1.2.5 References

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Arthur, R. S,; Munk, W. H.; Isaacs, J. D. 1952 (Dec.). "The Direct Construction of Wave Rays." Transactions American Geophysical Union. Vol. 33 (No. 6).

Wirt, L. S. 1978 (Feb.). Extraction of Wave Energy. CALAC Report No. LR28501. Sunnyvale, CA: Lockheed Missiles and Space Company, Inc.

4.1.3 Systems Evaluation Study—Eric Midboe et al.*

4.1.3.1 Objective

The Wave Energy Systems Evaluation Study (Gibbs & Cox, Inc. 1980) is designed to develop a comprehensive methodology to evaluate wave energy systems from an engineering/cost perspective, to synthesize generic wave energy systems from identified wave energy extraction and conversion techniques, and to perform an initial evaluation of the generic systems. The methodology developed and the resultant comparative assessments made will be important factors in planning future research and development priorities for the SERI wave energy program.

4.1.3.2 Approach

The overall approach of the study is shown in Fig. 4-7. The first step is to identify and classify wave energy extraction, conversion, and utilization techniques based on existing literature and engineering judgment. Next, a work breakdown structure (WBS) is developed to frame the development of the wave systems and is organized around the four functional areas involved with the acquisition of a major system; i.e., project management, design, acquisition, and operations.

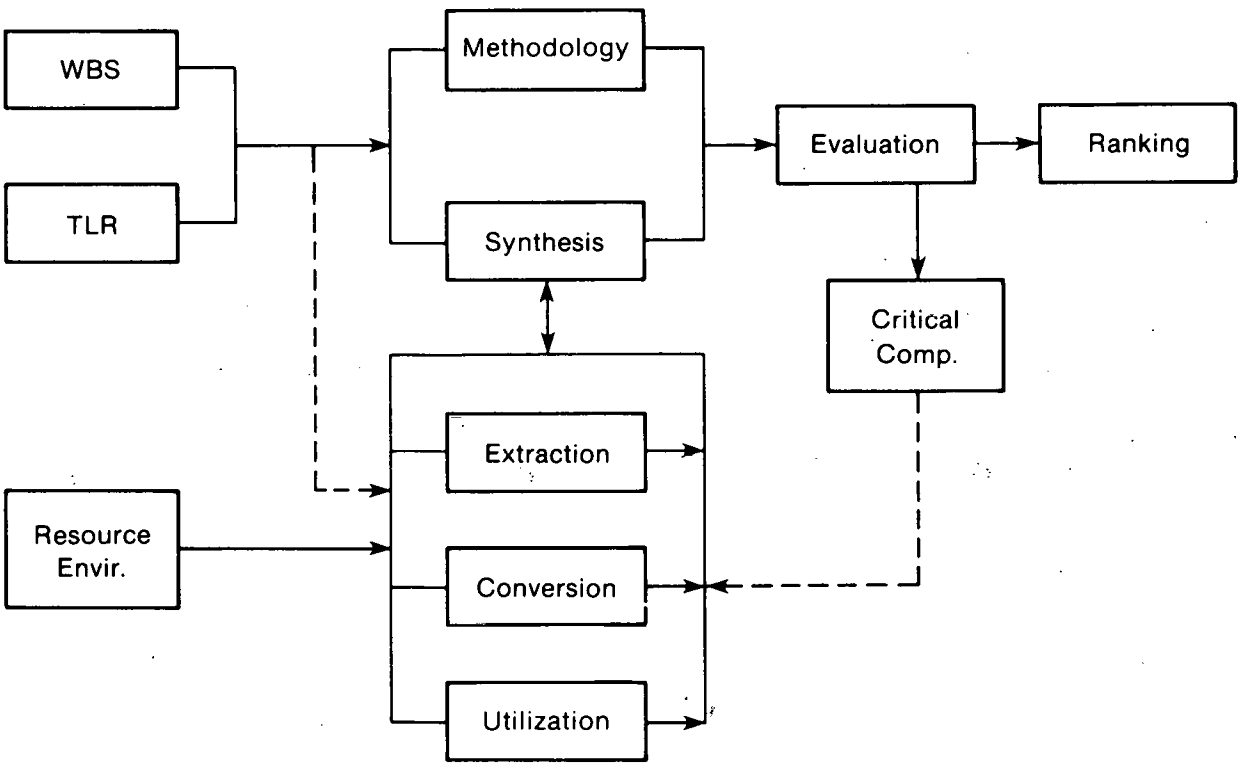

Figure 4-7. Wave Energy Systems Study Flowchart

*Gibbs & Cox, Inc.

Top-level requirements are also developed that establish very broad mission requirements and constraints necessary for a feasible design. Included are life-cycle costs, performance (power output), constructability, deployability, reliability, maintainability, operability, survivability, environmental impact, and safety. The requirements begin as a general document and increase in level of detail as the design passes from feasibility through conceptual, preliminary, and contract design.

Environmental conditions for system design and operation are then established that are typical for high resource areas within the United States. Design considerations are based on survival of the 100-year storm while operations are based on the predominant wave or swell conditions found in the area.

Next, extraction and conversion techniques are assessed as functions of device size, configuration, and sea state characteristics. Wave energy systems are then synthesized from compatible extraction and conversion techniques and required ocean subsystems (i.e., structure, mooring, support subsystem, and power transmission) to define their general characteristics.

Life-cycle costs are developed so comparisons can be made among the systems, and high-cost risks can be identified. The cost factors reflect the cost of the total wave system amortized over a reasonable life expectancy. The costs for construction, deployment, operation, overhaul, transmission/utilization, unique construction facilities, and salvage are included.

The final step is to evaluate the wave energy systems based on a Figure of Merit (FOM) defined as:

$$\text{FOM} = \frac{\text{Benefit}}{\text{Cost}} = \frac{\text{Energy Produced}}{\text{Cost to Produce}} .$$

The benefit is expressed as the energy produced over the life of the system, and the cost is the life-cycle costs previously noted.

This is an evolving iterative approach, although each iteration need not be composed of the full cycle. As the iterative process proceeds, it is hoped that precision and detail will increase; therefore, totally definitive answers will not be part of the initial results. As the data base grows and the number of candidate systems are narrowed, the leading systems can be further defined as to their characteristics and relative attractiveness for commercial power production.

The major deliverable will be a report that details the approach developed; presents the WBS, top-level requirements, performance data, synthesized generic systems, life-cycle costs, and FOMs; and presents the results of the initial evaluation of generic wave energy systems.

4.1.3.3 Status

The systems study consists of the tasks shown in Fig. 4-8. Presently, Tasks 1 and 2 have been completed and Tasks 3 and 4 are underway. At this stage, it is not possible to definitively identify the knowns and unknowns; however, preliminary results indicate that relatively little work has previously been done in evaluating total wave energy systems.

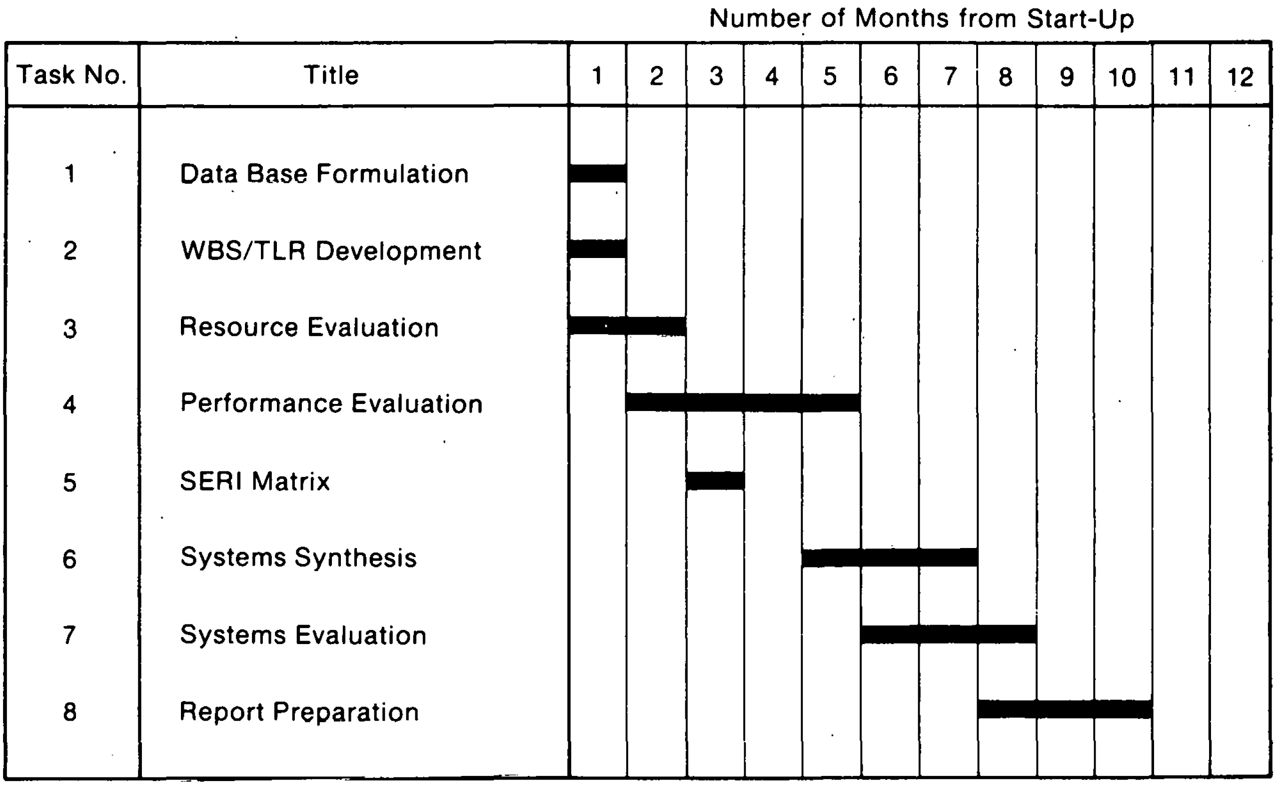

Figure 4-8. Wave Systems Study Schedule

4.1.3.4 Expected Results/Future Effort

This study will provide SERI with a standard method for evaluating wave energy systems and with an initial evaluation of generic systems. Since it is an iterative approach, more detailed assessments of the systems are anticipated as the data base increases and the need arises.

4.1.3.5 References

Gibbs & Cox, Inc. 1980 (Feb.). Wave Energy Systems Evaluation Study. Unsolicited proposal to the Solar Energy Research Institute, 4 February 1980.

Midboe, E. et al. 1980 (June). "A Systematic Evaluation of Wave Energy Systems." Proceedings of the Seventh Ocean Energy Conference. June 1980.

Rogalski, W. et al. 1979 (Dec.). The State of the Art in Alternate Ocean Energy Systems. Presented at the Chesapeake Section, SNAME, 12 December 1979.

4.1.4 Kaimei Data Analysis—Michael E. McCormick*

4.1.4.1 Objective

The wave energy study in the Sea of Japan tested several wave energy conversion turbines under real sea conditions. It is sponsored by the International Energy Agency (IEA) and managed by their Wave Energy Executive Committee. Their data are being used in the present SERI-sponsored study.

These data must be analyzed to show the interrelationships of the 81 parameters monitored during the test. The purpose of this study is to perform a preliminary analysis of the data. Once the interrelationships between the parameters are established, similar wave energy conversion tests can be better planned.

4.1.4.2 Approach

Three quantities were studied:

- the rms of approximately 40 sensors to establish their behavior over a three-day period,
- the spectral density of 28 sensors to determine their energy content as a function of frequency, and
- the cross-correlation of 28 sensor pairs to establish the interrelationship of the variables.

Results of these analyses showed strong cause-and-effect relationships between (a) waves and ship motions and (b) ship motions and internal pressures.

4.1.4.3 Status

The contracted study was finished and a final report written in August 1980. This report contains data showing strong interrelationships between ship motions and chamber pressures—particularly in the pitching motion effects. As expected, the turbine positions close to the bow and stern were optimum because of the large pitching motions of the Kaimei ship.

The test results do not show the optimum performance of the system because of the off-design of Kaimei in the waters near Yuru. This off-design resulted in rather small heaving motions that we hoped would be the primary driving motion for the turbines. As a result, the Kaimei is now being lengthened for its next sea trials.

4.1.4.4 Future Effort

The analytical quantities suggested in the approach are only three of many possible quantities; however, the Wave Energy Executive Committee will decide the final method of analysis.

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*U.S. Naval Academy.

4.1.4.5 References

AERE Harwell. 1980 (Jan.). "IEA Wave Energy Project." Annual Report of the Executive Committee. Oxfordshire, England.

McCormick, Michael E. 1980 (Aug.). Sea of Japan Wave Energy Conversion Data Analysis. EW-12-80, Annapolis, MD: U.S. Naval Academy.

4.1.5 Turbine Development and Testing—John Miles*

4.1.5.1 Objective

The United States is cooperating with Canada, Ireland, Japan, and the United Kingdom in a full-scale study of wave conversion devices under the auspices of IEA. The major joint activity resulting from this consortium was the approximately 6-month open-sea trial of eight pneumatic wave energy conversion devices in the Sea of Japan that started in August 1979. The operating agency that executed the trials was Japan's Marine Science and Technology Center.

4.1.5.2 Approach

All eight devices consisted of an air turbine and its connected generator mounted over a port atop a large air chamber resting on the ocean surface. The turbine and generator devices were tested on the Kaimei, a barge-like structure 80 m x 12 m with nine air chambers each approximately 50-m^2 in cross-sectional area. Seven of the turbines were Japanese and one came from the United Kingdom. The ninth chamber was intended for the U.S. turbine, but it was not ready at the time of the trial. All turbines had a design output of 125 kW_e when experiencing waves with an average period of 6 s or 7 s and a significant height of 3 m.

The characteristic air turbine/chamber arrangement can convert the large force and low velocity of the waves into a low force and high velocity movement of the turbine rotor. This advantage results from the approximately 250:1 area ratio between the chamber cross section and the air port. Furthermore, all the devices require some technique for yielding unidirectional rotation of the turbine when being driven by the oscillating, piston-like movement of the ocean surface within the air chamber. Three of the Japanese turbines used a two-valve flow rectification scheme, while the other four Japanese units plus the U.K. unit used a 4-valve rectification scheme. The U.S. air turbine has a novel design and accomplishes unidirectional rotation by a pair of counter-rotating rotors interacting rather than employing valves with their inherent flow losses.

The U.S. turbine was conceptualized by Dr. Michael McCormick of the U.S. Naval Academy. Professor Robert Latham, also of the U.S. Naval Academy, performed the preliminary design with support from Gibbs & Cox, Inc. Further refinements plus the coordination of the manufacturing were done by the Naval Ship R&D Center (NSRDC). NSRDC also started fabricating the turbine, and Custom Engineering of Denver is completing the fabrication and assembling the entire system, which is scheduled for completion in March 1981. Project management was transferred to SERI in FY 1980.

4.1.5.3 Status

Because of the unique features of the U.S. turbine, and the need to provide performance data comparable to that obtained for the other turbines on the Kaimei trial, a detailed test and evaluation program is necessary. SERI is presently developing a test plan for the turbine.

*SERI, Ocean Systems Program Branch

4.1.5.4 Expected Results/Future Effort

This plan includes the instrumentation required to gather the necessary data to thoroughly analyze the turbine's performance plus a statement of the desirable test conditions. SERI intends to test the turbine under steady-state conditions and then to analytically model its dynamic behavior when operating under more realistic oscillating conditions. This modeling will include the hydrodynamic interaction of the ocean waves with the air chamber coupled with the dynamic response of the turbine/generator system.

4.1.6 Analytical Methods—Chiang C. Mei*

4.1.6.1 Objective

The long-range objective is to calculate a priori information on hydrodynamic performance of various wave power devices and to find the optimum efficiency and quantitative information on the factors affecting efficiency and safety. The predicted information may be incorporated into a larger systems study that includes economics.

The short-range objectives are to:

- determine the theoretical efficiency discounting friction losses,
- optimize criteria for the power take-off mechanism,
- evaluate wave forces on the device, and
- analyze the motion of the device.

For Hagen-Cockerell rafts, the above items have provided information on raft geometry (slenderness, draft, train-length-to-wavelength ratio) and incident waves (regular waves, normal and oblique incidence, random waves) for the single raft; and raft geometry (slenderness, train-length-to-wavelength ratio, spacing) for a parallel array of rafts.

For the Kaimei ship, the optimum impedance of the turbines will be studied using simple models. The aerodynamics in the air chambers will be studied along with the water wave theory.

Other designs being studied are point absorbers with air turbines and Mehlum's focusing lens.

4.1.6.2 Approach

All proposed research deals with the dynamics of floating bodies in small amplitude waves. The inviscid incompressible theory of potential flows will be adopted; the boundary conditions will be linearized; and new analytical tools (such as a parabolic approximation for head sea diffraction) will be developed when needed. Effective numerical tools, such as integral equations, also will be developed.

Two papers have been submitted to SERI describing parts of the contracted work on isolated Hagen-Cockerell rafts. Haren and Mei (1981) describe a new analytical tool suited for head sea diffraction that can be applied to a simplified model of Kaimei ship of small draft. The essential results for an isolated Hagen-Cockerell raft are summarized in Haren and Mei (1980). This paper will be presented at the 13th Naval Hydrodynamics Symposium in Tokyo and published in its proceedings. The symposium will include a session on wave power with speakers from Japan, the United Kingdom, and the United States. A third paper on an array of raft trains and a report summarizing all three papers is in preparation. The project should ideally be accompanied by experiments to confirm the deduced results. This was not proposed and is not done under the present

*Massachusetts Institute of Technology

contract because of man-power and facilities limitations. Since the papers include specific lists of recommendations based on quantitative analysis, the value of the projects lies in promoting better designs.

4.1.6.3 Status

The study on Hagen-Cockerell rafts—single and multiple arrays—is essentially finished (see Fig. 4-9) and has been included in the Ph.D. dissertation recently completed by Haren. It will soon be submitted to SERI as a final report, and a third paper on multiple rafts is being prepared. The study found that for a single raft train the length of a wave, no more than three rafts with two power take-off hinges is best. Variable power take-off impedances that adjust to varying incident seas is desirable to achieve maximum efficiency for a broad band of wavelengths. To achieve good overall efficiency, the down-wave hinge may need to give out energy to maximize the absorption of the up-wave hinge and, therefore, of the total. The power take-off should have sufficient effective inertia or negative spring (the latter suggests electronic controls). For waves longer than the train length, less than optimum efficiency should be expected since the raft motion is too large for a slender raft and the optimal control is difficult. Graphs of raft efficiency are shown in Figs. 4-10, 4-11, and 4-12.

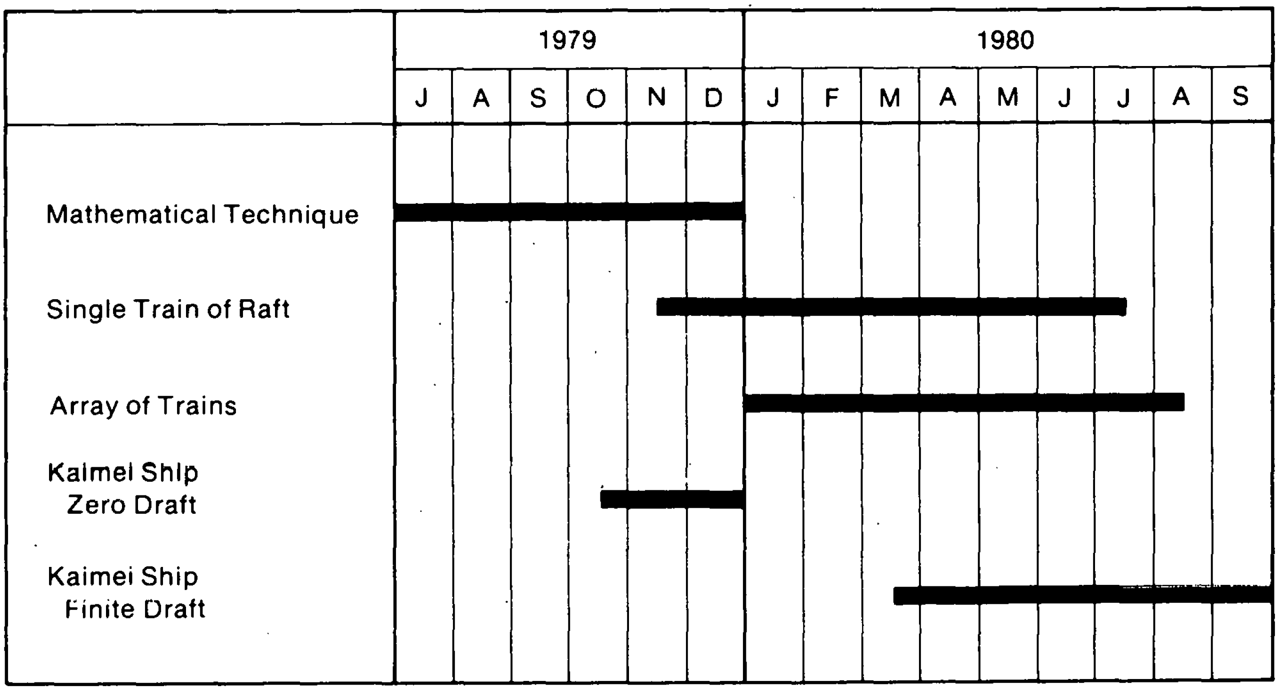

Figure 4-9. Analytical Methods Milestone Chart for Hagen-Cockerell Rafts

The study concluded that for an array of similar rafts the optimum spacing between adjacent rafts should equal the total length of a raft train, and the gain in total efficiency over a single raft is about 20%.

The power take-off mechanism has not been developed so far. In our theory, it is always modeled schematically by a linear inertia-damper or spring-damper system; therefore,

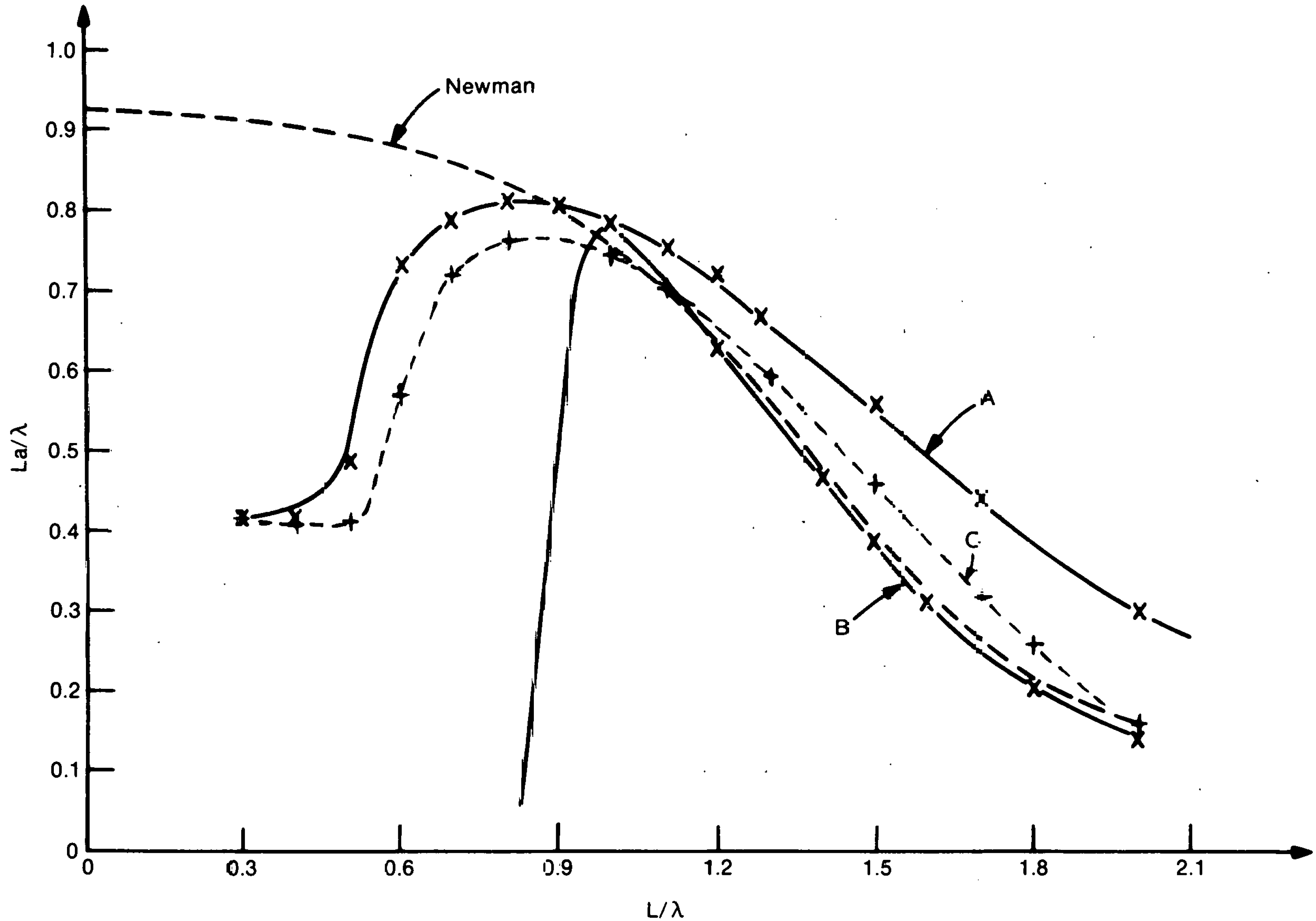

Figure 4-10. Effects of Changing Wavelengths on Raft Efficiency

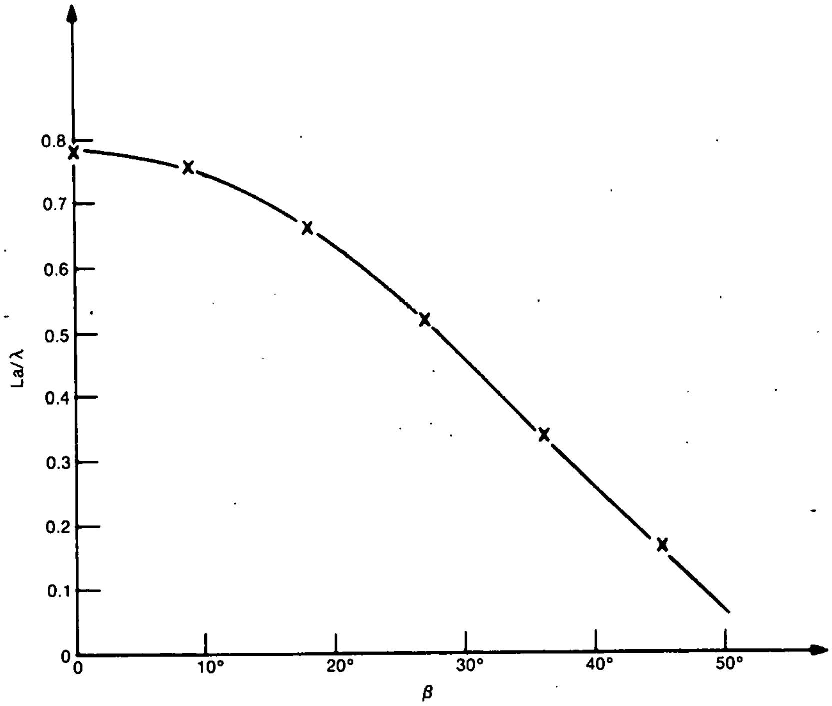

Figure 4-11. Variation of Raft Efficiency with Angle of Incidence of the Incoming Waves

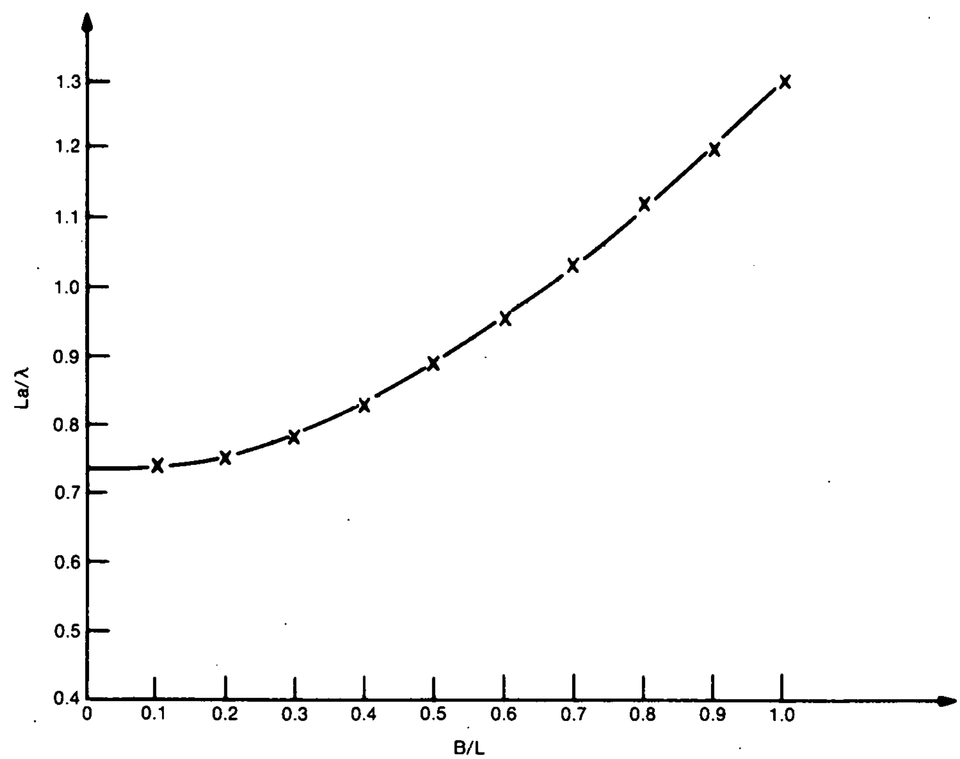

Figure 4-12. Variation of Raft Efficiency with Width Ratio

the inertia or spring constant and damping coefficient, in fact, are unknown. For any future design, these coefficients should be found empirically. The following items need to be designed:

- power take-off devices that give these equivalent impedances, and
- control mechanisms so that impedances may be varied to suit the incident waves.

4.1.6.4 Expected Results/Future Efforts

The results for research in the last years are already described. It is hoped that these results will have an impact on the perception of wave power. We believe, as do most theoretical workers in the field, that the current pessimism is based on the criterion that the future of wave power be judged by the available off-the-shelf technology. However, our studies show that new technology on power take-off design with variable impedances is necessary. Unfortunately, in many proposed or existing prototype designs too much stress is put on existing technology that does not recognize the potential of wave power.

The hydrodynamic analysis of other devices such as the Kaimei ship and point absorbers coupled with air turbine chambers will be continued. In the latter case, the likely nonlinear effect of air in the chamber will be studied along with the surface waves. The turbine will be represented by a simple model, and Mehlum's idea of using a lens for wave focusing possibly with a point absorber at the focus will be studied.

4.1.6.5 References

Haren, Pierre; Mei, Chiang C. 1981 (Mar.). "Head Sea Diffraction by a Slender Raft with Application to Wave Power Absorption." Journal of Fluid Mechanics. Vol. 104: pp. 503-524.

Haren, Pierre; Mei, Chiang C. 1980 (Oct.). "Rafts for Absorbing Wave Energy." Presented at the 13th Naval Hydrodynamics Symposium, 6-10 October 1980. Tokyo office of Naval Research, Editor: Ralph B. Cooper.

4.1.7 Wave Power Absorption Studies—J. H. Duncan and C. E. Brown*

4.1.7.1 Objective

The objective of this project is to develop and use a numerical model that can hydrodynamically evaluate wave energy systems with arrays using discrete oscillatory absorbers. This evaluation includes the response or power output of the system. Given the variability in wave climate, economically-attractive systems must work efficiently for a range of incoming frequencies and directions. The present hydrodynamic analysis is the first step in any economic evaluation. The present computer program, with minor modifications, could be used to analyze wave focusing systems with discrete oscillatory or stationary elements.

A short-range objective was to develop and validate the model, which has been completed.

4.1.7.2 Approach

A working computer program was delivered to SERI in June 1980 that calculates the power available from an array of similar, arbitrarily shaped and spaced buoys that can oscillate with six degrees of freedom when forced by an incoming wave. The calculation also includes the effect of interactions between buoys (see Fig. 4-13).

4.1.7.3 Status

The computer program is now operational and has been used in one calculation to validate its accuracy when compared with analytical calculation, since the results indicate that the program is working accurately. SERI needs to determine a wave energy array system to be analyzed.

4.1.7.4 Expected Results/Future Effort

If the computer program is used to evaluate a particular wave energy system, it will yield the power hydrodynamically available as a function of incoming wave frequency and direction. This information combined with wave climate data can be used to evaluate or optimize a system for a particular area. For example, it may be that there is a trade-off between the number of absorbers per unit wave front and the range of wave periods for which the system has adequate power absorption. However, the advantage gained in a particular area by the larger number of buoys will have to be compared with the additional cost of more buoys.

4.1.7.5 References

Duncan, J. H.; Brown, C. E. 1980 (Mar.). Development of a Numerical Method for the Calculation of Power Absorption by Arrays of Similar Arbitrarily Shaped Bodies in a Seaway. Technical Report 8005-2. Laurel, MD: Hydronautics, Inc.

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*Hydronautics, Inc.

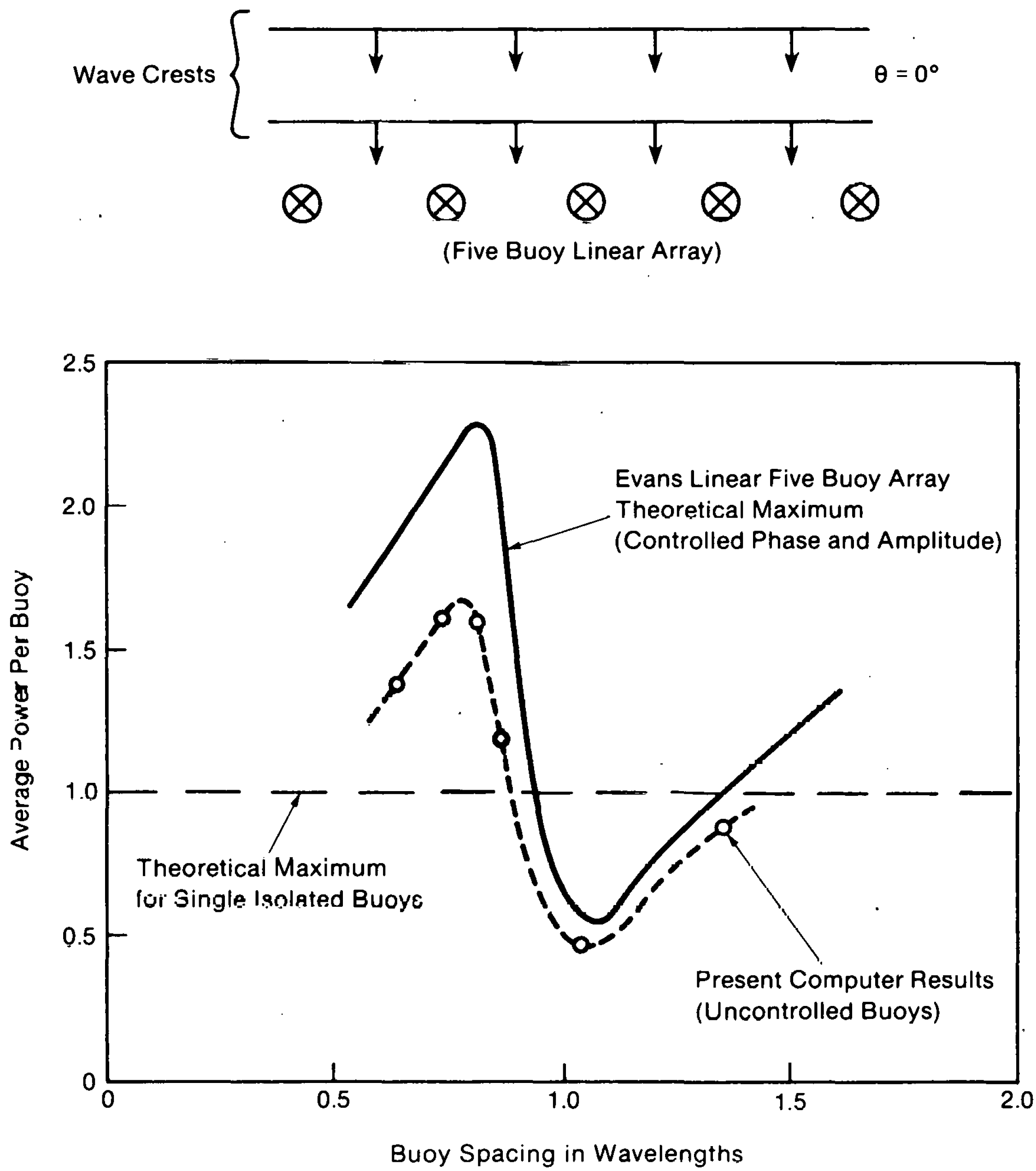

Figure 4-13. Comparison of Computer Results with Analytical Calculations

4.1.8 International Liaison—Ben Shelpuk*

4.1.8.1 Objective

An important element of the Wave Research Program is the International Liaison Task. Its objective is to assure that the U.S. effort is complementary to the broader world-wide research program.

4.1.8.2 Approach

During the past year, international activity has included:

- formal involvement in a multilateral program in wave energy under the auspices of IEA;
- participation in international professional meetings; and
- informal technical interactions.

4.1.8.3 Status

Other IEA activity in this report was covered in Secs. 4.1 and 4.1.5. This cooperative agreement will expire during FY 1981 and will be documented with a final technical report. The program involved two separate deployments of an ocean going test bed (the Kaimei ship) and cooperation with research teams in England, Ireland, Japan, and Canada.

There were two international professional meetings during FY 1980. The first was at the Symposium on Wave Energy Utilization in Gothenburg, Sweden, held 30 October - 1 November 1979. Eric Midboe of Gibbs & Cox, Inc., was the U.S. representative. The results are published in a proceedings of the meeting.

Clive Grove-Palmer presented a report on the U.K. wave energy program at the Seventh Ocean Energy Conference in Washington, D.C., held 2-5 June 1980. Two upcoming meetings may provide further opportunity for interaction. They are:

- the Eighth Ocean Energy Conference, Washington, D.C., June 1981; and
- the Second International Symposium on Wave and Tidal Energy, Cambridge, England, September 1981.

To maintain an informal interchange with the U.K. wave energy program, SERI has visited several U.K. research organizations and followed this with correspondence. SERI has also had contact with the Norwegian wave community.

Based on the information obtained during the year, at least five countries plus the Eurocean consortium of companies has organized activity in wave energy conversion. Listed in order of level of activity are the countries involved: Japan, United Kingdom, United States, Norway, and Sweden. The Eurocean consortium has the least activity.

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Of course, IEA has five participants in the Kaimei Program: England, Ireland, Japan, Canada, and the United States.

4.1.8.4 Expected Results/Future Efforts

United Kingdom The U.K. Program is managed by Clive Grove-Palmer and primarily is funded by the U.K. Department of Energy. The first phase concentrated on developing the Salter Duck, the Hagen-Cockerell raft, the oscillating water column, and the rectifier.

These devices were studied experimentally and theoretically, and cost estimates eventually were generated from the reference designs of a 2000-MW station by some U.K. consultants. Cost studies range upward from 400 £/kW ($832/kW) and electric energy costs are reported at 30-50 p/kWh (600-1000 Mils/kWh).

The U.K. program for 1979-80 is directed at reducing first generation system concept cost; substantiating the potential for second generation machines; and reassessing the resource and various machine capture efficiencies.

The second generation concepts being explored include:

- flexible bag approach,
- seabed oscillating water column,
- submerged oscillating cylinder,
- triplate converter, and
- wells air turbine.

Theoretical studies on wave focusing are going on as well as a significant amount of work on electric generating and power transmission equipment.

The initial pessimism generated by the cost studies in Phase 1 has given way to optimism arising out of cost reduction ideas for Phase 1 concepts and the promise of lower costs for Phase 2 ideas.

Japan Commander Masuda, Japan, has taken turbines used in low-power buoy applications and integrated them into a multiple turbine arrangement (the Kaimei). His first deployment showed significantly less output than expected. This partly was because of quiet seas during the tests. Applying a subsequent theory appears to permit an increase in power output, and Masuda is expecting large improvements in the turbomachinery being supplied for his second deployment. Air turbines solve one of the most difficult wave energy problems, coupling the low-frequency high-force source into a practical electric generator. The Kaimei concept also uses a different hydrodynamic approach than previous machines; specifically, the device heads into the wave crest to reduce mooring loads. Energy is extracted in a serial array of devices that appears to provide diminishing input to each device. In reality, there is two-dimensional focusing as the depleted crest is filled from lateral portions of the same crest.

This is an approach being pursued by the British in the flexible bag and Hagen-Cockerell raft innovations and would be a valid generalized approach for more cost-effective systems.

Norway The work in Norway appears to be centered in the Institute for Experimentation, University at Trodheim, and the Central Institute for Industrial Research. The Trodheim work is headed by Budal and Falnes and involves heaving point absorbers in resonance. The Norwegian researchers have set up a complementary program of theory (based on radiation theory) and experiment looking at point absorbers and interacting fields of point absorbers. The program appears to be a well-structured effort to understand and demonstrate the concept.

The work at the Central Institute is very similar to the refractive focusing work being done in the United States: developing the theory and demonstrating the concept of diffractive focusing of ocean swells. Their report does not make clear their progress or future plans. Any U.S. assessment on wave focusing technology should encompass contacting their principal investigator, E. Mehlum.

Sweden The Swedish Program is funded by the National Swedish Board for energy source development. It is primarily a university-based effort largely directed toward resource assessment. In addition, they are looking at the practical problems associated with the heaving body concept, specifically:

- performance in an irregular sea,
- a linear generator conversion system,
- mooring, and
- power takeoff.

The Swedes have quoted energy costs at 64 Mils/kWh for their buoy system operating in the Baltic Sea.

The perspective of the International Program in wave energy provides an effective framework within which the U.S. program could be structured. The U.S. Program cannot be effective if it is spread over the full spectrum of possible wave energy machines. Those areas where the prospects seem brightest or where obvious gaps exist should be indentified for funding. Then, if effective communications with the other programs can be established, then our cost effectiveness can be maximized. This remains the function and philosophy of the liaison effort.

4.1.8.5 References

Proceedings of the Symposium on Ocean Wave Energy Utilization, Gothenburg, Sweden, 30 October - 1 November 1979.

Proceedings of Wave Energy Conference, Heathrow Hotel, London 22-23 November 1978 ISNB-0-70-580751-7.

4.1.9 Unsolicited Proposals—John Miles*

The Ocean Systems Program Branch at SERI has approximately 75 unsolicited proposals on wave devices. All these proposals have been waiting to be evaluated until a plan was developed that would provide an equal opportunity for all inventors to compete for contract award. This office feels it should optimize the development of new and worthwhile wave device ideas and concepts that might not otherwise come to the attention of the appropriate offices, and provide a way to fairly and systematically respond to the many unsolicited proposals that are received.

Presently, we are implementing a plan whose features are contained in a statement of intent recently submitted to the Commerce Business Daily:

> **GENERAL SOLICITATION FOR INNOVATIVE WAVE DEVICE CONCEPTS**
>
> The Ocean Systems Program Office of the Solar Energy Research Institute is preparing a bidders list for a general wave energy device solication. The solicitation will make one or two awards in two categories. The first category would provide low-level funding allowing award recipients the opportunity to more fully develop their concepts. The deliverable item to SERI in return for the support would be a complete definition of the device technically and graphically. The second level of award would be greater than the former and its intent would be to allow for more detailed development such as in terms of life-cycle costing, system engineering analysis, numerical analysis, or limited experimental testing. In both cases SERI would reserve the right to withhold any award funds should the technical proposal review committee indicate that there were no innovative concepts received by the solicitation activities. Estimated date of solicitation mailing is early January. Receipt of a letter of interest requesting placement on a "subcontractors' bidding list" must be received prior to 23 December 1980. As soon as authorization from DOE headquarters is received solicitations will bo issued. Letters of interest should be sent to:
>
> Subcontracts Branch
> Solar Energy Research Institute
> 1617 Cole Blvd.
> Golden, CO 80401
> Attn: Kevin F. Wright 18/2

The responses to this Request for Proposal (RFP) will be reviewed by an outside organization with expertise in this area. Final decision on any awards will be made by program office personnel subject to available funds. Future unsolicited proposals will be handled in a similar manner on an annual or semiannual basis. Scheduling and other details will be refined as experience dictates.

*SERI, Ocean Systems Program Branch

4.2 OCEAN CURRENT OVERVIEW—Peter Davidoff*

Although the Ocean Current Program is considerably smaller than the Wave Energy Program, the goals are the same as the overall program goals. The immediate objectives include:

- determining the ocean current resources;
- investigating ocean current devices;
- investigating marine engineering considerations; and
- determining institutional and market barriers and system economics.

The program supports promising device development. To this end the Coriolis project is assessing a system economics based on revised resource estimates and device design. A linear ocean current turbine (drogue chute) is being tested and the data will help assess the practicality of large-scale versions.

Japanese and independent U.S. researchers have begun investigating ocean currents as possible magnetohydrodynamic energy systems. It is anticipated that the U.S. program will assess this type of device.

Progress in FY 1980

The structure of the ocean current program (shown in Fig. 4-14) is similar to the structure of the wave program. Currently, the program is continuing DOE-originated initiatives, specifically:

- Power System Studies: No work has been initiated in this area as the technical data base is still under development.
- Axial Flow Turbine: The Coriolis studies continue. Work on hydrodynamic instabilities and studies on blade dynamics have been completed. Under SERI contract, preliminary rimdrive and duct designs will be studied. A rigorous systems engineering study will provide a legitimate estimate of cost and performance.

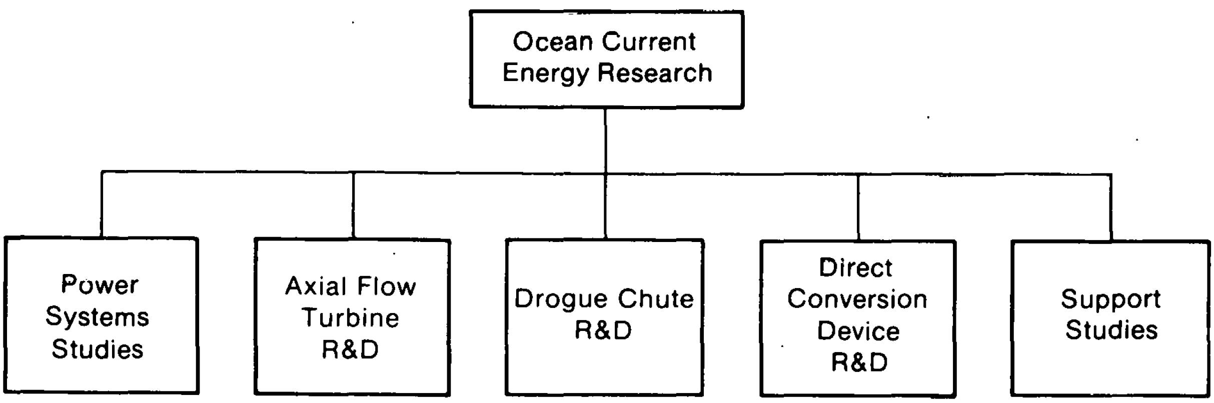

Figure 4-14. Five Year Plan—Ocean Current Program

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*SERI, Ocean Systems Program Branch

- Drogue Chute: Under DOE funding, WLVEC built a drogue chute linear ocean current device. SERI has provided the funds to perform inland simulation and testing of the device. A final report is due in early FY 1981.
- Direct Conversion: No work was done in this area.

Plans for FY 1981

The program plans for the Ocean Current Program include:

- Continued support of the Coriolis work started in FY 1980. A critical decision point will be reached at the very end of FY 1981 or early FY 1982 regarding the progress of Coriolis into the hardware development phase of the research.
- An initiative to solicit new ocean current devices and/or other ocean technologies.
- Some in-house research and possibly some funding that will be directed toward a preliminary study of an ocean current MHD program.

Five-Year Plan

The five-year plan (shown in Fig. 4-15) for the current energy program is similar to the wave energy program. New technologies will be assessed and research will be continued for new and innovative ocean current devices. Devices will be developed in two phases: (1) models and feasibility studies and (2) prototype design and deployment. Resources will be assessed and general research will continue that includes a system study, experimental programs, data base development, and market and institutional studies.

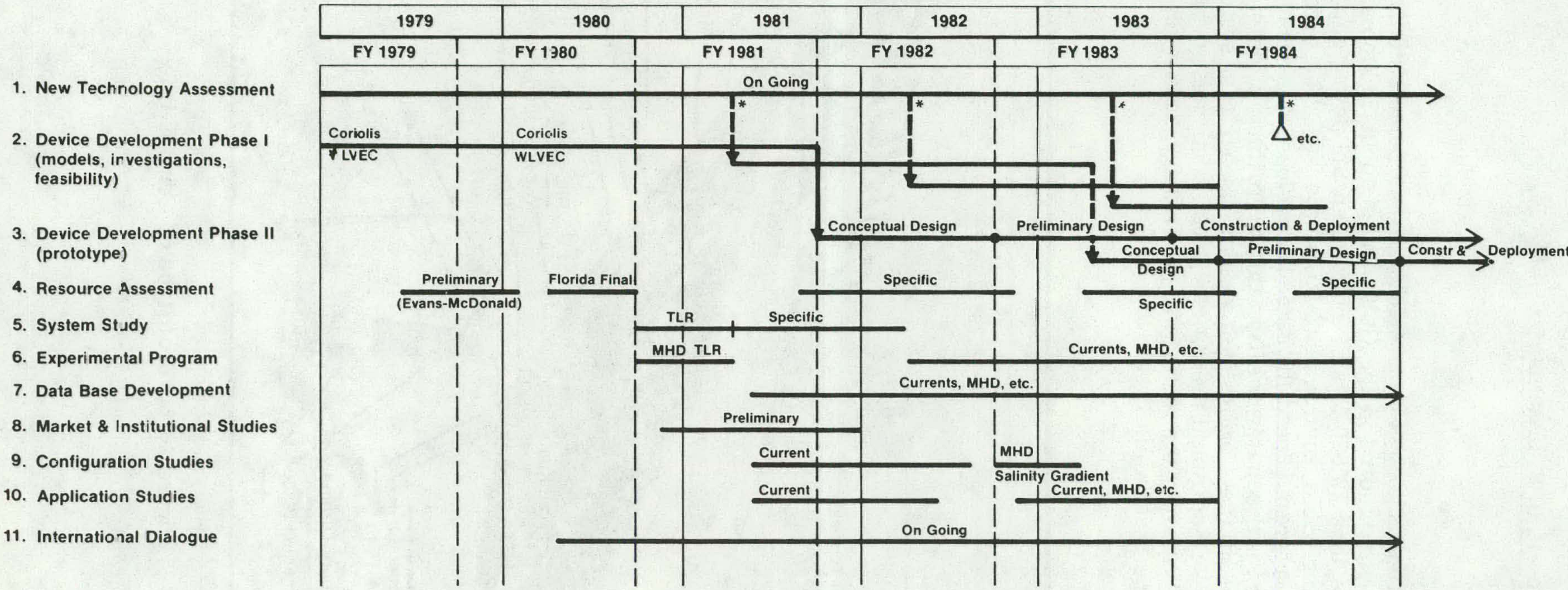

Figure 4-15. Ocean Current Program Organizational Structure

4.2.1 Coriolis Program—P. B. S. Lissaman*

4.2.1.1 Objective

The long-range objective is to generate electricity at commercially viable costs using large-ducted turbine units moored in the Gulf Stream about 30 km east of Miami, Fla. It is estimated that more than 10,000 MW of average annual power can be generated by an array of units with negligible environmental disturbance. The purpose of the current phase of the Coriolis Program (Phase III) is to (1) develop the hydrodynamic design of the high augmentation duct and counter-rotating turbine rotors; (2) define the rim-drive system, a unique feature of the Coriolis unit design; (3) perform system engineering and economic studies that will optimize the overall Coriolis unit design for minimum cost per kilowatt-hour; and (4) specify the scale and preliminary design for a test module. A picture of the prototype is shown in Fig. 4-16.

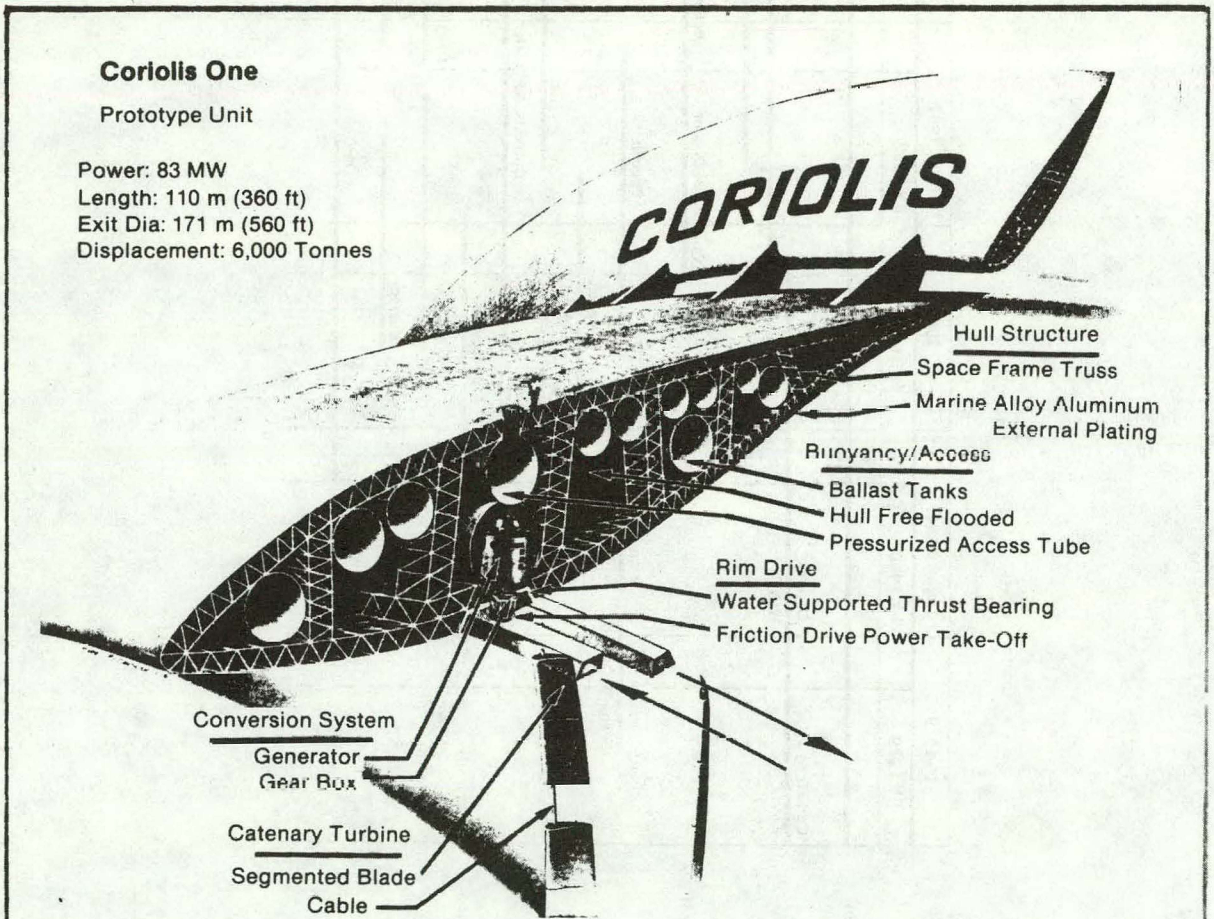

Figure 4-16. Prototype of Coriolis One

*AeroVironment, Inc.

4.2.1.1 Approach

Phase III has the following deliverables for the first three tasks: The duct hydrodynamic design task is involved in developing a nonlinear computer model to design and analyze duct shapes, designing a high performance duct, and designing a two-stage counterrotating turbine.

Task 2 is involved in specifying the rim drive design and analyzing the dynamics of the rim drive.

The system engineering and economic study will determine production unit costs by system component; perform a failure analysis and identify major potential hazards; and determine optimum mooring design for different possible sites. It also will determine most cost-effective size of full-scale unit and a next-phase test module and determine life-cycle costs for both single units and arrays of units including a study of potential markets.

Phase III can be evaluated in terms of the completion and applicability of each of the deliverable items. All program subtasks require considerable judgment as to the depth of analysis; however, the goal of each subtask is to provide information that is directly applicable to developing hardware. Thus, each item should be evaluated in terms of its contribution to the system design and optimization for cost-effectiveness.

4.2.1.3 Status

Phase III was initiated 1 August 1980, and no major subtasks have been completed at this time. Phase I of the program was an initial design and costing study privately funded by HydroEnergy Associates of Pennsauken, New Jersey. Phase II was a study of key technical features of the system that included: (1) hydrodynamic and hydroelastic analysis of the duct and rotors, (2) a water channel hydroelastic test of a 1-m dynamic power-producing model rotor, and (3) an analysis of the system mooring configuration and dynamics. The Phase II study showed no adverse dynamic behavior and projected reasonable system costs. At this point, the following are definitely known:

- duct augmentation power ratios of 3:4 are achievable (substantiated by Phase II analysis and supported by Grumman test data);
- the catenary turbine blades have a desirable dynamic behavior (substantiated by Phase II test and analysis); and
- the mooring system can be designed to be dynamically stable (substantiated by Phase II analysis).

These are definitely not known:

- actual current resource (Gulf Stream current speed);
- optimal system design;
- actual cost of the complete system;
- maintenance requirements; and
- unit lifetime.

The following constitutes the minimum knowledge required to make the next major program decision:

- As optimized for the best estimate of the Gulf Stream resource, does the system appear economically viable?
- What is the proper size and preliminary design for an engineering test module unit? and
- Where and how should the test module be evaluated?

4.2.1.4 Expected Results/Future Effort

Phase III should answer the questions required for initiating hardware development. In Task 1, the most cost-effective design will be developed for the duct. A high augmentation duct of minimum axial length should be the best design. The result will be the specification of the hydrodynamic shape of the duct and turbine blades along with an estimate of their expected performance.

In Task 2, the rim drive will be specified to a design level that will substantiate the basic concept and provide an estimate of transmission efficiency. This definition will be adequate for the preliminary design of the engineering test module.

In Task 3, the overall system will be optimized for cost-effectiveness and the following system features will be determined:

- size of the full-scale unit,
- shape and augmentation ratio of the duct,
- turbine rotor design,
- system component cost targets,
- size and preliminary design of the test module, and
- a plan for construction and evaluation of the test module.

If the results indicate that the system is viable and cost-effective by appropriate DOE standards of performance, then the work performed will provide an adequate basis for designing hardware for test module construction.

4.2.1.5 References

Lissaman, P. B. S.; Radkey, R. L. 1980 (Mar.). Coriolis Program: Analysis of the Potential of Ducted Turbine Energy Systems. Presented at the Oceanology International '80 Conference, Technical Session N; Brighton, England, March 1980. AV-TP-80/513. Pasadena, CA: AeroVironment, Inc.

Lissaman, P. B. S.; Radkey, R. L.; Mouton, W. J.; Thompson, D. F. 1980. Evaluation of Hydroelastic and Dynamic Behavior of Key Components of the Ocean Turbine System. DOE/ET/20518-1. Pasadena, CA: AeroVironment, Inc.

Radkey, R. L. 1980. Coriolis Program: The Prospect of Renewable Cost-Effective Energy from Ocean and River Currents. Presented at the Seventh Ocean Energy Conference, Washington, DC, 2-5 June 1980, TP-A-80/522R. Pasadena, CA: AeroVironment Inc.

4.2.2 Drogue Chute—Gary Steelman*

4.2.2.1 Objective

The long-range objective of the WLVEC project is the commercialization of the world's ocean current energy resource. The short-range objective of the ongoing WLVEC Phase II—Device Testing and Data Acquisition Project is to gather performance data from the 1980 model WLVEC ocean turbine and static force data of open and collapsed drogues as used with the WLVEC ocean turbine.

The Phase II test results can be used as part of a data base by which the economic potential of a drogue chute energy conversion system can be evaluated.

4.2.2.2 Approach

The short-range objective has been met by operating a prototype in a simulated ocean current. Open and closed drogues were towed at specific velocities and drag forces were measured. The power output of a WLVEC system of drogues was also measured using a dynamometer on the output shaft. Texting has been completed. The results are being analyzed and will be documented in a final report.

4.2.2.3 Status

The WLVEC Project has progressed from concept (1973) to first, second, and third generation hardware. In 1976, the 1975 model WLVEC successfully produced electricity in the Atlantic Ocean. This experiment demonstrated the mechanical feasibility of the device. In August-September-October 1980 (as per the Phase II tests), the 1980 model successfully developed measured net power that was absorbed into a dynamometer. These 1980 tests will provide experimental quantitative data that will augment and collaborate the 1976 experiments. This is important because for the first time actual operational power output data will be available, which will be valuable for device assessment and future engineering design criteria.

At the time of this writing, it is definitely known and demonstrated that:

- The WLVEC ocean turbine is a very simple machine.
- The 5-ft diameter chute WLVEC ocean turbine will produce net power when operated in ocean current velocities of 0.5–4 knots.
- At experimental sizes, the parachutes and ropes can be constructed that are strong enough to withstand the stresses and environment of ocean currents.
- Parachute systems can potentially produce power from any ocean current stream cost-effectively.

The optimum design or size for commercial plants is not known but may be determined with a comprehensive engineering study.

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*WLVEC Technology Company

The minimum knowledge necessary to make the next major decision as to future development of the WLVEC ocean turbine is the performance, cost and operational data necessary to quantify its potential cost-effectiveness. That knowledge will include force data, power output data, device durability and reliability, cost estimates, and marine structures requirements. Analysis of these data will define the potential of the concept and identify major hardware development issues. When this assessment is complete, it will be possible to identify the nature and pace of any prototype hardware development effort.

Phase II testing will provide quantitative experimental data that will define how much net power can be extracted from a flowing stream with drogue devices at various velocities. It will also indicate how effectively it can be converted to usable mechanical power via the WLVEC System. The acquired data will provide the basis for making a performance prediction of a drogue system. This, combined with cost, operational, and resource data will permit an assessment of this ocean energy system concept.

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4.3 SALINITY GRADIENT OVERVIEW—V. J. Ciccone*

Salinity gradients occur naturally where fresh water rivers meet either the oceans or salty bodies of water such as the Great Salt Lake or the Dead Sea. Two methods of converting the free energy of high and low saline waters into work have been investigated. The first uses the principles of direct osmosis, and the second employs reverse electrodialysis to develop the dialytic battery. Both systems use a membrane technology similar to that developed for reverse osmosis and electrodialysis in water desalination processes.

The osmotic power system uses a semipermeable membrane that permits low saline water to permeate the membrane thus diluting a high saline water and creating hydraulic pressure. If the concentrated solution is seawater (3.5% salt), the osmotic pressure is approximately 2413 kPa (350 psi). If the concentrated solution is a saturated sodium chloride brine (26% salt), the osmotic pressure is approximately 38612 kPa (5600 psi). If the salt side of the membrane is gradually pressurized, the permeate flow will decrease until no flow occurs when the applied pressure equals the osmotic pressure of the salt solution. If on the salt side a flow of salt slurry plus recycled salt solution maintain a hydraulic pressure at approximately half the osmotic pressure, pressure retarded osmosis occurs. The resulting permeation of solvent with recycled salt solution provides the energy to drive a hydroturbine. Ideally, the power output increases with the square of the osmotic pressure difference and linearly with membrane area and the water permeation coefficient. With fresh water and seawater, power outputs of 3.2 W/m^2 are predicted, and with fresh water and brine solution, power densities in excess of 25 W/m^2 are expected.

Dialytic power, or reverse electrodialysis (RED), is accomplished by alternately placing anion-permeable and cation-permeable membranes in a battery configuration. Salt water is then passed through parallel compartments containing alternate membrane pairs, and fresh water is passed through adjacent compartments. The salt, which is ionized in solution, loses sodium ions to the cation-permeable membrane and chloride ions to the anion-permeable membrane. The positive and negative charges on the respective membranes are then transferred to electrodes located at the ends of the membrane stack. Thus, the system acts as a battery.

In the dialytic battery, the driving force depends on the ratio of the concentration of the dilute and concentrated solutions. Since the ratio of fresh water and seawater is relatively low, considerable membrane area and abundant water resources are required. It is estimated that with thinner membranes and thinner cell dimensions, a power density of 1.7 W/m^2 could be attained. With brine solutions (26% salt) and fresh water, power densities of at least 10 W/m^2 are expected.

Both systems require abundant supplies of fresh and saline waters within close proximity of each other. Ideal locations for open-cycle systems are river estuaries, but, unfortunately, these waters are usually turbid and require costly pretreatment to protect the membranes. A semiclosed-cycle system at inland locations and sites where concentrated brine solutions from salt domes or evaporation ponds can be obtained is potentially useful. These systems have the advantage of greater power production per unit membrane area, provided an abundant dilute solution resource is available. However, the environmental problems of brine disposal and land requirements may be restraining. A closed-cycle system using a stratified saturated solar pond for both concentrated and dilute

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water resources significantly reduces the environmental and pretreatment problems identified in the open or semiclosed systems. Presently, to be cost-effective the closed-cycle system requires an inexpensive salt whose solubility and density change with the temperature and stratefy in a solar pond.

The preliminary design of a 50- kW_e osmotic plant with a closed-cycle saturated stratified solar pond revealed that it was not cost competitive with other ocean thermal energy systems. Estimated capital costs for a 1-MW plant were $3,075/kW when the solar pond was unlined and the initial salt charge was considered an operating cost. When the pond lining and cost of salt were included, the capital costs were $22,300/kW.

Most present-day technical and economical assessments of osmotic and dialytic power as a system for generating electrical energy have been based on the costs and performances of reverse osmosis or electrodialysis membranes used for desalination of water. This is because these desalination membranes are currently commercially available. In osmotic power applications, the quantity of water that permeates through the semipermeable membrane determines the amount of electrical energy produced. A hydrostatic pressure in excess of 13,790 kPa (2000 psi) can be achieved with a saturated salt solution on the concentrated side of the membrane and a fresh water solution on the dilute side of the membrane. Osmotic power membranes should have a combination of high salt rejection in the skin layer and high salt diffusion in the porous support layer to avoid internal concentration polarization. Internal concentration polarization, compaction at high pressures, and operation with saturated salt solutions tend to reduce the water permeation rates and operating life of current membranes. These factors significantly increase capital costs and operating and maintenance costs for osmotic power systems.

Dialytic battery power production depends on the voltage generated across each RED cell consisting of a cation membrane, a spacer, and an anion membrane. Technical and economic assessments currently have been based on membranes and spacers used for desalination. The internal electrical resistance of currently available desalination membranes will range from 1.2-12 ohm/cm^2 in sodium chloride solutions and up to 60 ohm/cm^2 in borax solutions. For dialytic battery membranes, an electrical resistance of 0.5 ohm/cm^2 or less is desired. Similarly, in desalination the minimum practical spacing of membranes is 0.05 cm. This spacing is needed to permit a high solution velocity that keeps the concentration polarization to a low level. In dialytic battery units, concentration polarization is of minor concern, and a low solution velocity is acceptable. Therefore, the desired membrane spacing may be as small as 0.01 cm. The thinner dilute solution compartments will decrease internal electrical resistance and increase net voltage output.

Present findings reveal that potential sites in the United States, environmental issues, and the membranes used in both systems limit the development of this energy source. Operating conditions affect the membrane performance and shorten its functional life, making current economic assessments appear unfavorable compared with other energy-producing technologies. Membrane research should be pursued to establish membrane performance characteristics and to reduce costs specifically required of the osmotic and dialytic processes as an electrical energy-producing technology.

4.3.1 Osmotic-Type Converter—S. J. Senatore*, S. I. Glasman*, and G. D. Mehta**

4.3.1.1 Objective

This project is to develop preliminary engineering studies for semiclosed- and closed-cycle osmotic-type salinity gradient energy conversion systems. Both systems are technically feasible with additional membrane development. All other components are available. The closed-cycle system is more technically favored because it requires less than one-tenth the pond area of the semiclosed-cycle system, is environmentally more desirable, and has the potential for many more sites. Schematics of both systems are shown in Figs. 4-17 and 4-18.

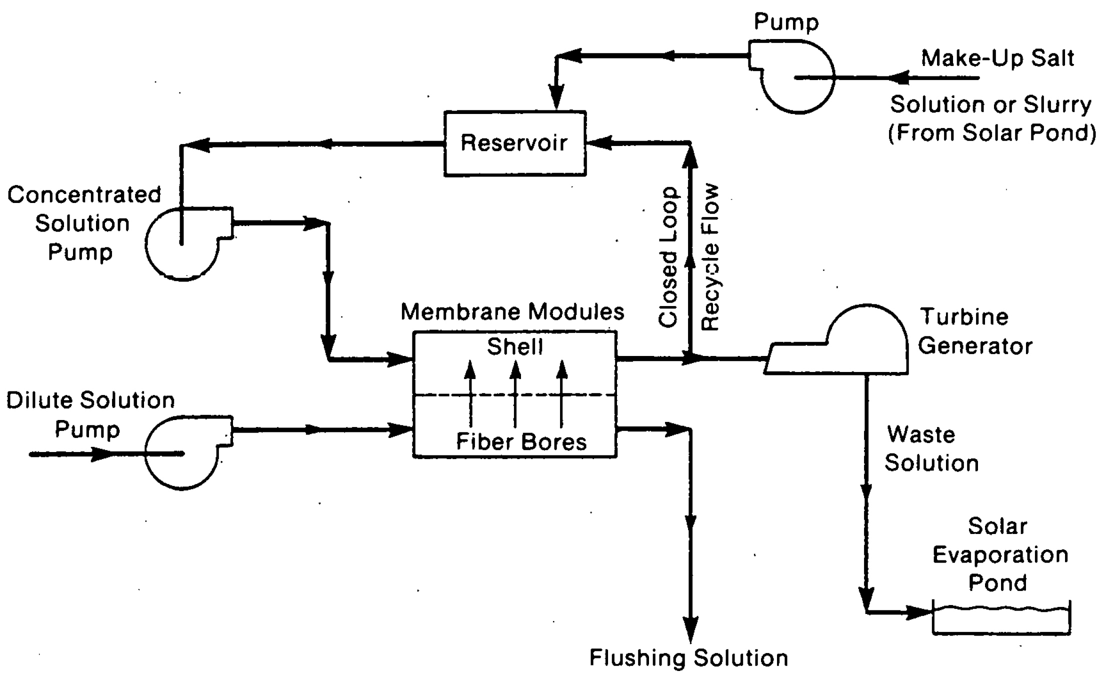

Figure 4-17. Schematic of an Osmo-Hydro Power System, Semiclosed Cycle

The objective is to examine the technical and economic feasibility of using osmotic power to generate electricity from aqueous salt solutions and to prepare a preliminary design of a 50-kW osmotic power system and extrapolate it to a 1-MW power system. In Phase I (semiclosed), seawater was used as the dilute brine, saturated salt solution as the concentrated brine, and a solar evaporation pond for salt recycling. Performance and

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**InterTechnology/Solar Corporation

cost estimates for this design using brackish water instead of seawater were also made. In Phase II (closed), the conventional solar evaporation pond was replaced with a stratified pond. Instead of using sodium chloride and seawater, the salt solution was potassium aluminum sulphate, one of the candidate salts. A schematic of a laboratory saturated pond is shown in Fig. 4-19.

4.3.1.2 Approach

The work is divided into several tasks. Phase I is concerned with acquiring, testing, and forecasting membranes. Pretreatment requirements of different flow streams based on the past experience of reverse osmosis plants need to be determined. The availability of major components, material requirements, performance, and cost must be determined. Environmental data must be gathered to determine the feasibility of siting such a system. The system needs to be optimized to obtain the lowest energy cost by varying the operation variables, system parameters, and fiber dimensions. The plant layout and flow diagrams for a 50-kW system using brackish water and seawater with saturated brine must be prepared and the capital costs of the proposed 50-kW system and a 1-MW system developed.

Phase II is also concerned with membranes. In addition, Phase II is concerned with identifying associated siting and environmental problems for the system; determining the pretreatment requirements for stratified pond closed-cycle osmotic power system; determining the availability and preparing performance specifications of the major components, material requirements, performance, and costs; optimizing the system to obtain the lowest energy cost by minimizing power cost produced as a function of dilute and concentrated solution flow rates; preparing the flow diagram and plant arrangement for the 50-kW stratified solar pond system; and developing the capital and operating and maintenance costs of the proposed 50-kW system and a 1-MW system.

4.3.1.3 Status

In Phase I the system design approach, including the computer model, was used to determine optimal system flow rates, membrane area requirements, turbine generator sizing, and solar pond area. Ebasco used the optimized system flow rates determined by the computer model to prepare the system flow diagrams, size all system components, determine siting restrictions, and estimate system capital costs.

The viable systems are the base case with 3.5% salt water (seawater), a saturated salt solution, and a solar evaporation pond. Also viable is the base case using brackish water instead of seawater. The systems that did not appear to be promising are the no-salt crystallization system, the once-through (no recycle) system, and the open-cycle river-seawater system.

The capital cost component of the total product cost for the 50-kW system using seawater is 39¢/kWh. Using brackish water instead of seawater would reduce the capital cost component to about 30¢/kWh. Based on commonly accepted scaling formulas, a 1-MW seawater pond system would yield a capital product cost component of 12¢/kWh, and a brackish water system would have a capital product cost component of about 9¢/kWh.

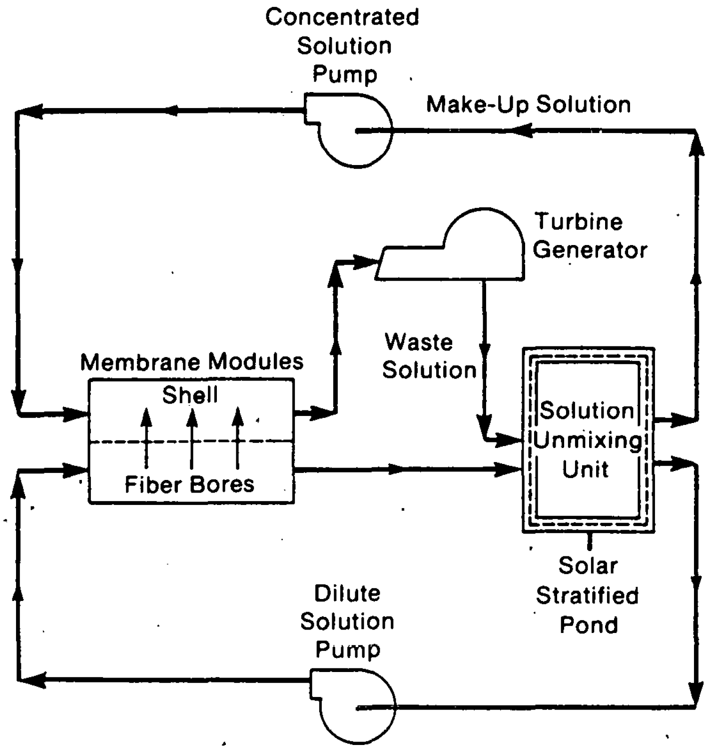

Figure 4-18. Schematic of an Osmo-Hydro Power System, Closed Cycle

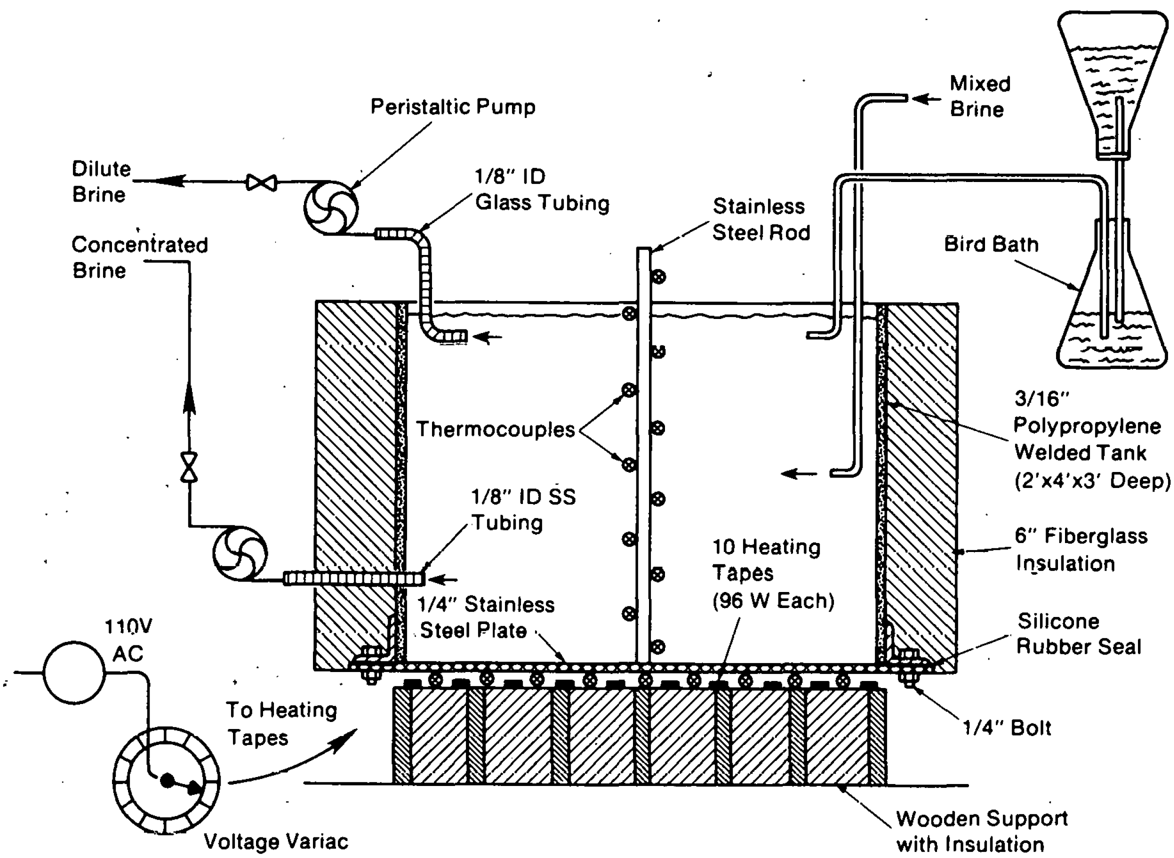

Figure 4-19. Schematic of a Laboratory Saturated Pond Used for Brine Stratifying Tests

A membrane needs to be developed for the osmotic power system application for a demonstration plant. Specific sites for a demonstration plant need to be located that optimize all the environmental and regulatory considerations.

The computer model was modified in Phase II to accommodate a stratified solar pond model and any salt suitable for closed-cycle systems. In addition to the items mentioned in Phase I, the model was used to determine salt requirements for the pond; and Ebasco also used the computer model to estimate system capital, operating, and maintenance costs.

Product costs for the 50-kW system were made first for the capital cost component and then for the combined capital cost plus the operating and maintenance costs. Estimates were also prepared for a 1-MW system. The estimates were prepared for different conditions and assumptions, with or without pond lining and with minimized or maximized salt costs. Estimates were made for both minimum and maximum costs. The most significant costs are for salt charge inclusion. This, in turn, would tend to limit the number of available sites.

As in Phase I, a membrane needs to be developed for this osmotic power system application and specific sites for a demonstration plant need to be located that optimize all the environmental and regulatory considerations. In addition, other eligible salts need to be evaluated for general design and their economic impact as related to site location, availability and costs, and impact on membrane development.

4.3.1.4 Expected Results/Future Efforts

In Phase I, osmotic power systems are feasible using either seawater or brackish water as the bore-side fluid with a saturated salt solution as the shell-side fluid and a solar evaporation pond for reconcentration of the salt. The capital product cost component for the output from a 1-MW system could be in the range of 9-12¢/kWh; however, actual system costs will be strongly site-dependent. With the exception of the membranes, all system components are available and can be easily purchased. Membranes need to be developed with characteristics suitable for osmotic power applications in pressure-retarded osmosis.

Future effort will be directed toward selecting actual sites for the seawater with a pond base case and a brackish water with pond case. Water pretreatment requirements and resulting estimated capital and operating costs for pretreatment (including chemicals and labor) will be determined for selected sites. Revised and updated flow diagrams for osmotic power systems will be prepared at each site. Total capital and operating and maintenance costs for systems located at the sites and the overall potential of saltwater osmotic power systems in the United States will be estimated. A demonstration plant will then be designed, constructed, and operated.

In Phase II, 50-kW osmotic power systems using a stratified solar pond as the stratifier for the mixed solution are feasible. Osmotic power systems larger than 50 kW can be developed and used. The capital cost of a 1-MW system would be in the range of $3,075-$22,312/kW, and product costs range from 7-49¢/kWh without operation and maintenance charges, and from 12-54¢/kWh with operation and maintenance charges. With the exception of the membranes, all system components are available and can be easily purchased.

Preliminary operational capabilities of spiral-wound modules in pressure-retarded osmosis were demonstrated. Membranes suitable for pressure-retarded osmosis will be developed. This includes evaluating other eligible salts for membrane design and use for economic impact as related to site location and availability and costs.

Actual U.S. sites will be selected for the saturated solar ponds. In siting the ponds, mineral deposits, evaporation, precipitation, soil conditions, and environmental factors will be considered. Water pretreatment requirements and resulting estimated capital and operating costs (including chemicals and labor) will be determined. The system size needs to be determined (total kilowatt electric output) for the particular sites selected, and flow diagrams for osmotic powered systems must be revised.

Preliminary performance specifications for the major components need to be sent to manufacturers to provide further confirmation of estimated capital costs, equipment efficiencies or sizes, material compatibilities, and expected life. Total capital, operating, and maintenance costs need to be estimated.

Membrane testing, discussions with membrane manufacturers, and membrane forecasting must be continued to predict future membrane permeation rate and pressure capabilities, membrane life time, and membrane costs under pressure-retarded osmosis conditions. Also, the optimum properties of currently available membranes are needed to demonstrate an osmotic power system. Finally, a demonstration plant needs to be designed, constructed, and operated at a given site.

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4.3.2 Salinity Power Heat Engine—G. D. Mehta*

4.3.2.1 Objective

The overall goal of this program was to develop and place in operation a small salinity power heat engine of 100-W capacity consisting of a saturated solar pond (SSP) coupled to a RED membrane assembly.

The objectives were to:

- demonstrate that an SSP can be used for stratifying a mixed brine into a dilute and concentrated brine stream;
- demonstrate that a RED system can generate power, even though it was realized that such a small capacity system will not be extremely efficient; and
- generate the necessary experimental data, which will be very useful for developing economical salinity power systems in the future, by operating a small RED-SSP heat engine in the laboratory.

4.3.2.2 Approach

One task was to contact various potential ion-exchanger manufacturers and procure an RED assembly of appropriate size and geometry that could generate about 100 net watts when supplied with a dilute brine and a concentrated brine stream of appropriate solute. Different solutes identified included borax ($Na_2B_4O_7 \cdot 10H_2O$), potassium nitrate (KNO_3), potassium perchlorate ($KClO_4$), potassium alum ($K_2SO_4Al_2(SO_4)_3 \cdot 24H_2O$), and disodium phosphate ($Na_2HPO_4 \cdot 12H_2O$).

As a result, several meetings and discussions were arranged with Southern Research Institute of Birmingham, Ala.; Ionics, Inc., of Watertown, Mass.; and Ben-Gurion University of the Negev in Beersheba, Israel. Because of time (about 15 months) and funding constraints and unforeseen difficulties in acquiring an appropriate RED assembly, it was decided to change the scope of work and concentrate only on the laboratory development of saturated solar ponds for brine stratification.

4.3.2.3 Status

As a result of this change, a report on RED systems was submitted to DOE (InterTechnology/Solar Corp. 1980a). This report shows that the electrical resistance of the present-day membranes, which are produced for electrodialysis and not reverse electrodialysis, and the solution compartments are very high. This causes the power density of present-day RED stacks to be very low in terms of watts per unit membrane area. This plus the high cost of present-day membranes results in very high costs for the RED stack. Furthermore, present-day membranes and adhesives for membrane assemblies cannot operate at 80° C for any reasonable length of time without severe deterioration.

*InterTechnology/Solar Corporation

Several areas requiring work include: (1) developing cheap ion-exchange membranes with low electrical resistance and high permselectivity; (2) developing very thin solution compartments; (3) developing RED stacks that can operate at high temperatures; and (4) laboratory testing small RED stacks to investigate the effect of temperature on stack performance and the fouling of RED membranes with time.

Another report summarizing the results of experimental work on developing saturated solar ponds in a laboratory has recently been submitted to DOE (InterTechnology/Solar Corp. 1980b).

Results from ponds using borax, potassium nitrate, and disodium phosphate conclusively demonstrated that saturated solar ponds can self-generate and self-maintain a stable density gradient. Moreover, these ponds reestablished stable density profiles after the ponds were externally mixed.

Based on preliminary results, the residence time for stratifying a brine of intermediate concentration into dilute and concentrated brine streams varied from a few days for the borax pond to about two weeks for the disodium phosphate pond, depending on the characteristics of the individual saturated solution. Because of a very small increase in the density of saturated solutions, a stable potassium perchlorate pond could not be established.

The results on a 1-m (3-ft)-deep alum saturated pond that is 25°C at the surface and 55°C at the bottom indicated that the residence time should be more than two weeks. However, it is possible that the residence time for the alum saturated pond with a temperature of 80°C at the bottom may be less than two weeks.

4.3.2.4 Expected Results/Future Effort

Further work is required for RED systems as previously outlined. Required work for saturated solar ponds is: (1) checking the technical feasibility of brine stratification by SSPs in the laboratory when they are heated by solar-simulating lamps followed by field tests; (2) identifying suitable solutes for osmotic, reverse electrodialysis and vapor pressure difference salinity gradient systems using an SSP; (3) estimating the performance of SSPs more accurately; (4) using conceptual design studies to estimate the cost of these systems more accurately; and (5) determining the overall potential of these systems.

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4.4 THERMOELECTRIC ENERGY CONVERSION—David Benson*

4.4.1 Objective

The long-range objective is to develop improved thermoelectric generators that may be used to produce economical electric power from low-grade thermal energy resources, such as ocean thermal gradients, solar ponds, geothermal water, or industrial waste heat streams. The immediate objective is to produce laboratory-scale proof-of-concept thermoelectric generators suitable for OTEC applications (see Fig. 4-20).

4.4.2 Approach

Detailed design analyses have been completed, and studies have identified several promising design options. Presently, these design options are being evaluated in the laboratory by fabricating and testing prototype thermoelectric generators and heat exchangers.

The thermoelectric generators require thin-film semiconductors such as Bi_2Te_3-Sb_2Se_3 and Sb_1Bi_1-x and compact, combined parallel-plate heat exchangers with specially enhanced heat transfer surfaces.

The research goals for FY 1981 include the fabrication of thermoelectric generators and heat exchangers with a combined performance that is within the range of practical interest for OTEC applications.

4.4.3 Status

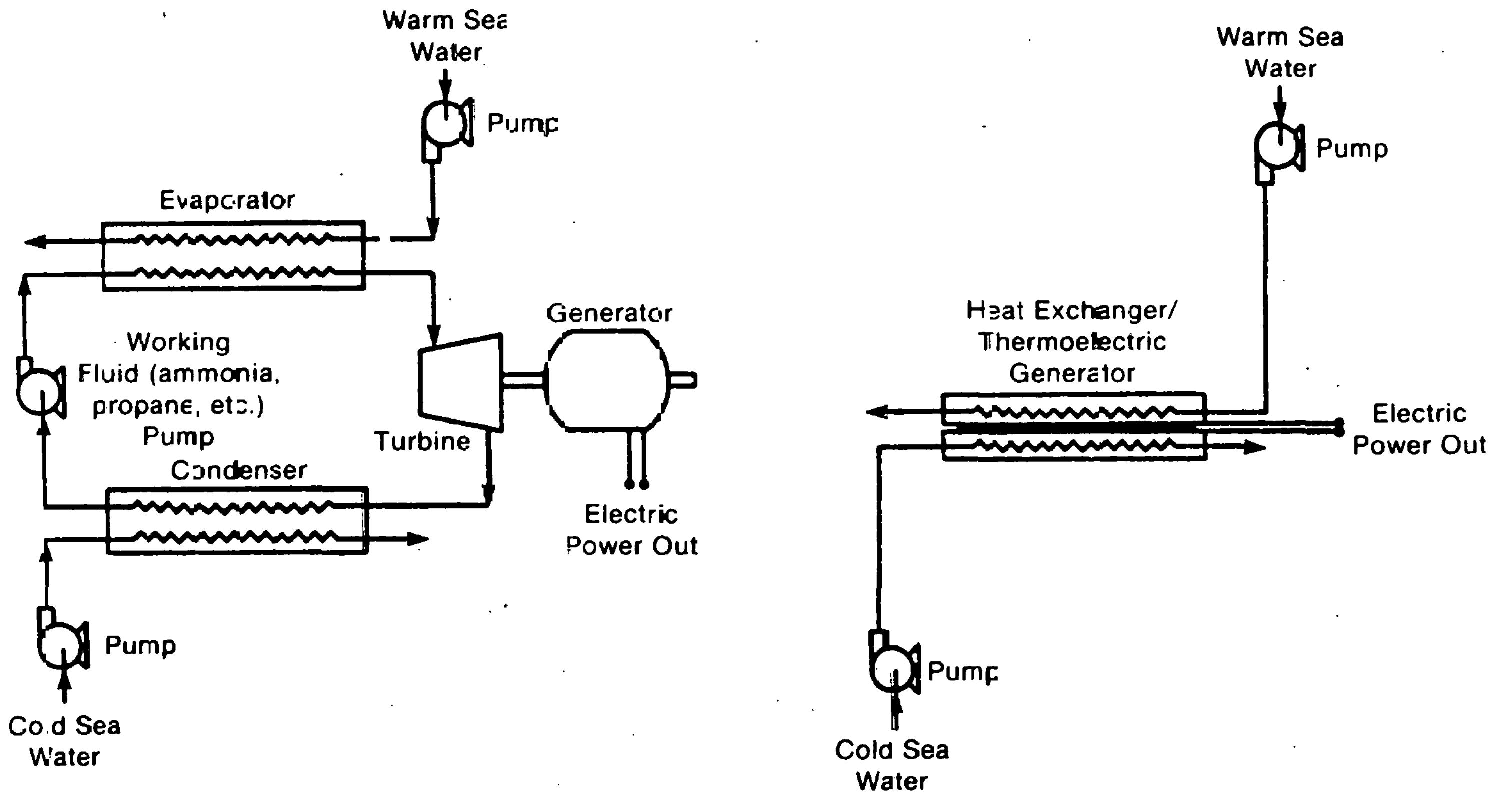
New design methods have been developed and used to define requirements for thermoelectric generators and their coupled heat exchangers in an OTEC system. A parametric method of capital cost minimization was used to guide the design process toward particularly promising but novel generator concepts. A patent application is being processed by DOE.

Although thin-film thermoelectric generators with an adequate conversion efficiency have been reported in the past, their designs were quite different and their suitability to mass production is questionable. Similarly, heat exchangers with suitably enhanced surfaces have been evaluated by others in the laboratory but not in the configuration nor operating environment (seawater) required of an OTEC application. Consequently, two unresolved issues remain:

- Can thin thermoelectric generators be adequately efficient and low in cost?
- Can suitably enhanced heat exchangers be made in a parallel plate configuration and withstand biofouling and corrosion?

These questions must be answered before the concept can be fully evaluated.

*SERI, Solar Thermal Branch



(a) Schematic of a Closed-Cycle OTEC

(b) Schematic of a Thermoelectric OTEC

Figure 4-20. Schematics of Closed-Cycle OTEC and Thermoelectric OTEC

4.4.4 Expected Results/Future Effort

The research under way is designed to resolve issues critical to the evaluation of the concept.

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SECTION 5.0

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SERI

APPENDIX

INFORMATION ON SUBCONTRACTORS

APPENDIX

This Appendix contains a compilation of data about the various subcontractors whose reports appear in the main portion of this document. The particular information presented will appear in the forthcoming publication:

Ocean Energy Systems
Program Summary, December 1980
U.S. Department of Energy

The "Bibliography Ref No:" on the back of the sheets applies to the above DOE summary and not to this document. The "Section" notations at the top right corner of the sheets refer to the sections in this document where the program is covered.

SERI

PROGRAM ELEMENT: Program Support
SUBELEMENT: Support Services

PRIME CONTRACTOR AND ADDRESS lar Energy Research Institute (SERI) dwest Research 1617 Cole Blvd. Golden, CO 80401	**TITLE** Open Cycle OTEC R & D (Program Management)
SUBCONTRACTOR(S) Westinghouse Electric Corp. Science Applications, Inc. Creare, Inc. Hydronautics, Inc.	**CONTRACT NUMBER** EG-77-C-04-4042 SERI 3452
PRINCIPAL INVESTIGATOR **NAME:** Benjamin Shelpuk **PHONE:** (303) 231-1759 FTS-327-1759	**PERIOD OF PERFORMANCE** October 1, 1979 to September 30, 1980 **FISCAL YEAR 1980 FUNDING** $89,000
WORK LOCATION Golden, CO 80401	**CUMULATIVE FUNDING** $660,000
CONTRACT FIELD OFFICE DOE Headquarters Washington, DC	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** S. Gronich, DOE Headquarters

SUMMARY

The long range objective of this program is to provide the DOE Ocean Systems Branch a definitive assessment of the potential of open-cycle OTEC. The purpose of this activity is to establish detailed programmatic objectives, then award and manage subcontracted activities, consistent with DOE guidance in meeting the overall Ocean System goals.

During 1980, subcontracts were awarded combining analysis and laboratory experiments, which will reduce the bands of scientific uncertainty in those subsystem technologies critical to the performance of an open cycle OTEC plant.

The three specific technologies were identified as: 1) Large low-pressure steam turbine development 2) Heat and mass transfer rates (thermal performance) for direct contact heat exchangers using seawater 3) Deaeration requirements for open cycle power system designs.

Currently, this program is being supported by ORNL in Deaeration Research and by in-house SERI research in the areas of heat and mass transfer and material research at a funding level of $566,000. SERI subcontracted programs totalling $411,000 are described under the Advanced Research and Technology Alternate Power Cycle program summaries.

BIBLIOGRAPHY REF NO: None

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PROGRAM ELEMENT: Advanced Research and Technology
SUBELEMENT: Alternate Power Cycles

PRIME CONTRACTOR AND ADDRESS
Solar Energy Research Institute (SERI)
Midwest Research
1617 Cole Blvd.
Golden, CO 80401

SUBCONTRACTOR(S)
Custom Engineering, Inc.
Dartmouth, Univ.
Roundtree, Inc.
CSMRI
Denver West, Inc.

PRINCIPAL INVESTIGATOR

NAME: Benjamin Shelpuk
PHONE: (303) 231-1759 FTS-327-1759

WORK LOCATION
Golden, CO

CONTRACT FIELD OFFICE
DOE Headquarters
Washington, DC

TITLE
Research and Development for OTEC
and Related Materials

CONTRACT NUMBER
EG-77-C-01-4042
SERI 3451 & 3454

PERIOD OF PERFORMANCE
October 1, 1979 to
September 30, 1980

FISCAL YEAR 1980 FUNDING
$434,000 - (SERI 3451)
$132,000 - (SERI 3454)

CUMULATIVE FUNDING
$566,000

GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS
E. H. Kinelski, DOE Headquarters

SUMMARY

The In-House OTEC R&D task involved three subtasks during FY80; System Analysis, Mist Lift Analysis, and the Heat and Mass Transfer Experiment.

The system analysis subtask involved developing an algorithm to analyze the performance of an open-cycle OTEC system, programming the algorithm for use on a computer, then document the results in a research report.

Mist Lift Analysis subtask invovled developing an analytical model of the mist-lift process, programming the model for use on a computer, and then use the program to perform a study of the mist lift response to parameter variations. A research report document is the result of this study.

The Heat and Mass Transfer Experiment subtask involved designing and constructing a laboratory to measure the performance of open-cycle OTEC evaporators and condensers and use this facility to measure the performance of a falling jet evaporator and condenser.

BIBLIOGRAPHY REF NO: 396 through 401

396. Kogan, A., Johnson, D.H., Green, H.J., and Olsen, D.A., "Open Cycle OTEC System with Falling Jet Evaporator and Condenser", Proceedings of the 7th Ocean Energy Conference, June 1980, Washington, D.C. U.S. Department of Energy, Ocean Energy Systems Branch.

397. Richter, J.J., "Application of a Jet Condenser Power Cycle to OTEC", Proceedings of the 7th Ocean Energy Conference, June 1980, Washington, D.C. U.S. Department of Energy, Ocean Energy Systems Branch.

398. Davenport, R.C., "Mist Lift Analysis Summary Report", July 1980, SERI/TR-631-627.

399. Lewandowski, A.A., Olson, D.A., and Johnson, D.H., "Open-Cycle OTEC System Performance Analysis", July 1980, SERI/TR-631692.

400. Kreith, Frank, "An Overview of SERI Solar Thermal Research Facilities", July 1980, SERI/SP-631-760.

401. Wallis, G.B., Richter, H.J., and Bharathan, D., "Analysis of the OTEC Mist Lift Process", September 1979, SERI-8317-1.

PROGRAM ELEMENT: Advanced Research and Technology
SUBELEMENT: Alternate Power Cycles

PRIME CONTRACTOR AND ADDRESS nce Applications, Inc. ___) Prospect Street La Jolla, CA 92038	**TITLE** Falling Film Evapoartor/Condenser Performance/Configuration Evaluation Program
SUBCONTRACTOR(S) Southwestern Engineering	**CONTRACT NUMBER** SERI-XJ-9-8190-2
PRINCIPAL/INVESTIGATOR	**PERIOD OF PERFORMANCE** June 1, 1980 to June 1, 1981
NAME: A. T. Wassel **PHONE:** (213) 640-0480	**FISCAL YEAR 1980 FUNDING** $50,000
WORK LOCATION El Segundo, CA	**CUMULATIVE FUNDING** $50,000
CONTRACT FIELD OFFICE Solar Energy Research Institute Golden, CO	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** T. R. Penney, SERI, Golden, CO

SUMMARY

The economic feasibility of an Open-Cycle approach to the OTEC power plant design is largely dependent on three (3) major system factors: 1) the operating characteristics of the evaporator and condenser; 2) the need for deaeration; and 3) innovative turbomachinery designs. The SAI program will develop the design methodology and experimental data base for open-cycle evaporators/condensers, with specific emphasis on direct-contact, falling-film configuration.

Analytic performance models for falling-film evaporators/condensers are being developed which combine basic considerations of heat and mass transfer processes in sea water with the practical considerations and constraints of actual hardware systems. A parallel laboratory experimental effort is being carried out to confirm modeling approaches using geometries and flow conditions analogous to an ultimate full scale system. The validated performance models will be exercised both to provide key data for preliminary subsystem conceptual designs and to establish a detailed test plan for full-scale evaluations of falling-film evaporator/condenser designs.

BIBLIOGRAPHY REF NO: None

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PROGRAM ELEMENT: Advanced Research and Technology
SUBELEMENT: Alternate Power Cycles

PRIME CONTRACTOR AND ADDRESS Creare Incorporated ox 71 Hanover, NH 03755	**TITLE** Testing and Analysis on Direct Contact Condensers and Turbulent Jet Evaporators
SUBCONTRACTOR(S) None	**CONTRACT NUMBER** SERI-XJ-0-8190-3
PRINCIPAL/INVESTIGATOR **NAME:** Bharatan R. Patel **PHONE:** (603) 643-3800	**PERIOD OF PERFORMANCE** June 1, 1980 to September 30, 1980 **FISCAL YEAR 1980 FUNDING** $50,000
WORK LOCATION Hanover, NH	**CUMULATIVE FUNDING** $50,000
CONTRACT FIELD OFFICE Solar Energy Research Institute Golden, CO	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** T. R. Penney, SERI, Golden, CO

SUMMARY

This project is part of Phase I of the overall program and addresses the evaporator and condenser which are two of the subsystems critical to the performance of the open-cycle OTEC plant. Direct-contact evaporators and condensers appear to be best suited for the open-cycle OTEC application and would eliminate the problems of high cost, biofouling, etc., that would occur in conventional heat exchangers. However, the direct-contact, heat-exchanger data base is very limited and inadequate for use in open-cycle OTEC plant design. Further, adequate design and optimization methods have not been developed.

The objective of this project is to develop the required heat and mass transfer data base, and a design methodology for the design and evaluation of direct-contact evaporator (falling turbulent jet) and condenser (falling turbulent jet and film) configurations suitable for open-cycle OTEC applications.

BIBLIOGRAPHY REF NO: None

402. Westinghouse Electric Corporation, "100 MWe OTEC Alternate Power Systems-Final Report", USDOE Contract No. EG-77-C-05-1473, March 5, 1979.

403. Rabas, T.J., Wittig, J.M. and Finsterwader, K. "OTEC 100-MWe Alternate Power Systems Study", Proceedings of the 6th OTEC Conference, June 1979, Washington, D.C. U.S. Department of Energy, Ocean Energy Systems Branch. (CONF-790631).

PRIME CONTRACTOR AND ADDRESS stinghouse Electric Corporation). Box 9175 Lester, PA 19113	**TITLE** Open Cycle OTEC Low Pressure Turbine Development Program
SUBCONTRACTOR(S) TM Development, Inc.	**CONTRACT NUMBER** SERI-XM-9-8190-1
PRINCIPAL/INVESTIGATOR **NAME:** Paul D. Ritland **PHONE:** (215) 595-2861	**PERIOD OF PERFORMANCE** February 1, 1980 to May 31, 1980 **FISCAL YEAR 1980 FUNDING** $260,000
WORK LOCATION Lester, PA	**CUMULATIVE FUNDING** $566,000
CONTRACT FIELD OFFICE Solar Energy Research Institute Golden, CO	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** T. R. Penney, SERI, Golden, CO

SUMMARY

The long range objective of the open-cycle program is to develop sufficient technology to allow construction of a prototype plant with confidence. The general objective of this project is to develop a data base through analysis and subsystem testing which will support a definitive assessment of the potential of open-cycle OTEC.

The specific short range objectives of the work covered under this contract are to:

- o Establish a 100 MWe open-cycle prototype turbine design.
- o Develop scale model test parameters.
- o Develop a turbine off-design and transient computer program to support blade design.

The key unknown in the overall evaluation of the Claude open cycle OTEC concept is the practicality of the extremely large single stage turbine required. This project will supply the design, manufacturability and cost information to determine whether a cost effective system is possible/competitive with other renewable energy systems. It will supply information to allow meaningful testing of small scale models of the prototype and provide the methodology for interpreting the results, and it will provide the tools to develop control strategies and evaluate turbine design adequacy for a range of heat exchanger models.

BIBLIOGRAPHY REF NO: 402 through 403

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PROGRAM ELEMENT: Advanced Research and Technology
SUBELEMENT: Alternate Power Cycles

PRIME CONTRACTOR AND ADDRESS H ' onautics, Inc. 7: Pindell School Road Laurel, MD 20810	**TITLE** Open Cycle Concept Demonstration - Deaeration Systems (Phase I)
SUBCONTRACTOR(S) None	**CONTRACT NUMBER** SERI-XJ-9-8190-4
PRINCIPAL/INVESTIGATOR	**PERIOD OF PERFORMANCE** June 1, 1980 to May 31, 1981
NAME: William T. Lindenmuth **PHONE:** (301) 953-3363	**FISCAL YEAR 1980 FUNDING** $46,500
WORK LOCATION Laurel, MD	**CUMULATIVE FUNDING** $46,500
CONTRACT FIELD OFFICE Solar Energy Research Institute Golden, CO	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** T. R. Penney, SERI, Golden, CO

SUMMARY

The design and performance of the condenser will be closely tied to the amount of noncondensible (free) gas that must be removed therefrom. Subsystems for removing gases from the warm water before reaching the evaporator and from the cold water before entering the condenser may serve to reduce the condenser's gas load significantly so as to improve its effectiveness and increase the power plant's efficiency. Gases that evolve in the evaporator and condenser or that lead through turbine seals, etc., must still be pumped from the condenser.

Design data specific to deaeration and air reinjection subsystems are being developed through a program of laboratory experiments and anlayses. Experiments will be conducted in a 35-foot tall flow loop. Feed water flowing up the loop's riser pipe will experience the same velocity and pressure gradients as in a full-scale prototype so as to stimulate the mass transfer of gas into bubbles with realistic time scales. Similarly, gas reinjection can be modeled in the downcomer side of the test loop.

BIBLIOGRAPHY REF NO: None

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PROGRAM ELEMENT: Program Support
SUBELEMENT: Support Services

PRIME CONTRACTOR AND ADDRESS ⁻⁻': Ridge National Laboratory t Office Box Y Oak Ridge, TN 37830	**TITLE** Alternate Power Cycles Development
SUBCONTRACTOR(S) R&D Associates University of Califronia, Los Angeles Carnegie-Mellon University University of Puerto Rico	**CONTRACT NUMBER** W-7405-ENG-26-E
PRINCIPAL/INVESTIGATOR **NAME:** F. C. Chen **PHONE:** (615) 574-0712 - (FTS) 624-0712	**PERIOD OF PERFORMANCE** October 1, 1979 to September 30, 1980
WORK LOCATION Oak Ridge, TN	**FISCAL YEAR 1980 FUNDING** $234,000
	CUMULATIVE FUNDING $571,000
CONTRACT FIELD OFFICE Oak Ridge Operations Office Oak Ridge, TN	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** E. H. Kinelski, DOE Headquarters

SUMMARY

The objective is to provide the DOE Ocean Energy Systems Division necessary programmatic and technical assistance, to perform subcontract management, contract monitoring, in-house R&D, and systems analysis tasks for the development of OTEC alternate power cycle technology, including Open, Mist Lift, and Foam Lift cycles. Work was carried out to provide planning analysis of hydraulic lift cycle concepts; technical monitoring of subcontractors' performance, and systems analysis tasks were performed in barometric intake system deaeration analysis and in the test data analysis. Also, an in-house gas desorption test loop was completed capable of conducting barometric intake deaeration, different deaerator configurations, and air ingestion experiments. Gas desorption tests of a column packed with Raschig rings and of a barometric intake system were completed. The total 1980 funding under contract W-7405-ENG-26-E was $575,000 of which $341,000 was for subcontract activities.

BIBLIOGRAPHY REF NO: 4 through 6

4. A. Golshani, and F. C. Chen, "OTEC Gas Desorption Study - Design of Experiments", ORNL/TM-7438/v.1, September 1980.

5. F. C. Chen, "Intrinsic Air Lifting in a Depressurizing Flow", J. of Fluids Engineering, American Society of Mechanical Engineering.

6. F. C. Chen and J. W. Michel, "Development of OTEC Lift Cycles", Proceedings of the 7th Ocean Energy Conference, June 1980, Washington, D.C. U.S. Department of Energy, Ocean Energy Systems Branch.

PROGRAM ELEMENT: Advanced Research and Technology
SUBELEMENT: Alternate Power Cycles

PRIME CONTRACTOR AND ADDRESS & D Associates ›st Office Box 9695 Marina del Ray, CA 90291	**TITLE** Mist Flow Ocean Thermal Energy Process
SUBCONTRACTOR(S) Dynamics Technology, Inc.	**CONTRACT NUMBER** ORNL/Sub - 7613
PRINCIPAL/INVESTIGATOR **NAME:** S. L. Ridgway **PHONE:** (213) 822-1715	**PERIOD OF PERFORMANCE** March 1, 1980 to November 30, 1980 **FISCAL YEAR 1980 FUNDING** $160,000
WORK LOCATION Los Angeles, CA	**CUMULATIVE FUNDING** $412,500
CONTRACT FIELD OFFICE Oak Ridge Operations Office Oak Ridge, TN	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** Fang C. Chen, ORNL, Oak Ridge, TN

SUMMARY

The objective of this project is to determine the feasibility of the mist lift ocean thermal energy process. Essential components of the system are to be developed and tested. The fluid dynamics of the two-phase flow that takes place in the lift tube should be understood in sufficient depth and detail to enable reasonable projections of the operating characteristics and boundaries of the possible capital costs of a mist flow ocean thermal energy plant. The influence of mist parameters (droplet size, droplet size distribution) and transport parameters (pressure gradient, duct profile, and velocity schedule) on the lift effectiveness of the two-phase flow is to be determined.

A new experimental apparatus has been designed and constructed for the purpose of studying the mist transport process under conditions of mist and vapor velocities characteristic of those to be expected in Mist Flow OTEC plants, and for studying droplet coalescence and breakup effects as the slip velocity of the vapor relative to the liquid is varied. The test section is a transparent rectangular duct 9" x 14" in cross section, and 12 feet in height. Liquid injection velocities between 3 and 30 m/sec will be available, and vapor ducting and condenser capacity for a vapor velocity of 60 m/sec is available. This equipment is now entering its shakedown phase, and preliminary results should be available in FY 81.

BIBLIOGRAPHY REF NO: 405 thrugh 407

405. Ridgway, S.L. and Hammond, P.R., "Mist Flow Ocean Thermal Energy Process - Final Report", ORO-1684, September 1978.

406. Charwatt, A.F., Hammond, R.P. and Ridgway, S.L., "The Mist-Transport Cycle: Progress in Economic and Experimental Studies", Proceedings of the 6th OTEC Conference, June 1979, Washington, D.C. U.S. Department of Energy, Ocean Energy Systems Branch. (CONF-790631).

407. Charwat, A.F., "Studies of the Vertical Mist Transport Process for an Ocean Thermal Energy Cycle--Final Report", SAN-0034-76-1, November 1978.

PROGRAM ELEMENT: Advanced Research and Technology
SUBELEMENT: Alternate Power Cycles

PRIME CONTRACTOR AND ADDRESS iiversity of California, Los Angeles . .5 Hilgard Avenue Los Angeles, CA 90024	**TITLE** Vertical Mist-Flow Transport Process for Application To OTEC
SUBCONTRACTOR(S) Charles Wyle Engineering Corp.	**CONTRACT NUMBER** W-7405-eng-26 Sub-7649
PRINCIPAL/INVESTIGATOR **NAME:** A. F. Charwat **PHONE:** (213) 825-4917	**PERIOD OF PERFORMANCE** January 1, 1980 to September 30, 1980 **FISCAL YEAR 1980 FUNDING** $20,900
WORK LOCATION Los Angeles, CA	**CUMULATIVE FUNDING** $274,100
CONTRACT FIELD OFFICE Oak Ridge Operations Office Oak Ridge, TN	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** Fang C. Chen, ORNL, Oak Ridge, TN

SUMMARY

The main objectives of the project are to identify the unit process of a mist-lift OTEC cycle and assess the pertinent technical and scientific background, and to operate a test facility which can generate design data for development of key components of the system and demonstrate the overall feasibility of the mist-lift cycle.

A numerical solution of the vertical mist transport problem capable of modeling the collisions among drops by a Monte-Carlo simulation technique, including transverse scattering variable coalescence efficiencies and wall deposition was successfully developed in this contract period. The analysis concerning wall deposition lends credibility to the experimental result. The last phase of the theoretical work aimed at analyzing the growth of dissipation of transverse disturbances is in progress.

BIBLIOGRAPHY REF NO: 410 through 412

410. Ridgway, S.L. and Hammond, P.R., "Mist Flow Ocean Thermal Energy Process - Final Report", ORO-1684, September 1978.

411. Charwatt, A.F., Hammond, R.P. and Ridgway, S.L., "The Mist-Transport Cycle: Progress in Economic and Experimental Studies", Proceedings of the 6th OTEC Conference, June 1979, Washington, D.C. U.S. Department of Energy, Ocean Energy Systems Branch. (CONF-790631).

412. Charwat, A.F., "Studies of the Vertical Mist Transport Process for an Ocean Thermal Energy Cycle--Final Report", SAN-0034-76-1, November 1978.

PRIME CONTRACTOR AND ADDRESS	TITLE
~~rtmouth College ayer School of Engineering Room 103 Hanover, NH 03755	Computer Modeling of the Dynamic Response in a Mist Lift Power Cycle
SUBCONTRACTOR(S) None	**CONTRACT NUMBER** SERI-S-9264
PRINCIPAL/INVESTIGATOR NAME: Graham Wallis PHONE: (603) 646-2789	**PERIOD OF PERFORMANCE** June 1, 1980 to November 30, 1980
WORK LOCATION Hanover, NH	**FISCAL YEAR 1980 FUNDING** $16,000
	CUMULATIVE FUNDING $16,000
CONTRACT FIELD OFFICE Solar Energy Research Institute Golden, CO	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** T. R. Penney, SERI, Golden, CO

SUMMARY

Previous work formed the basis for the steady flow analysis in a mist lift power cycle now in use at SERI. Results of computer simulation have revealed a sensitivity of the performance to small changes in flow rate or the pressure upstream of the injection nozzles. Whether or not the system is stable cannot, however, be determined without incorporating time into the model as an independent variable. It is also desirable to be able to predict the system response to transients such as start-up or changes in condenser temperature.

The general objective is to obtain theoretical models that can be used for evaluating the performance characteristics of a Mist Lift OTEC system. The major short range objective is the construction of a computer model for the transient response of the mist lift column to changes in boundary conditions at the droplet generator and the condenser. Secondary objectives include the consideration and analysis of concepts for improving performance.

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PROGRAM ELEMENT: Advanced Research and Technology
SUBELEMENT: Alternate Power Cycles

"" 'ME CONTRACTOR AND ADDRESS negie-Mellon University 5000 Forbes Avenue Pittsburgh, PA 15213	**TITLE** Development of a Foam OTEC Cycle
SUBCONTRACTOR(S) None	**CONTRACT NUMBER** ORNL/Sub - 7654
PRINCIPAL/INVESTIGATOR	**PERIOD OF PERFORMANCE** October 1, 1979 to September 30, 1980
NAME: Tomlinson Fort, Jr./Clarence Zener **PHONE:** (412) 578-2538	**FISCAL YEAR 1980 FUNDING** $88,400
WORK LOCATION Pittsburgh, PA	**CUMULATIVE FUNDING** $413,000
CONTRACT FIELD OFFICE Oak Ridge Operations Office Oak Ridge, TN	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** Fang C. Chen, ORNL, Oak Ridge, TN

SUMMARY

The long term goal is to establish the economic feasibility of the Foam OTEC System. Currently work has been structured to understand the detailed mechanism of foam growth, and to use this understanding to reduce significantly the required surfactant concentration.

Carnegie-Mellon University has constructed and operated a complete Foam Lift System on a laboratory scale using a 4" diameter 30' high column to investigate the foam lift phenomena. This system consisted of foam generation, foam lift, foam breaking, liquid and vapor separation, and finally segregation of liquid into a standing pipe, condensation of vapor by a cold-water spray. In this laboratory system, an upward flux density comparable to that anticipated for a commercial size system was used. This flux density of 1 gram/cm^2/sec would give a net power of 1 kW/ft^2.

BIBLIOGRAPHY REF NO: 408 through 409

408. Zener, C. et al., "Recent Development in the Foam OTEC Systems", Proceedings of the 6th OTEC Conference, June 1979, Washington, D.C. U.S. Department of Energy, Ocean Energy Systems Branch. (CONF-790631).

409. Kay, M.I., "Description and Status Report of a Program to Define Seawater-Surfactant Interactions in Relation to the Foam System", Proceedings of the 6th OTEC Conference, June 1979, Washington, D.C. U.S. Department of Energy, Ocean Energy Systems Branch. (CONF-790631).

PRIME CONTRACTOR AND ADDRESS
University of Puerto Rico
Center for Energy & Environmental Research
College Station
Mayaguez, PR 00708

TITLE
Seawater Surfactant Systems and Their Relation to the Foam OTEC System

SUBCONTRACTOR(S)
None

CONTRACT NUMBER
EY-76-C-05-1833

PERIOD OF PERFORMANCE
October 1, 1979 to
September 30, 1980

PRINCIPAL INVESTIGATOR

NAME: M. I. Kay
PHONE: (809) 832-1414

FISCAL YEAR 1980 FUNDING
$70,000

WORK LOCATION
Mayaguez, PR

CUMULATIVE FUNDING
$125,600

CONTRACT FIELD OFFICE
Oak Ridge National Laboratory
Oak Ridge, TN

GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS
E. H. Kinelski, DOE Headquarters

SUMMARY

Projected Goals for F.Y. 1980 as (1) construct generator, (2) build a safer more accessible tower scaffold, (3) attempt to build a deairator for the column, (4) begin measurements of minimum surfactant concentration necessary to maintain mass transport in sea water and distilled water.

The first two goals were met by June 1980. The objective of the deairator was to better control nucleation at low mass flow rates where superheating occurs and prevent uncontrolled foam formation. A low pressure packed column was tried alone and in conjunction with a pumped box. Laboratory experiments showed remaining air as expected depends on the flow rate through the system. Preliminary experiments in the foam column yielded at least an extra couple of degrees of supercooling.

Initial experiments with Neodol 25-3A (ionic) (Also used by CMU) and Neodol 91-6 (non-ionic) brought minimum concentrations needed to sustain mass flow down to 250 ppm. Later alterations to a 20 foot column, and changes in initial temperature, as per the reported CMU results at the VII OTEC conference, brought minimum surfactant concentration below 75 ppm.

Results with several commercial mixtures have thus far shown no difference, in the needed surfactant to maintain a flow, between sea water and distilled water, indicating that flow dynamics may still be the limiting factor. It is expected that the differences will be noted as lower concentrations are reached and higher precision attained. Calculations also show the equilibrium surface concentration of an expanded dilute foam will deplete the bulk solution, thus causing, the equilibrium surface concentration of surfactants to depend mainly on the amount of surfactant added. Thus far, the best results have been obtained with smaller hydrophobic carbon chains and moderate sized hydrophillic groups.

Seawater will not foam without surfactant.

BIBLIOGRAPHY REF NO: 395

395. Chen, F.C., and Michel, J.W., "Development of OTEC Lift Cycles", Proceedings of the 7th Ocean Energy Conference, June 1980, Washington, D.C. U.S. Department of Energy, Ocean Energy Systems Branch.

PRIME CONTRACTOR AND ADDRESS C[illegible] University of New York (CUNY) 1[illegible] Street & Convent Avenue New York, NY 10022	**TITLE** Wave Resource Analysis
SUBCONTRACTOR(S) None	**CONTRACT NUMBER** OLD = ET-78-C-05-5697 NEW = DE-AC-05-78ET20488 (FY 1979) NEW = SERI AS-0-9110-01 (FY 1980)
PRINCIPAL INVESTIGATOR **NAME:** Willard Pierson **PHONE:** (212) 690-8315	**PERIOD OF PERFORMANCE** October 1, 1978 to March 31, 1980 **FISCAL YEAR 1980 FUNDING** $2,500
WORK LOCATION New York, NY	**CUMULATIVE FUNDING** $78,738
CONTRACT FIELD OFFICE Oak Ridge Operations Office, Oak Ridge, TN (FY79) SERI, Golden, CO (FY80)	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** B. Shelpuk, SERI, Golden, CO

SUMMARY

There are two objectives of this study. The first is to prepare a climatology of available wave power for selected locations. The second is to provide a wave and wind climatology for four potential OTEC sites. These results will be based on Wave Hindcasts prepared by the Fleet Numerical Weather Center, presently archived at the David Taylor Naval Ship Research and Development Center. This climatology is to be for a selected set of grid points for the North Atlantic and North Pacific Oceans. The contract has been extended to include Pueto Rico, Wake Island, and Hawaii.

The approach is:

1. Prepare a master data file of SOWM spectra for the North Pacific and North Atlantic areas.
2. Modify spectral data to account for near shore effects within the 100 mile offshore range.
3. Validate modified spectra against available measurements along the California coast.
4. Run sample data analysis to establish presentation format.
5. Analyze spectral data to assess wave energy resources for the North Pacific and North Atlantic, with consideration for seasonal variations.
6. Prepare summary and final report.

Mr. R. E. Salfi will stay at the David Taylor Naval Ship Research and Development Center until the master data file is generated.

BIBLIOGRAPHY REF NO: 413

413. Pierson, W., "Development of Wave Forecasting Methods", October 1980, City University of New York, 175 pps.

PROGRAM ELEMENT: Related Ocean Energy Technology
SUBELEMENT: Wave Energy

PRIME CONTRACTOR AND ADDRESS :kheed Missiles and Space Company, Inc. ean Systems Division P.O. Box 504 Sunnyvale, CA 94086	**TITLE** Dam-Atoll
SUBCONTRACTOR(S) T. Y. Lin, International	**CONTRACT NUMBER** SERI XJ-8316-01
PRINCIPAL INVESTIGATOR **NAME:** Clint Sherborn **PHONE:** (408) 742-7136	**PERIOD OF PERFORMANCE** June 1, 1980 to July 1, 1981 **FISCAL YEAR 1980 FUNDING** $250,000
WORK LOCATION Sunnyvale, CA	**CUMULATIVE FUNDING** $250,000
CONTRACT FIELD OFFICE Solar Energy Research Institute Golden, CO	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** B. Shelpuk, SERI, Golden, CO

SUMMARY

Objective: Investigate the technical, economic and commercial viability of the Dam-Atoll wave focusing concept. This will be done by a systems engineering study and a model test program.

Approach: This is a two phase program.

Phase I	Task I	Design Background
	Task II	Model Test Plan
	Task III	Model Design
	Task IV	System Engineering
Phase II	Task I	Test Plan Research
	Task II	Instrumentation
	Task III	Fabrication
	Task IV	Testing
	Task V	Results and Conclusions

Phase I, currently funded is a 13 month program.

BIBLIOGRAPHY REF NO: None

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PROGRAM ELEMENT: Related Ocean Energy Technology
SUBELEMENT: Wave Energy

IME CONTRACTOR AND ADDRESS bs and Cox, Inc. 2341 Jefferson Davis Highway Suite 1020, Century Building Arlington, VA 22202	**TITLE** Technical Support Services and Wave Energy Systems Study
SUBCONTRACTOR(S) Michael McCormick	**CONTRACT NUMBER** XJ-0-9365 XJ-0-9368 XJ-0-9366 XJ-0-9369 XJ-0-9367
PRINCIPAL INVESTIGATOR **NAME:** Eric Midboe **PHONE:** (703) 979-1240	**PERIOD OF PERFORMANCE** July 1, 1980 to June 30, 1981 **FISCAL YEAR 1980 FUNDING** $100,000
WORK LOCATION Arlington, VA	**CUMULATIVE FUNDING** $190,000
CONTRACT FIELD OFFICE Solar Energy Research Institute Golden, CO	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** B. Shelpuk, SERI, Golden, CO

SUMMARY

To provide technical support via:

- Telephone Consultations
- Unsolicited Proposal Reviews
- Technical Report Reviews
- Solicitation Support

— as needed. The support subcontract started July 1980 and extends through December 31, 1980 with optional six months of additional support.

The Systems Study consists of seven tasks:

- TLR
- Bibliography
- Resource Scenario Development
- Performance Evaluation
- Synthesis
- Evaluation
- Final Report

The work extends through March 1981 using FY81 funds.

BIBLIOGRAPHY REF NO: None

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PROGRAM ELEMENT: Related Ocean Energy Technology
SUBELEMENT: Wave Energy

PRIME CONTRACTOR AND ADDRESS al Systems Engineering Dept. U.S. Naval Academy Annapolis, MD 21402	**TITLE** Kaimei Tape Analysis
SUBCONTRACTOR(S) None	**CONTRACT NUMBER** AJ-0-9257
PRINCIPAL INVESTIGATOR **NAME:** Michael McCormick **PHONE:** (301) 267-3873	**PERIOD OF PERFORMANCE** June 16, 1980 to October 1, 1980 **FISCAL YEAR 1980 FUNDING** $8,914
WORK LOCATION Annapolis, MD	**CUMULATIVE FUNDING** $8,914
CONTRACT FIELD OFFICE Solar Energy Research Institute Golden, CO	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** B. Shelpuk, SERI, Golden, CO

SUMMARY

The objective of this study is to analyze the data taken from the Kaimei experiment.

The methods of analyses of the data resulting from the wave energy conversion tests in the Sea of Japan are outlined. The tests, sponsored by the International Energy Agency and performed on the floating platform called the "Kaimei", resulted in fifty magnetic tapes on which are recorded data from eighty sensors. The data on the tapes are in voltages and must, therefore, be converted to dimensional data. Furthermore, the data are in digital form. Algorithms must be written to reduce the data and analyze the results. The analyses include (1) averaging each sensor output every twenty minutes over a twenty-four hour period, (b) the cross-correlation of sensor outputs to determine the relative dependence of one variable on the other, and (c) the calculation of the spectral densities of specific sensor outputs to determine the various energies of the variables. Data from these analyses are presented in graphical form.

BIBLIOGRAPHY REF NO: None

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PROGRAM ELEMENT: Related Ocean Energy Technology
SUBELEMENT: Wave Energy

PRIME CONTRACTOR AND ADDRESS C--tom Engineering 5 S. Tejon Street Englewood, CO 80110	**TITLE** Fabrication and Assembly of a Prototype Wave Energy Converter
SUBCONTRACTOR(S) General Electric T. M. Development Quality Metal Products	**CONTRACT NUMBER** SERI-XT-0-9247
PRINCIPAL INVESTIGATOR NAME: C. Castle PHONE: (303) 761-7585	**PERIOD OF PERFORMANCE** August 1, 1980 to February 28, 1981 **FISCAL YEAR 1980 FUNDING** $175,000
WORK LOCATION Englewood, CO	**CUMULATIVE FUNDING** $175,000
CONTRACT FIELD OFFICE Solar Energy Research Institute Golden, CO	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** T. R. Penney, SERI, Golden, CO

SUMMARY

The purpose of this contract is to complete fabrication and assembly of a prototype wave energy converter. The turbine generator concept was conceived by Professor Michael McCormick of the U.S. Naval Academy for testing on a Japanese barge, the KAIMEI, sponsored by members of the International Energy Agency.

BIBLIOGRAPHY REF NO: None

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PRIME CONTRACTOR AND ADDRESS	TITLE
M----achusetts Institute of Technology 7 assachusetts Avenue Cambridge, MA 02139	Three Ocean Wave Power Conversion Systems Trains as Wave Power Systems
SUBCONTRACTOR(S) None	**CONTRACT NUMBER** 79-ET-21062
PRINCIPAL INVESTIGATOR	**PERIOD OF PERFORMANCE** July 1, 1979 to August 31, 1980
NAME: C. C. Mei **PHONE:** (617) 253-2994	**FISCAL YEAR 1980 FUNDING** $0
WORK LOCATION Cambridge, MA	**CUMULATIVE FUNDING** $50,000
CONTRACT FIELD OFFICE Chicago Operations Office Argonne, IL	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** B. Shelpuk, SERI, Golden, CO

SUMMARY

The objective is to study the technical potential of the Cokerall floating raft wave energy conversion system. Comparison will be made with the Salter Cam and the Russel Rectifier wave energy conversion systems.

The contractor will extend the existing numerical and analytical methods for floating bodies to study the following features as a function of geometry and incident wave characteristics, both sinusoidal and random:

1. Theoretical efficiency of the systems for a wide range of parameters.
2. Optimum design with given indicent wave spectra and sea depth.
3. Wave forces on the systems.
4. Motion of the systems.

These quantities are determined primarily from hydro-dynamics and should provide design guidance for the gross dimensions and shape for the systems. Conversion techniques within the computed theoretical limit are not treated. Only a one-dimensional spectrum is studied. Crude economical considerations and optimization of the technical parameters will be considered.

This phase of the contract has been completed. A new phase is being sponsored by SERI. The major findings of the past contract are as follows:

- o It is optimal to use a three raft configufation with two power take-off hinges.
- o Variable power take-off impedences improve efficiency.
- o Parallel raft trains should be spaced about a train length apart—leading to about a 20% improved efficiency.

BIBLIOGRAPHY REF NO: 416 through 417

416. Mei, C.C., "Numerical Methods in Water-Wave Diffraction and Radiation, Annual Reviews", Fluid Mechanics, 1978, Vol. 10, pp. 393-416.

417. Mei, C.C., "Power Extraction From Water Waves", Journal of Ship Research, 1976, Vol. 20, No. 2 - pp 63-66.

PROGRAM ELEMENT: Related Ocean Energy Technology
SUBELEMENT: Wave Energy

PRIME CONTRACTOR AND ADDRESS ''assachusetts Institute of Technology Massachusetts Avenue Cambridge, MA 02139	**TITLE** Technical Potential of Floating Raft Trains as Wave Power Systems
SUBCONTRACTOR(S) None	**CONTRACT NUMBER** XW-0-9359
PRINCIPAL INVESTIGATOR **NAME:** Chiang C. Mei **PHONE:** (617) 253-2994	**PERIOD OF PERFORMANCE** September 1, 1980 to February 28, 1981 **FISCAL YEAR 1980 FUNDING** $36,000
WORK LOCATION Cambridge, MA	**CUMULATIVE FUNDING** $86,000
CONTRACT FIELD OFFICE Solar Energy Research Institute Golden, CO	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** B. Shelpuk, SERI, Golden, CO

SUMMARY

The objective of this task is to provide theoretical analysis of the technical potential of the wave contouring raft trains, with emphasis on the optional energy that can be obtained with constrained motion; and an examination of the efficiency of a Kaimei type ship under various scenarios.

The approach will be via numerical analysis.

BIBLIOGRAPHY REF NO: 418 through 419

418. Mei, C.C., "Numerical Methods in Water-Wave Diffraction and Radiation, Annual Reviews", Fluid Mechanics, 1978, Vol. 10, pp. 393-416.

419. Mei, C.C., "Power Extraction From Water Waves", Journal of Ship Research, 1976, Vol. 20, No. 2 - pp 63-66.

PROGRAM ELEMENT: Related Ocean Energy Technology
SUBELEMENT: Ocean Current Energy

RIME CONTRACTOR AND ADDRESS AeroVironment, Inc. 145 North Vista Avenue Pasadena, CA 91107	**TITLE** Coriolis Phase III
SUBCONTRACTOR(S) W. J. Mouton Associates T. M. Development, Inc.	**CONTRACT NUMBER** XJ-0-9241-01
PRINCIPAL INVESTIGATOR	**PERIOD OF PERFORMANCE** August 1, 1980 to July 31, 1981
NAME: Peter Lissaman/Bob Radkey **PHONE:** (213) 449-4392	**FISCAL YEAR 1980 FUNDING** $80,000
WORK LOCATION Pasadena, CA	**CUMULATIVE FUNDING** $309,977
CONTRACT FIELD OFFICE Solar Energy Research Institute Golden, CO	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** B. Shelpuk, SERI, Golden, CO

SUMMARY

There are three objectives to this task:

- Develop a detailed methodology for calculating the hydrodynamic performance of high performance augmenter ducts, then design a cost-effective duct and rotor system for a prototype and test module.
- To study the rim drive concept and make a preliminary engineering design of the mechanical and structural arrangements, including an analysis of the rim mechanism dynamics.
- Review overall system design engineering and mooring concepts and reassess the economic feasibility of the full-scale unit, including attention to the cost-effectiveness of the duct and the size of the unit.

The approach to reach these objectives is via twelve subtasks, ranging from model development, analysis, trade off studies, and life cycle costing.

BIBLIOGRAPHY REF NO: None

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PROGRAM ELEMENT: Related Ocean Energy Technology
SUBELEMENT: Ocean Current Energy

PRIME CONTRACTOR AND ADDRESS	TITLE
WLVEC Technology Company 10 South 11th Street Odel, IA 50003	Mechanical Feasibility of the WLVEC Engine
SUBCONTRACTOR(S) None	**CONTRACT NUMBER** OLD = ET-77-C-05-5397 NEW = DE-AC05-77ET20163 NEW = SERI AS-0-9213-01
PRINCIPAL INVESTIGATOR NAME: Gary Steelman PHONE: (515) 993-3604	**PERIOD OF PERFORMANCE** January 1, 1977 to November 15, 1980 **FISCAL YEAR 1980 FUNDING** $25,000
WORK LOCATION Odel, IA	**CUMULATIVE FUNDING** $34,990
CONTRACT FIELD OFFICE Oak Ridge Operations Office Oak Ridge, TN	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** B. Shelpuk, SERI, Golden, CO

SUMMARY

The objective is to demonstrate the technical feasibility of a drogue-chute type model ocean energy conversion system.

The contractor will build a demonstration drogue-chute type ocean energy conversion test model to assess the efficiency of mechanical power conversion and perform scaling analysis of model to prototype.

A demonstration model has been fabricated. Most of the equipment has been purchased and assembled. The Power Loop (parachutes and drive cables) is completed. The Power Extraction wheels are partially completed. Testing will follow completion.

This phase has been completed through fabrication of the WLVEC Engine. Testing of the WLVEC has been funded by SERI, Golden, CO.

BIBLIOGRAPHY REF NO: 425

425. Steelman, G.E., "An Invention Designed to Convert Ocean Currents into Useable Power" Proceedings of the MacArthur Workshop on the Feasibility of Extracting Useable Energy from the Florida Current, February 27 -March 1, 1974, Palm Beach Shores, FL.

PROGRAM ELEMENT: Related Ocean Energy Technology
SUBELEMENT: Salinity Gradient Energy

PRIME CONTRACTOR AND ADDRESS ⁻' asco Services, Inc. 'o World Trade Center New York, NY 10048	**TITLE** Osmotic Pressure Energy Converter
SUBCONTRACTOR(S) InterTechnology/Solar Corp.	**CONTRACT NUMBER** DE-AC05-79-ET-21001
PRINCIPAL INVESTIGATOR **NAME:** S. J. Senatore **PHONE:** (212) 839-3387	**PERIOD OF PERFORMANCE** January 1, 1979 to September 30, 1980 **FISCAL YEAR 1980 FUNDING** $0
WORK LOCATION New York, NY	**CUMULATIVE FUNDING** $299,508
CONTRACT FIELD OFFICE Oak Ridge Operations Office Oak Ridge, TN	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** E. H. Kinelski, DOE Headquarters

SUMMARY

The objective of this study is to develop the preliminary design for a 50 KW osmotic power generating unit based on a site selected in the U.S. and to develop cost estimates for its design, construction, operation and maintenance.

The study was conducted in two phases. Phase I provided preliminary designs of the semi-closed cycle using saturated brine and brackish water or saturated brine and sea water. Both systems required large evaporation ponds for disposal of brine effluents and recovery of salt. The open cycle system using sea water and river water required 4,500,000 sq. ft. of membrane area per net electrical kilowatt and was considered economically not feasible. Based on Phase I findings, it was determined that Phase II should study only the closed cycle system using a saturated stratified solar pond for collection and unmixing of the salt solutions.

By comparison, the stratified solar pond was approximately 1/10 the size of the evaporation pond. Potassium alum, with desirable osmotic pressure characteristics, was the preferred salt because of its wide variations in solubility and density with changes in solution temperature. Capital costs for a 1-MW osmotic power plant were $3075/KW when the stratified solar pond was not lined and located near a natural salt deposit where the cost of the salt would not be a factor. If the location of the plant required lining of the pond and purchase of the salt, the capital cost increased to $22,300/KW. It was also determined that membrane research was necessary to develop membrane performance characteristics acceptable for osmotic applications.

BIBLIOGRAPHY REF NO: 426 through 427

426. Ebasco Services, Incorporated, "Preliminary Design of an Osmotic-Type Salinity Gradient Energy Converter, Phase I", April 30, 1979.

427. Ebasco Services, Incorporated, "Preliminary Design of an Osmotic-Type Salinity Gradient Energy Converter, Phase II", September 1980.

PROGRAM ELEMENT: Related Ocean Energy Technology
SUBELEMENT: Salinity Gradient Energy

PRIME CONTRACTOR AND ADDRESS	TITLE
· ·erTechnology/Solar Corporation ꞁ Main Street Warrenton, VA 22186	Salinity Power Heat Engine - 100 Watts Heat Engine
SUBCONTRACTOR(S) Ben Gurion University, Israel	**CONTRACT NUMBER** OLD = EG-77-C-05-5560 NEW = DE-AC05-78ET20471
PRINCIPAL INVESTIGATOR NAME: Gurmukh D. Mehta PHONE: (703) 347-7900	**PERIOD OF PERFORMANCE** August 15, 1978 to September 30, 1980 **FISCAL YEAR 1980 FUNDING** $0
WORK LOCATION Warrenton, VA	**CUMULATIVE FUNDING** $126,771
CONTRACT FIELD OFFICE Oak Ridge Operations Office Oak Ridge, TN	**GOVERNMENT TECHNICAL REPRESENTATIVE AND ADDRESS** E. H. Kinelski, DOE Headquarters

SUMMARY

The objective of this study is to develop a 100 w dialytic battery unit coupled to a stratified pond for recovery and recycle of saturated solutions. The concept of a stratified solar pond has been examined with a simulated bottom heated mini-pond in the laboratory.

Using a borax solution, stratification in the pond was maintained for several days with a temperature difference of 34 degrees F between bottom and top layers. Other salt solutions, especially potassium nitrate, have been found acceptable because their saturation concentrations and solution densities increase rapidly with temperature increases. The stratified solar pond recovers and recycles brine solutions and enhances use of a closed cycle system for either dialytic or osmotic power units.

The subcontract with Ben Gurion University for the membrane stack to be used with the 100 w dialytic battery unit was not awarded because of their request for additional funds and time to make delivery. Ben Gurion University was to provide a stack with 48 m^2 of membrane area consisting of membranes with desired low electrical resistance and very thin dilute solution spacers. These stack characteristics are currently not available in the U.S. An interim report was prepared and remaining effort in the contract was directed to developing the operational feasibility of the stratified solar pond using potassium alum as the solution. A laboratory 2'x4'x3' pond was fabricated and heated from the bottom by electrical tapes. The pond was filled with potassium alum solution and after stratification the unmixing tests were performed. Dilute solution was withdrawn from the top layer of the pond and concentrated solution from the bottom layer. The solutions were externally mixed and returned to the middle layer of the pond. The continuous unmixing test was conducted for 22 days with no significant change in concentration-temperature profile of the pond contents.

BIBLIOGRAPHY REF NO: 428 through 432

428. InterTechnology/Solar Corporation, "Reverse Electrodialysis Systems for Salinity Power Systems Using a Stratified Saturated Solar Pond", February 22, 1980.

429. Jain, S.C., Mehta, G.D., "Laboratory Demonstration of Self-Creation, Self-Maintenance and Self-Correction of Saturated Solar Ponds", Presented at the Fifteenth Intersociety Energy Conversion Engineering Conference, August 18-22, 1980, Seattle, WA.

430. Loebs, Mehta, G.D., "A Two-Coefficient Water Transport Equation for Pressure-Retarded Osmosis", 1979, Journal of Membrane Science, Volume 4, pages 351-362.

431. Mehta, G.D., Loebs, "Internal Polarization in the Porous Substructure of a Semipermeable Membrane Under Pressure - Retarded Osmosis", 1978, Journal of Membrane Science, Volume 4, pages 261-265.

432. Mehta, G.D., Loebs, "Performance of Permasip B-9 and B-10 Membranes in Various Osmotic Regions and at High Osmotic Pressures", 1979, Journal of Membrane Science, Volume 4, pages 335-349.

Document Control Page	1. SERI Report No. TR-634-1011	2. NTIS Accession No.	3. Recipient's Accession No.

4. Title and Subtitle Ocean Energy Conversion Systems Annual Research Report	5. Publication Date March 1981 6.
7. Author(s) Benjamin Shelpuk, Peter H. Davidoff, David Johnson, John B. Miles, Terry R. Penney	8. Performing Organization Rept. No.
9. Performing Organization Name and Address Solar Energy Research Institute 1617 Cole Boulevard Golden, Colorado 80401	10. Project/Task/Work Unit No. 1113.00 and 1115.00 11. Contract (C) or Grant (G) No. (C) (G)
12. Sponsoring Organization Name and Address	13. Type of Report & Period Covered Technical Report 14.

15. Supplementary Notes

16. Abstract (Limit: 200 words) The major R&D effort of the U.S. Ocean Energy Program is to evaluate alternative power cycle concepts and develop those that show potential for delivering power in a cost-effective and environmentally acceptable fashion. Concepts are classified according to the ocean energy resource: thermal, waves, currents, and salinity gradient. Research projects have been funded and reported in each of these areas. The lift of seawater entrained in a vertical steam flow can provide potential energy for a conventional hydraulic turbine conversion system. Quantification of the process and assessment of potential costs must be completed to support concept evaluation. Exploratory development is being completed in thermoelectricity and 2-phase nozzles for other thermal concepts. Wave energy concepts are being evaluated by analysis and model testing with present emphasis on pneumatic turbines and wave focussing. Likewise, several conversion approaches to ocean current energy are being evaluated. The use of salinity resources requires further research in membranes or the development of membraneless processes. Using the thermal resource in a Claude cycle process as a power converter is promising, and a program of R&D and subsystem development has been initated to provide confirmation of the preliminary conclusion.

17. Document Analysis

a. Descriptors Hydraulic Turbines ; Ocean Thermal Energy Conversion:T1 ; Pneumatics; Research Programs:Q1 ; Salinity Gradients ; Thermal Conduction ; Thermoelectricity ; Thermoelectric Conversion ; Water Currents ; Wave Energy Converters ; Wave Power ;

b. Identifiers/Open-Ended Terms Conversion ; Currents ; Direct Energy Conversion ; Electricity ; Energy Conversion ; Energy Sources ; Energy Transfer ; Fluid Mechanics ; Heat Transfer ; Mechanics ; Renewable Energy Sources ; Solar Energy Conversion ; Turbines ; Turbomachinery

c. UC Categories 64

18. Availability Statement National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, Virginia 22161	19. No. of Pages 194 20. Price $9.00

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