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Quarterly Report

OCEAN ENERGY SYSTEMS

at The Johns Hopkins University Applied Physics Laboratory

OCTOBER — DECEMBER 1982

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THE JOHNS HOPKINS UNIVERSITY ■ APPLIED PHYSICS LABORATORY

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FOREWORD

The Applied Physics Laboratory issues the *Quarterly Report* series to provide the defense establishment and the scientific community with current awareness of selected APL activities. At present, the *Quarterly* consists of the following volumes:

Programs	Report Designators
Department of Defense Programs	
Research and Development	RQR
Exploratory Development for Missile Propulsion	DQR
Civil Programs	
Ocean Energy Systems	OQR
Biomedical Research, Development, and Engineering (Annual Report)	MQR

The nomenclature for the APL *Quarterly Report* is as follows. The designation for *Quarterly Report*, "QR," is preceded in each case by a letter that indicates the volume's program area. After the "QR," a virgule is followed by a year indicator (e.g., "82-") and a number from 1 to 4 to specify the calendar quarter.

The format is designed so that most technical articles can be presented on a single sheet of paper. Each article is given a section number (e.g., §24), which applies to the current *Quarterly* only. Each article is keyed to its major program area (e.g., Research and Exploratory Development), its technical instruction (e.g., Amorphous Semiconductors), its budget code (e.g., A3), the Laboratory Group or Groups that performed the work (e.g., BBE), and the agency that supported it (e.g., SEA-62R).

Certain Laboratory programs, including some that report a portion of their activities through the *Quarterly Report*, use document series other than the *Quarterly* to report the bulk of their activities. Those series are available only to individuals and organizations that are directly concerned with the specific programs involved.

Requests for *Quarterly Reports* should be directed to: Supervisor, Technical Publications Group, Applied Physics Laboratory, Johns Hopkins Road, Laurel, Maryland 20707.

PREFACE

The Johns Hopkins University Applied Physics Laboratory, under a contract with the U.S. Department of Energy's Division of Ocean Energy Technology (DOE/DOET), is engaged in developing Ocean Thermal Energy Conversion (OTEC) systems that will provide synthetic fuels (e.g., methanol), energy-intensive products such as ammonia (for fertilizers and chemicals), and aluminum. The work also includes assessment and design concepts for hybrid plants, such as geothermal-OTEC (GEOTEC) plants. APL has been designated the Lead Laboratory in these areas by DOE/DOET. Another effort that began in the spring of 1982 is a technical advisory role to DOE with respect to their management of the conceptual design activity of the two industry teams that are designing offshore OTEC pilot plants that could deliver power to Oahu, Hawaii. In addition, the Laboratory is now taking part in a program in which tests of a different kind of ocean-energy device, a turbine that is air-driven as a result of wave action in a chamber, are being planned. This *Quarterly Report* summarizes the work on the various tasks as of 31 December 1982.

TABLE OF CONTENTS

OCEAN THERMAL ENERGY CONVERSION

§1	OTEC Pilot Plant Conceptual Design Review.....	9
§2	OTEC Methanol.....	13
§3	Financial and Legal Considerations in OTEC Implementation	19
§4	GEOTEC Plant Investigations	25
§5	Supervision of Testing of Pneumatic Wave Energy Conversion System	29

OTEC PILOT PLANT CONCEPTUAL DESIGN REVIEW

The Department of Energy, Division of Ocean Energy Technology (DOE/DOET) awarded two contracts for conceptual designs of OTEC-40 MW pilot plants, both at Kahe Point, Hawaii. An OTEC Pilot Plant Program Management Office has been set up with C. Castellano as Program Manager. The Energy Technology Engineering Center (ETEC) of Rockwell International is the Technical Support Contractor providing management and coordination support. APL has been designated as a Technical Advisory Laboratory, in addition to the National Oceanic and Atmospheric Administration (NOAA), Lawrence Berkeley Laboratory (LBL), and Argonne National Laboratory (ANL). The working group, formed from these organizations, monitors the progress on the two contracts, with APL a participating member of the group.

SUMMARY

The two design contractors – Ocean Thermal Corporation (OTC) and the General Electric Company (GE) – continued to build up from their slow start (Ref. 1), and development progress in each of the designs during the quarter was evident. Design report deliverables, which were reviewed and on which comments were furnished by APL, are listed in Table 1. The GE consortium deliverables generally were received later than those from OTC, although design completion dates and Phase II proposal delivery dates remain unchanged. GE interim deliverables received and reviewed in December 1982 paralleled those listed in the OTC column of Table 1 for November.

APL participated in program management and design review meetings including: Phase II Preliminary Design, Statement of Work Development on October 6; Preparatory and DOE Response Coordination Meeting

Table 1

Order of deliverables for OTEC pilot plant project.

Order No.	Item No.	Description	APL Review Response	
			GE	OTC
1	7a	Initial report, Site Description	7-12-82	6-18-82
2	2a	Initial set, Design and Operational Data Sets	—	—
3	9a	Initial report, Cost Assessment	8-17-82	7-26-82
4	15a	Initial report, Preliminary System Interface Integration Criteria	10-15-82	7-26-82
5	3a	Interim report, Site Specific EA (Environmental Assessment)	—	—
6	5a	Initial plan, Required Permits and Licenses	—	—
7	6b	Interim report, Preliminary Safety Analysis Report	9-13-82	—
8	11a	Initial report, Operation and Maintenance Plan	9-13-82	—
9	12a	Initial report, Commercialization Plan	10-22-82	9-7-82
10	2b	Interim report, Design and Operational Data Sets	—	—
11	3b	Interim report, Site Specific EA	—	—
12	1b	Interim report, Conceptual Design of OTEC Concept	—	11-29-82
13	2c	Draft Final Report, Design and Operational Data Sets	—	—
14	7b	Interim report, Site Description	—	—
15	8b	Initial report, Risk Analysis	—	11-29-82
16	9b	Interim report, Cost Assessment	—	11-29-82
17	11b	Interim report, Operational and Maintenance Plan	—	11-29-82
18	12b	Interim report, Commercialization Plan	—	11-29-82
19	13b	Interim report, Preliminary Test Plan Long Lead Item List	—	11-29-82
20	15b	Interim report, Preliminary System Interface Integration Criteria	—	11-29-82

Table 1
Order of deliverables for OTEC pilot plant project. (Continued)

Order No.	Item No.	Description	APL Review Response	
			GE	OTC
21	3d	Final report, Site Specific EA		
22	4b	Interim report, Plan Site/Design Specific EIS (Environmental Impact Statement)		12-8-82
23	10b	Interim Report, Physical Model Test Plan		
24	1c	Draft final report, Conceptual Design of OTEC Concept		
25	4c	Draft final report, Plan Site/Design Specific EIS		
26	6d	Final report, Preliminary Safety Analysis Report		
27	7c	Draft final report, Site Description		
28	8c	Draft final report, Risk Analysis		
29	9c	Draft final report, Cost Assessment		
30	10c	Draft final report, Physical Model Test Plan		
31	11c	Draft final report, Operation and Maintenance Plan		
32	12c	Draft final report, Commercialization Plan		
33	13c	Draft final report, Preliminary Test Plan and Long Lead Item List		
34	15c	Draft final report, Preliminary System Interface Integration Criteria		
35	14a	Initial report, Technology Transfer Plan		
36	1d	Final report, Conceptual Design of OTEC Concept		
37	2d	Final report, Design and Operational Data Sets		
38	4d	Final report, Plan Site/Design Specified EIS		
39	7d	Final report, Site Description		
40	8d	Final report, Risk Analysis		
41	9d	Final report, Cost Assessment		
42	10d	Final report, Physical Model Test Plan		
43	11d	Final report, Operational and Maintenance Plan		
44	12d	Final report, Commercialization Plan		
45	13d	Final report, Preliminary Test Plan and Long Lead Item List		
46	14d	Final report, Technology Transfer Plan		
47	15d	Final report, Preliminary System Interface Integration Criteria		

prior to the GE Initial Design Review on October 26; and a similar meeting held prior to the OTC Interim Design Review on December 8. The GE Initial Design Review Meeting was held in Los Angeles, on October 27-28, and the OTC Interim Design Review Meeting was held in Los Angeles on December 9-10.

DISCUSSION

The confidentiality requirements of the design review process still restrict discussion of details of either design outside the working group. APL reviews of the design submissions have resulted in comments, suggested design modifications, and whether further analyses are required.

Fig. 1 General Electric Kahe OTEC pilot plant concept. (82-4/52)

Fig. 2 General arrangement of Ocean Thermal Corporation's 40-MWe plant concept (courtesy J. Yaffo of OTC). (82-4/53)

The developing designs by each of the contractors have, in general, followed the original concepts described in Ref. 2. The GE concept for a shelf-mounted tower at a depth of 100 m is shown in Fig. 1. The main change has been the selection of ammonia as the working fluid following comparative analyses and the choice of a single 60-MWe gross turbine generator. The level of effort has been impressive, but significant questions remain to be resolved.

The original OTC island plant concept, shown in Fig. 2, has been changed. Water depth is now 15m, and the plant is located 460m offshore. Warm surface water is drawn from the shore side with the discharged (heated) cooling water from the Hawaiian Electric Company's Kahe generation plant. Two effluent pipes discharge the mixed warm and cold water toward the shelf break. Major changes have been made in the design shown in Fig. 2, and significant questions remain to be resolved.

The draft of the final reports—effectively the Conceptual Design Final (9 month) Review Documents—are due by February 17, 1983, and contractor proposals for the Phase II, Preliminary Designs are due on February 28, 1983.

FUTURE PLANS

APL support of the OTEC Pilot Plant Program is anticipated to continue at the present 1.1 to 1.2 man per month level through Phase II. Funding for this activity, and for a somewhat lower level if only one Phase II contract award is made, has been proposed to DOE.

REFERENCES

1. Section 1, *Quarterly Report, Jul-Sep 1982*, JHU/APL OQR/82-3.
2. Section 1, *Quarterly Report, Jan-Mar 1982*, JHU/APL OQR/82-1.

 

OTEC METHANOL

The use of slowly cruising plantships to produce synfuels and energy-intensive products makes the tropical oceans a virtually unlimited, renewable resource for world energy needs. Conversion of only 0.05% of the heat absorbed in the waters at the ocean's surface to chemical energy would supply fuel equivalent to the 1980 world oil consumption. The present program is part of a broad effort to identify and prioritize OTEC products and processes that could have significant effects on U.S. oil imports and electric power requirements in the 1990's and beyond. OTEC methanol is a particularly attractive candidate fuel because it can replace gasoline as a motor fuel and is the preferred fuel for high-efficiency fuel cells for power generation. In both applications, preliminary analysis indicates that costs will be comparable to (or possibly below) those projected for alternative energy sources.

SUMMARY

A study has been made of the space requirements and potential output of a 160 MW OTEC methanol plantship, based on a design by Brown and Root Development, Inc. (BARDI) described in a previous *Quarterly Report* (Ref. 1), but with the Texaco gasifier replaced by a molten carbonate gasifier designed by Rockwell International. The higher efficiency of the Rockwell gasifier and its use of pulverized dry coal instead of coal slurry increase the estimated methanol output of the plantship from 1000 to 1450 metric tons/day (mt/day). Preliminary estimates of the cost of methanol delivered to a U.S. port from this plantship are in the range of \$0.45 to \$0.60 per gallon. OTEC methanol would compete favorably with methanol from other sources at this cost and would give a lower cost per mile for automobile transportation than unleaded gasoline at present gasoline costs.

The encouraging results of the study have led to a decision to fund a small engineering contract to define the component requirements, layout, methanol output, and estimated costs of the process using the Rockwell system. Results of the study will be available in mid-summer of 1983.

BACKGROUND AND DISCUSSION

Results of an engineering study of an OTEC methanol plantship design conducted by BARDI under an APL subcontract were presented in Ref. 1. The process requirements, output, and costs were defined for a plantship designed to use the hydrogen and oxygen produced by on-board electrolysis of water for production of methanol from a coal-water slurry via the Texaco

gasification process and using a Lurgi methanol synthesis reactor design.

A presentation of the BARDI study was held at APL on September 29, 1982, for DOE and APL review. The limited scope of the study was emphasized: (a) to develop a plantship design concept using available components and current technology to obtain accurate equipment requirements (including space and weight) integrated with the OTEC power and electrolysis systems, and (b) to obtain real system cost estimates.

The data developed by the BARDI work enable an evaluation of the processes and economics on which further development and process optimization can be based, and from which real life commercial development scenarios and costs may be established.

Review comments by DOE and APL were subsequently incorporated in the final BARDI report, work on which was essentially completed by October 25, 1982. A BARDI artist's rendering of the final plantship concept arrangement was commissioned (Fig. 1) to be used in a joint APL-BARDI presentation to a larger audience consisting of DOE personnel and the DOE-OTEC support contractors. (The presentation was planned for December but, because of scheduling problems was held on January 19, 1983).

The BARDI study resulted in a 1000 mt/day methanol process plant occupying a 275-ft-long section at the center of the plantship with two 80 MWe OTEC power systems on either side (fore and aft), each with a (nominal) 40-ft-diameter cold-water pipe (CWP). The electrolysis systems supplying oxygen for coal gasification and hydrogen are packaged inboard of each CWP within the OTEC power system limits (Fig. 2). Crew accommodations, bridge, main propulsion diesel generators (non-OTEC operation), ships' auxiliaries, and controls are forward, and product/feedstock transfer aft, as described in Ref. 1. The resulting 1000 mt/day 160 MW plantship is 900 ft long, 355 ft wide, and 92 ft deep (65 ft operating draft) with the beam defined by the (APL) CWP and OTEC power system design requirements. Warm water pump sponsons added in the outfitting phase add 35 ft to the overall beam width.

This plantship concept was developed from earlier APL studies and concepts for 325 to 360 MWe OTEC plantships for hydrogen, ammonia, and/or methanol via liquid CO₂ supply production (Refs. 2 and 3). For each of these processes, the product plants (electrolysis and hydrogen liquefaction and storage for hydrogen; electrolysis, air separation, ammonia synthesis, and storage for ammonia; and electrolysis, CO₂ storage and vaporization, and methanol synthesis and storage for methanol) could be packaged with relative ease within the available volumes and platform configuration defined by the OTEC power systems. It was recognized that OTEC methanol-from-coal feedstock via typical coal gasification systems would require additional dedicated platform space and greater integration complexity than the methanol-from-liquid-CO₂ process, but increased product volume per megawatt and lower costs warranted detailed investigation.

Fig. 1 Artist's concept of 160 MW, 1000 mt/day OTEC methanol plantship as defined by the BARDI Investigation. (82-4/44)

P & S = port and starboard

Fig. 2 Layout of one of two 80 MWe electrolyzers located in-board of each CWP. (82-4/45)

PLANTSHIP NAVAL ARCHITECTURE (BARDI)

Initial BARDI plantship studies on a 325-MW, 2000 mt/day two-train process plant concept, based on prior

APL studies, indicated that construction of the plantship appeared impractical because of size limitations in existing shipyard facilities and because of launch and outfitting draft requirements. A decision to reduce the plant size to a single (nominal) 1000 mt/day process train led to the dimensions shown in Table 1.

The design of the plantship is based on developments within the existing technology of floating industrial plants and has incorporated safety aspects and reliability considerations common to vessels of this type. Among the special conditions required for these vessels are

1. Collision bulkheads,
2. Separation by void or ballast tanks of product and raw material storage from the remainder of the ship,
3. Zero discharge systems,
4. Increased ventilation of product pumping rooms,
5. Laboratory and control room requirements, and
6. Increased auxiliary machinery capacity for standby operation.

The conceptual arrangement shows a block spacing of the methanol plant with a minimum maintenance planform. Maintenance service is effected by local bridge cranes (OTEC turbine hulls, process plant compressor house), local monorails, and crawler cranes as shown in Fig. 1. Deck area-ways are provided so that the crawler cranes (Manitowoc 3900 or equal) can service all requirements for heavy lift on the plantship. It is noteworthy that the planform of the plant determines the overall length of the ship and not the process storage requirements, which have been defined from a 28-day cycle with a 2-day variance.

The displacement of the vessel is approximately 506,000 LT at a draft of 65 ft. The draft at launch with closed heat exchanger wells would be 34.5 ft. Ballast requirements are met with bow and stern tanks and double-bottom tanks below the process plant. Additional ballast can be placed throughout the vessel to achieve proper trim.

Powering requirements and wave motion data were developed; it has been shown that the vessel can operate in the 18 ft significant-wave-height sea (predicted for approximately 30 h/yr). Maximum motions in the survival sea state will produce bow immersion 40 times during a 30 min period, with a maximum of 8.9 ft at the bow on centerline in a head sea. This depth of green water will be dispersed by a specialized wave-dampening fairwater design. Preliminary powering requirements using ducted thrusters in close proximity to flat hull surfaces indicate that an installed capacity of 15,000 hp is required to keep the vessel in motion at 0.5 kt against a 25 kt wind; this power requirement does not include the effects of waves. Detailed analyses, including survival requirements to maintain heading, have not been made. Also, while analysis of the motions, loads, and stresses of the two 40-ft-dia, off-center CWP's could not be included in this limited study, it is assumed that they would not be greater than those of the 30-ft-dia CWP for the 40 MW pilot plant design because of the reduced motions of this much larger platform.

For the accommodations block, a ship-type manning was assumed, and a minimum manning for the OTEC

plant and the methanol plant was developed. Accommodations for 110 people including visitors were provided, and the superstructure was designed to house them. Hotel loads of 2.2 MW electrical load and a 300 ton cooling load were estimated.

Table 1

Principal dimensions for ammonia pilot plantships and for OTEC-methanol plantships using the BARDI process.

	40 MW Pilot Plantship (ammonia)	335 MW Plantship (methanol)	160 MW Plantship (methanol)
Overall length (ft)	453	1650	900
Beam molded (ft)	140	400	355
Over pump wells (ft)	178	435	390
Depth (ft)	89	105	92
Operating draft (ft)	65	65	65
OTEC capacity (MW)	40	325	160
Methanol capacity (mt/day)	—	2000	1000

BARDI PROCESS DESIGN

A block diagram of the BARDI process (shown in Fig. 3) is taken from the final report. The report also includes detailed process flow sheets, equipment sizing, weights, plant layout, and cost estimates. BARDI's cost estimate for the onboard process plant (including contingency) is \$161.4 million. The plant would produce 1000 mt/day of fuel grade, 98% methanol from 750 mt/day of coal shipped as a slurry. As noted earlier, coal slurry would be supplied; waste water and slag would be removed for on-land treatment on a 28-day cycle. The methanol product would be removed, and process chemicals and other needs would be supplied on a similar interleaved cycle. While BARDI provided design data and costs for the land-based coal preparation processes, our estimates have included these costs as part of the per-ton supply and transport costs—on the basis that a probable scenario would include dedicated land facilities servicing a multiple plantship fleet.

PROCESS OPTIMIZATION

The BARDI study defined an area for the methanol plant that occupies a 275-ft-long section at the center of the ship. Approximately one-half of this area is assigned in the Texaco gasification process to the equipment for acid gas removal by the Selexol process and for sulfur

Fig. 3 Block diagram of OTEC coal-to-methanol process. (82-4/46)

Fig. 4 OTEC methanol process, fuel utilization. (82-4/47)

recovery by the Stratford process. A preliminary examination indicates that this space could be reduced considerably if the new type of gasifier developed by Rockwell International were used instead of the Texaco process. The Rockwell gasifier offers a significantly improved process efficiency and hence lower costs. Figure 4 indicates the flow rates: the coal fixed rate is increased from 750 to 1210 mt/day, and the methanol production from 1000 to 1450 mt/day, compared to the aforementioned BARDI process design. Figure 5 is a flow diagram of the Rockwell process. In brief, pulverized coal (1/4-in. mesh) is injected along with oxygen and steam at the bottom of a reaction vessel containing molten sodium carbonate at a temperature of 1800 to 1900°F. In the vigorously stirred melt, the coal reacts rapidly to produce a gas consisting of CO and H₂ with about 5% by volume of carbon dioxide and traces of sulfur and nitrogen. The ash in the coal dissolves in the melt, and the sulfur reacts with the melt to form sodium sulfide, trapping almost all of the sulfur. The melt is continuously recycled by allowing a small overflow at the surface, which is processed to remove sulfur and ash and regenerate sodium carbonate, and then is reinjected. Water quenching

of the hot melt causes the dissolved sulfide to be liberated as H₂S in a low-volume gas stream that is easily handled by a relatively small Claus unit to recover the sulfur as a commercial product.

Since it appears from this preliminary examination of the Rockwell process that the output will be greater and the equipment cost lower than for the Texaco process, a more thorough study of the system is desirable. Therefore, a decision has been made to extend the date for completion of the energy products work until a plant layout and cost estimate can be completed. Data from a DOE-supported 1 ton/h pilot plant operation of the Rockwell process (Ref. 4) give the estimated flow rates for the 160 MW plant shown in Fig. 3. The methanol plantship investment has been estimated using an in-house Rockwell study of a 40 billion Btu/day gasifier in combination with data from the BARDI study to be approximately \$550 M, or \$710 M with 30% contingency. With appropriate financing as proposed in Ref. 5 and estimated operating and shipping costs, the indicated delivered cost of methanol is \$0.45/ to \$0.58/gal. Details of the process studies and cost estimates will be presented in the next *Quarterly Report*.

R - Rockwell
E - EBAASCO

Fig. 5 Flowchart for OTEC methanol plantship with Rockwell gasifier. (82-4/48)

REFERENCES

1. Section 2, *Quarterly Report, Jul-Sep 1982*, JHU/APL OQR/82-3.
2. G. L. Dugger, R. W. Henderson, E. J. Francis, and W. H. Avery, "Projected Costs for Electricity and Products from OTEC Facilities and Plantships," presented at IECEC '80, "Energy to the 21st Century," Seattle (18-22 Aug 1980); also in *J. Energy* 5, 231-236 (1981).
3. D. Richards, E. J. Francis, and G. L. Dugger, "Conceptual Designs for Commercial OTEC-Ammonia Product Plant-

ships," presented at 3rd Miami International Conf. on Alternative Energy Sources, Miami Beach (15-17 Dec 1980).

4. *Molten Salt Coal Gasification, Process Development Unit Phase I*, Rockwell International, Environmental and Energy Systems Group, Canoga Park, Calif., final report, SAN-10296-66 (corr. Apr 1982).
5. *Projected Costs of Electricity from Nuclear and Coal-Fired Plants*, Energy Information Agency, DOE, DOE/EIA-3056/1 (Aug 1982).

FINANCIAL AND LEGAL CONSIDERATIONS IN OTEC IMPLEMENTATION

In recent years, technical development and engineering design studies have concluded that commercial OTEC plants and plantships will produce electric power and energy products at costs competitive with or lower than those for plants based on fossil fuel or nuclear power. However, suitable financial structures and legal and institutional mechanisms must be developed before industry will be able to proceed with the construction and operation of OTEC systems. The work being done in this part of the APL program has the objectives of (a) defining the economic requirements for OTEC financing and (b) indicating procedures that will facilitate early growth of U.S. industrial capability to produce OTEC plants and plantships in numbers large enough to make significant contributions to U.S. energy needs in the 1990's.

SUMMARY

Work during the quarter has included additional discussions with senior corporate management to evaluate OTEC as a capital-intensive venture and has defined the willingness of the insurance industry to underwrite OTEC risks. Additional effort has been given to updating the status of OTEC projects, assessing the effects of the 1982 tax act and potential OTEC-related legislation, and determining the availability and adequacy of OTEC construction sites. Activities have included discussions with OTEC researchers, the two OTEC Pilot Plant Program teams, Maryland industry and Baltimore City officials, and the marine industry through participation in the Industrial Plant Vessel Seminar sponsored by the Shipbuilders Council of America and the U.S. Maritime Administration.

MANAGEMENT CONSIDERATIONS IN EVALUATION OF OTEC VENTURES

Management decisions continue to be the critical factor. Technical development and testing and financial analysis continue to show that OTEC construction and deployment are feasible and offer an attractive business opportunity. Management decisions in the United States not only continue to be difficult but are perceived as being less urgent now than a year ago because of a glut (probably temporary) in oil and natural gas supplies and consequent oil price reductions. Saudi Arabian production of oil has been cut back to about half that country's capacity. U.S. crude oil imports from all sources for the first 10 months of 1982 are down to 52% of their 1977 peak (Ref. 1). Oil prices in August 1982 were down 8%,

with the average cost to steam electric at \$4.59 per million Btu compared with \$4.94 a year earlier. Natural gas production during the first 10 months of 1982 was 7.6% lower than in the comparable period in 1981, while consumption was 5.6% lower (Ref. 1). The average cost of natural gas delivered to steam electric plants, however, was up in August 1982 to \$3.56 per million Btu, 22% above the previous year's cost (Ref. 1).

Interest rates are down on quality long-term bonds to about 12%, although long-term financial markets remain limited for large financing projects (Ref. 2). The lack of new projects continues to indicate flexibility on the part of insurance companies in their ability and willingness to underwrite risks. As discussed below, it is now apparent that insurance coverage for the design risk and tax credits recovery risk for an OTEC project is available at a reasonable cost, thus reducing the risk of a new OTEC project essentially to that of any other large-scale new construction project. Special considerations, such as the availability of the 15% business energy investment credit provided by the Windfall Profits Tax Act, continue to create a special situation for OTEC construction, which may be of interest to management because of the tax advantages and the resulting large positive early years' cash flow. However, the need to extend the current December 31, 1985, expiration date for these credits is becoming imperative. APL contacts and discussions with key management officials have not led to any additional specific understanding of what other roadblocks remain. For the shipbuilding industry, comments made during the October 1982 Industrial Plant Vessel Seminar generally indicated that the industry is presently too depressed to take the lead in OTEC projects.

INSURANCE INDUSTRY UNDERWRITING

In early 1982, it became apparent that industry executives perceived the first OTEC large-scale demonstration vessels to be high-risk undertakings, primarily in those areas where industry had no specific related experience. As a method for reducing these risks to manageable levels, the insurance industry was requested to provide coverage for the design risk and for the risk of tax credits recapture in the event of OTEC vessel shutdown or performance reduction below acceptable levels during the first five years of operation.

The insurance industry has responded favorably with coverage available through at least two sources (Refs. 3 and 4). The Alexander and Alexander "broker's indication" is for an insurance premium for normal risks, design risks, and tax-credits-recovery risks coverage of approximately 3% of plant investment during construction and 2.3, 1.9, and 1.7% per year, respectively, of

plant investment during the first three years of operations. Details of the type of coverage provided were included in Ref. 5. Complete details of the coverages and estimated exposure related to the specific quotation are available from APL (Refs. 6 and 7). Exhibits 1 and 2 are examples of the coverages available for case 1 (see the discussion under Profit Potential).

Because insurance can now be obtained at a reasonable cost to cover the risk that (a) the plant will not operate if built to specifications and (b) performance during the first five years will maintain at least minimum levels, it is the opinion of the author that the risks to be borne by private financiers of an OTEC venture have been reduced to a level equivalent to those for other one-third to one-half-billion dollar construction projects.

PROFIT POTENTIAL

Assuming that a large-scale OTEC demonstration vessel can be built and that investment tax credits, business energy investment credits, and 87.5% Title XI bond financing can be obtained, the profit potential for a privately financed OTEC venture is dependent on the

take-and-pay or take-or-pay contract for the product and on the actual construction costs.

Table 1 is a summary of financial statistics for a series of OTEC vessel project cases, which indicate that even the first OTEC demonstration vessel could be a profitable, privately financed venture, given the variety of assumptions used. The top 10 cases in Table 1 are for a conservative scenario in which major component replacements are made in operating years 10, 15, and 20. The bottom 11 cases are for similar cases that include the "broker's indication" of insurance costs for normal risks, design risk, and tax-credits-recapture risk coverage.

For example, case 1 (see Exhibits 1 and 2) is for an OTEC vessel that would deliver an average of 51.4 MW of OTEC-produced electric power by cable to the Puerto Rico Electric Power Authority (PREPA) grid. The construction cost is estimated at \$450.6 million (December 1985 dollars), the combined investment tax credits and business energy investment credits are assumed to average 22.5% of construction costs, the tax credit reduction factor is assumed to reduce the depreciable base to 87.5% of plant investment, various selling prices for delivered power in December 1986 are

Exhibit 1 OTEC-utility joint venture, backup cash flow projections as of November 19, 1982.
Case 1: OTEC cost projections for Puerto Rico; 51.4 MW delivery, 330 days/yr operations (1980 dollars).

CAC	Transfer and distribution costs included (mills/kWh)	0.000	FYPF	First year production factor (%)	65.000
SCPST	Customer billing and collection included (mills/kWh)	0.000	PPD	Percent private debt	87.500
CC	Construction costs (M\$)	227.300	PGF	Percent government financed	0.000
ASP	Power selling price (mills/kWh)	77.993	BF	Brokerage fees (%)	0.800
BCSC	Boat charter, stevedore cost (\$)	10000.000	XIIF	Title XI investigation fee (%)	0.125
SCC	Ship chandler costs (\$)	25000.000	STKF	Stockbroker fee (%)	2.000
TC	Transportation costs (\$)	25000.000	TSR	Tax package sale rate (%)	100.000
MC	Miscellaneous costs (\$)	25000.000	XIAFC	Title XI annual fee, construction (%)	0.375
CPCM	Cost per crew member (\$)	40610.000	XIAF	Title XI annual fee (%)	0.750
CPI	Cost per inspector (\$)	60000.000	MGTF	Management fee, construction (%)	15.000
FPST	Final production (Mwh)	407367.000	MGTF	Management fee (%)	5.000
GFC	Auxiliary fuel costs (\$)	30000.000	TCRF	Tax credit reduction factor (%)	87.500
CPM	Cost per manager (\$)	60000.000	NI	Number of inspectors	0.0
LPGC	Logistics personnel costs	50000.000	NC	Number of crews	1.0
ATC	Air travel costs (\$)	0.000	NM	Number of general managers	5.0
SC	Stores costs (\$)	140000.000	NYC	Number of years of construction	3.0
APPF	NOAA application fee (\$)	250000.000	DY	Years of depreciation	5.0
BCC	Boat charter cost (\$)	365000.000	DR	Depreciation rate	1.5
LF	Legal fees (\$)	500000.000	NCM	Number of privately funded members/crew	30.0
IIR	Insurance rate (% of plant investment)	0.500	NYPB	Number of years for payback of Title XI bond	25.0
MMF	Factor for maintenance materials costs (% of plant investment)	1.000	WCLP	Working capital period (days)	120.0
TCF	Training cost factor (% of crew cost)	5.000	YC	Year of costs	1980
IR	Inflation rate (%)	9.000	YSO	Year of start of operation	1986
RPIR	Real price inflation rate (%)	0.000	YEO	Final year cost projections	2011
MIR	Interest rate of Title XI debt (%)	13.000	OPSUB	Operating subsidy (M\$)	0.0
STMIR	Short-term interest rate (%)	0.000	YOPS	Years that subsidy applies	8.0
PPROF	Percent profit	12.000	DTABL	Declining balance, depreciation table, if = yes	Yes
PCONT	Percent contingency	10.000	DTC	Depreciation table, last year of construction, if = yes	Yes
PITC	Investment tax credit (%)	22.500	DT(1)	First year depreciation	0.1500
PPC1	Percent private capital, year 1 construction	10.000	DT(2)	Second year depreciation	0.2200
PPC2	Percent private capital, year 2 construction	40.000	DT(3)	Third year depreciation	0.2100
FITR	Federal income tax rate (%)	46.000	DT(4)	Fourth year depreciation	0.2100
			DT(5)	Fifth year depreciation	0.2100

Table 1

Summary of financial statistics for a series of OTEC vessel projects.

Case No.	Construction Cost (M dollars)	Selling price (mills/kWh in 1985)	Start of Operation	Inflation Rate (%)	Profit (%)	Management Fee Construction (%)	NPV, Projected Cash Flow (%)		FMRR Projected Cash Flow (%)			'84-'88 Cash Flow (M dollars)
							15	10	15/15%	15/18%	10/10%	
Without Insurance costs												
1	450.6	120	12/86	9	12	15	76,748	153,174	27.114	28.909	24.133	170
2	442.5	120	12/86	9	10	10	85,451	163,693	36.598	38.584	33.224	147
3	450.6	120	1/87	9	12	15	62,585	140,253	21.277	22.904	18.353	120
4	442.5	120	1/87	9	10	10	73,042	152,844	24.115	25.784	21.061	107
5	450.6	90	12/86	9	12	15	18,421	41,720	21.557	22.667	16.506	146
6	442.5	90	12/86	9	10	10	28,462	54,362	31.414	33.001	28.124	132
7	450.6	90	1/87	9	12	15	6,057	31,208	16.048	17.267	13.335	106
8	442.5	90	1/87	9	10	10	16,230	43,766	18.488	19.780	15.637	94
9	407.5	109.4	12/86	7	12	15	58,154	101,200	27.381	29.490	23.814	154
10	407.5	70	12/86	7	12	15	-6,367	-19,239	11.588	11.798	-6.845	137
With Lloyd's Insurance												
11	450.6	120	12/86	9	12	15	64,675	138,528	24.689	26.310	21.970	147
12	442.5	120	12/86	10	10	10	74,841	151,172	28.900	30.663	25.963	133
13	450.6	120	1/87	9	12	15	52,064	127,516	19.647	21.208	16.882	105
14	442.5	120	1/87	9	10	10	62,443	140,338	21.520	23.112	18.608	93
15	450.6	90	12/86	9	12	15	7,675	29,158	17.283	17.728	13.235	132
16	442.5	90	12/86	9	10	10	17,643	41,348	22.963	23.776	16.177	120
17	450.6	90	1/87	9	12	15	-4,778	18,369	14.241	15.220	11.706	92
18	442.5	90	1/87	9	10	10	5,600	31,193	16.039	17.112	13.471	80
19	407.5	109.4	12/86	7	12	15	48,351	89,603	24.515	26.476	21.202	141
20	407.5	70	12/86	7	12	15	-12,442	-22,546	9.870	10.077	6.496	125
21	407.5	90	12/86	7	12	15	18,390	34,356	20.988	22.797	17.546	133

*The cases shown include an investment tax credit of 22.5% and a tax credit factor of 87.5% in 1985.

Exhibit 2 Proforma profit and loss and cash flow for case 1.*

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Construction costs	39529	172346	234821												0	0
Capitalized fees	1016	1206	1644												0	0
Total actual costs	40545	173552	236464												0	0
Construction payments, equity	4984	21730	29607												0	0
Sale, tax credits and losses/two	13764	60799	122650	57908	43146	39809	36268	0	0	0	0	0	54296	0	0	0
Stockbroker fees	275	1216	2453	1158	863	796	725	0	0	0	0	0	1086	0	0	0
Equity cash flow	8505	37854	90590	56750	42283	39012	35543	0	0	0	0	0	53210	0	0	0
Revenues	0	0	0	37752	63307	69004	75215	81984	89362	97405	106171	115726	113527**	137494	149869	163357
Expenses																
Operations	0	0	0	9231	10061	10967	11954	13030	14202	15481	16874	18393	178866†	21852	23819	25963
Title XI annual fee	65	416	1090	2957	2839	2720	2602	2484	2365	2247	2129	2011	1892	1774	1656	1538
Title XI interest	2635	16552	43203	51251	49201	47151	45101	43051	41001	38951	36901	34851	32801	30751	28701	26651
Insurance	0	0	0	2253	2253	2253	2253	2253	2253	2253	2253	2253	2253	2253	2253	2253
Depreciation	0	0	58629	85989	82080	82080	82080	0	0	0	0	0	0	0	0	0
Legal fees	500	500	500	0	0	0	0	0	0	0	0	0	0	0	0	0
Management fee	6082	26033	35470	1888	3165	3450	3761	4099	4468	4870	5309	5786	6307	6875	7493	8168
Total expenses	9283	43501	138891	153568	149599	148622	147751	64917	64290	63802	63465	63293	222119	63505	63922	64571
Pretax earnings	-9283	-43501	-138891	-115816	-86293	-79617	-72536	17067	25072	33603	42706	52433	-108592	73990	85947	98785
Federal income tax	0	0	0	0	0	0	0	7851	11533	15457	19645	24119	0	34035	39536	45441
Net earnings	-9283	-43501	-138891	-115816	-86293	-79617	-72536	9216	13539	18145	23061	28314	-108592	39954	46411	53344
Depreciation	0	0	58629	85989	82080	82080	82080	0	0	0	0	0	0	0	0	0
Debt repayments	0	0	0	15770	15770	15770	15770	15770	15770	15770	15770	15770	15770	15770	15770	15770
Operations cash flow	-9283	-43501	-80262	-45597	-19982	-13307	-6226	-6553	-2231	2376	7292	12544	-124362	24185	30642	37574
Total cash flow	-778	-5647	10328	11153	22301	25706	29317	-6553	-2231	2376	7292	12544	-71152	24185	30642	37574

(continued)

Exhibit 2 Continued

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Construction costs	0											
Capitalized fees	0											
Total actual costs	0											
Construction payments, equity	0											
Sale, tax credits and losses/two	0	39556	0	0	0	0	64234	0	0	0	0	0
Stockbroker fees	0	791	0	0	0	0	1285	0	0	0	0	0
Equity cash flow	0	38765	0	0	0	0	62949	0	0	0	0	0
Revenues	178058	174675**	211551	230590	251342	273962	268757**	325494	354788	386719	421523	459460
Expenses												
Operations	28299	217979†	33622	36648	39946	43541	367031§	51731	56387	61462	66994	73023
Title XI annual fee	1419	1301	1183	1064	946	828	710	591	473	355	237	118
Title XI interest	24601	22551	20500	18450	16400	14350	12300	10250	8200	6150	4100	2050
Insurance	2253	2253	2253	2253	2253	2253	2253	2253	2253	2253	2253	2253
Depreciation	0	0	0	0	0	0	0	0	0	0	0	0
Legal fees	0	0	0	0	0	0	0	0	0	0	0	0
Management fee	8903	9704	10578	11530	12567	13698	14931	16275	17739	19336	21076	22973
Total expenses	65475	253788	68136	69945	72113	74671	397225	81101	85053	89556	94659	100417
Pretax earnings	112584	-79113	143415	160645	179229	199292	-128468	244394	269735	297163	326864	359043
Federal income tax	51788	0	65971	73897	82446	91674	0	112421	124078	136695	150357	165160
Net earnings	60795	-79113	77444	86748	96784	107618	-128468	131973	145657	160468	176507	193883
Depreciation	0	0	0	0	0	0	0	0	0	0	0	0
Debt repayments	15770	15770	15770	15770	15770	15770	15770	15770	15770	15770	15770	15770
Operations cash flow	45026	-94883	61675	70979	81014	91848	-144238	116203	129888	144699	160737	178114
Total cash flow	45026	-56118	61675	70979	81014	91848	-81289	116203	129888	144699	160737	178114

*Parameters for case 1 may be found in the text.

**Reduction of revenues by 10% in replacement year.

†Replacement of heat exchanger at \$500/kWe (nominal) plus \$10M for deployment etc. (1980 \$).

††Replacement of turbines (\$6M), thrusters (\$11.4M), one-third of water pumps (\$9.7M/3), plus \$10M for transportation, deployment, etc. (1980 \$).

§Replacement of heat exchanger at \$400/kWe (nominal) plus \$10M for deployment etc. (1980 \$).

To: 1984 after 25 years of operation:

NPV at 15% = \$88,261

FMRR at 15% = 27.587%

To: 1983 after 25 years of operation:

NPV at 15% = \$76,748

NPV at 10% = \$153,174

FMRR at 15%/15% = 27.114%

FMRR at 15%/18% = 28.909%

FMRR at 10%/10% = 24.133%

assumed, the inflation rate for power selling price and variable costs is assumed to be 9% (the Title XI interest rate assumed is 4% higher than the inflation rate), and the overall profit to the general partner is assumed to be 12%, which is included in the \$450.6 million construction cost. The high-risk nature of the venture is reflected in a management fee during construction for the general partner of 15% of the project cost. There is a 5% of revenues management fee during operation; operation would begin in December 1986.

With these assumptions, the cash flow for the 28-year OTEC project is calculated to be \$77 million at a 15%/yr discount rate to 1983 or \$153 million at a 10% discount rate. The calculated financial management rate of return (FMRR) for the total cash flow for the project to 1983 using various combinations of short- and long-term reinvestment rates and a zero reinvestment threshold are 27% at 15% short term, 15% long term, and a zero reinvestment threshold (15/15/0); 29% at 15/18/0; and 24% at 10/10/0. The first five years of the project (including three construction years and the first two

operating years) provide a positive cash flow (current years dollars) to the general partner of \$160 million. Table 2 presents the data in a more expanded form for Case 1. Detailed data in the format of Table 2 are available at APL for each of the 21 cases summarized in Table 1.

Additional runs have been made reducing the number of years to pay back the Title XI loan to a more rapid schedule (e.g., from 25 to 10 years). This enables assessing the feasibility of selling the OTEC project to the utility (PREPA for the cases presented) at an early date. At the end of five years of operation, for example, the outstanding Title XI loan has been reduced from \$7670 to \$3835/kW. At the end of the eighth year of operation, the outstanding debt is \$1535/kW. If a sale were arranged at either of these points, there would be substantial supporting documentation of plant performance.

One further item of note is the identification of an available and apparently adequate site for OTEC construction at Port Covington within Baltimore, Md. In addition to rail and road access and the ready availability of supporting industry, the key element of the newly

Table 2

OTEC 5-year profit potential for case 1.*

	Discounted to 1983		1984	1985	1986	1987	1988
	15%	10%					
Total cash flow, 28 yr discount	\$76.7M	\$153.2M	-778k	-5,647k	10,328k	11,153k	22,301k
To limited partners at 30% 9-mo average	50.4	58.9					
To general partner	\$26.3M	\$94.3M					
Construction profit, 12%	34.2	38.0	4,235	18,466	25,159	--	--
Management fee, construction, 15%	48.3	53.7	6,082	26,033	35,470	--	--
Management fee operation 5%	2.6	3.3	--	--	--	1,888	3,165
Engineering profit, 30%	1.7	1.8	1,950	--	--	--	--
			11,489k	38,852k	70,957k	13,041k	25,466k
Totals to general partner	113.1M	191.1M	Cash flow		\$159,805,000*		

*Case 1 parameters may be found in the text.

identified site is adequate draft alongside the pier. The OTEC concrete barge-type vessel design calls for about 200 ft width alongside the finishing pier with a launch draft and depth to the open ocean of at least 35 ft. Earlier Baltimore area construction sites required dredging to the main Baltimore Harbor channel (42 ft depth), which made construction schedules more uncertain.

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4. Alexander and Alexander lett., to Evans J. Francis, JHU/APL, 7 Jan 1983.
5. Section 3, *Quarterly Report, Jul-Sep 1982*, JHU/APL OQR/82-3.
6. Alexander and Alexander lett., to Stuart S. Janney III of Niles, Barton and Wilmer, 4 Oct 1982.
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GEOTEC PLANT INVESTIGATIONS

For near-ocean sites where a geothermal water resource with a temperature in the 120 to 200°C range is available, a combination of geothermal and ocean thermal energy conversion (OTEC) technology (GEOTEC) including seawater cooling may be attractive as a renewable-energy resource. The leading candidate site for possible use of a GEOTEC plant at a U.S. Naval Station is the Naval Air Station at Adak Island, Alaska. This report addresses Adak and the status of cycle analysis and plant design efforts.

RESOURCE ASSESSMENT AT ADAK

As reported in Ref. 1, Adak was visited by representatives of the Naval Weapons Center (NWC), China Lake, Calif., and APL from July 27 to August 8, 1982. The various sampling and data-gathering efforts by a team from the Geothermal Utilization Division, Public Works Department, NWC, as reported by J. A. Whelan (consultant to NWC), are discussed below.

The field data from the gravity, land magnetics, and trace mercury studies were reduced to allow preliminary interpretation of information. The microseismic study on Mt. Adagdak will be reported next quarter.

The preliminary gravity results agree very well with those USGS reported in the Hoover report (Ref. 2). In general, the island is characterized by a northward dipping gravity signature with nearly 40 mGal ($40 \times 10^{-5} \text{ m/s}^2$) difference between the Finger Bay area and southern Mt. Adagdak (Fig. 1). It is likely that this defines a large east-west trending feature, such as a fault, that may act as the boundary between the solid substratum of southern Adak and the possible molten substratum of the area beneath Mt. Adagdak. There is a local unclosed gravity high emerging from the western side of Mt. Adagdak, which is probably due to remnant rocks of the eroded Andrew Volcano. However, since the aerial extent of the high contains the Adagdak hot springs, it also seems possible that this high may be the gravity signature of a geothermal reservoir.

Preliminary land magnetics disclosed numerous highs thought to define near-surface cooled intrusion on northern Adak, as well as several lows associated with the local fill area near the present airfield (Fig. 2). However, there is not enough data near Mt. Adagdak to delineate completely magnetic lows caused by any elevated subsurface temperatures.

The trace-mercury study delineated lows near the airfield, the communication station, and at the south end of Clam Lagoon (Fig. 3). Highs exist near Finger Bay,

Fig. 1 Complete Bouguer anomaly (gravity) survey of Adak Island, Alaska (preliminary). (82-4/49)

west of the airfield, and on the western side of Mt. Adagdak. The mercury lows generally overlap land magnetic highs and are believed indicative of cooled, near-surface intrusions. Many of the highs can probably be explained by soil type or residual mercury spilled on the ground during World War II. However, the high near Mt. Adagdak cannot as yet be explained by any phenomena other than subsurface heat.

GEOTECHNICAL INFORMATION FOR ADAK

The soil on Adak Island may be described, in general, as volcanic in origin. The lower slopes on Northern Adak Island (a possible area of interest for a plant location) are covered with a uniform volcanic ash layer 3 to 6 ft thick, generally overlying glacial drift. At the lower elevations, soils are generally sandy with interspersed peat and high organic layers in the bogs and poorly drained areas. The hills are covered with a spongy organic mat of soil derived from plant material over the acid volcanic ash.

Fig. 2 Land magnetic survey of Adak Island, Alaska (preliminary). (82-4/50)

Many of the construction projects on Adak are centered around Sweeper Cove, which is southwest of the tentative GEOTEC plant site. Sites at this location can be composed of fill placed above fine sand. The fill consists of brown gravelly sand and sandy gravel material with various amounts of broken asphalt and organic material.

Fig. 3 Survey of mercury content of soils of Adak Island, Alaska (preliminary). (82-4/51)

The depth varies between 1 and 4 ft; however, deeper deposits may be encountered. From the description of the fill, used to backfill inland waterways, it is believed that the fill placement was not structurally controlled and was therefore susceptible to settlement problems. Below the fill is an organic layer. In the past, foundation recom-

mendations have been to either bypass the organic layer using pile foundations or to remove the organic layer and overlying fill and replace it with a structural fill. While the foregoing is relevant to Sweeper Cove, similar subsurface profiles may exist at the GEOTEC plant site. In the Mt. Adagdak region, geothermal exploration wells encountered substantial depths of volcanic ash that had been altered to montmorillonite, which would present swelling and settlement problems.

A soil profile is not available for the cold-water inlet and pump house site; however, it is believed to consist primarily of sand dune material that would typically be classified as a poorly graded (or uniform grain size) sand. The material comprising the surfzone, in which the cold-water pipe will be anchored, is primarily sand and rock with a moderate-to-steep slope. The cold-water conduit, approximately 3 ft in diameter, which will extend into the surf, will experience strong wave action based on evidence that heavy ordnance disposed off the Andrew Bay shore becomes periodically washed ashore. Heavy anchorage will most likely be required.

GEOTEC PLANT DESIGN FOR ADAK

The latest results of cycle analysis for the estimated geofluid and seawater conditions at Adak were presented in Refs. 3 and 4. Reference 4 also presents in detail the methodology used in the single- and dual-binary cycle analyses by APL. The concluding remarks in Ref. 4 are as follows:

"These preliminary results indicate that the dual-binary cycle offers a substantial cost savings over the binary cycle. At $T_{GF} = 180^{\circ}\text{C}$, now believed to be the probable geofluid wellhead temperature for Adak, the minimum cost of a 10-MWe-net plant using the dual-binary cycle would be \$42M or \$4200/kWe with geofluid reinjection temperature (T_{inj}) of 70°C , whereas, for the binary cycle, the cost is \$56M or \$5600/kWe with $T_{inj} = 80^{\circ}\text{C}$. The costs are very sensitive to T_{GF} and T_{inj} .

"At $T_{inj} = 70^{\circ}\text{C}$, the geofluid still contains a substantial amount of energy that could be used for a secondary heating application. However, the resulting cooling of the brine could lead to problems of precipitation of the dissolved solids. Another alternative, dependent on environmental constraints, may be to reject the brine into the sea, resulting in a substantial cost saving by elimination of reinjection wells.

"It should be emphasized that this analysis has been based on a simplified thermodynamic cycle and relatively crude cost algorithms. Future studies should employ a more sophisticated analysis including, e.g., calculations of system pressure losses as functions of component designs and operating conditions. In addition, the thermodynamic properties should be extended into the superheat region so that the cycle studies can incorporate degrees of superheat to obtain desired vapor qualities from the turbine exit. The cost studies should also be refined by developing a larger data base from which to make cost estimates of various system components."

Some of the latter refinements to the analyses will be done during the next quarter.

NWC is preparing to let a small subcontract for conceptual design of a 12-MWe GEOTEC plant for Adak during the next quarter. APL also plans to let a subcontract for generic design of GEOTEC plants next spring.

REFERENCES

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4. G. L. Dugger, L. L. Perini, and D. Richards, "Hybrid Geothermal-Ocean Thermal Energy Conversion (GEOTEC) Power Plant Analysis and Cost Estimates," presented at 5th Miami Conf. on Alternative Energy Sources, Miami Beach, Fla. Dec 13-15, 1982, JHU/APL AEO-82-114 (Dec 1982).

SUPERVISION OF TESTING OF PNEUMATIC WAVE-ENERGY CONVERSION SYSTEM

The Department of Energy, Division of Ocean Energy Technology (DOE/DOET) has funded the development of a novel Pneumatic Wave-Energy Conversion System (PWECS) originally conceived by M. McCormick of the U.S. Naval Academy (USNA). In this device, an oscillating airflow—induced in a capture chamber by passing waves—drives a pair of counter-rotating turbines whose shafts are connected to an electrical generator by means of a combining gearbox. A prototype PWECS device was designed for at-sea testing on a barge together with other wave-energy devices in an international experiment, but the PWECS device was not completed in time. APL has been asked to perform a systems analysis of PWECS and to put the device in an at-sea test “ready” state.

Under APL’s technical direction, the Naval Civil Engineering Laboratory (NCEL) has been requested to prepare the device for the at-sea test and document the performance characteristics of the counterrotating turbines. As part of the systems study, APL has developed a numerical model of PWECS and defined a wave tank model test of the combined hydrodynamics and aerodynamics of the device, which will be used to validate the numerical model. A limited study of costs of the commercial viability of PWECS has been initiated.

SUMMARY

The NCEL site survey and the cost study for a PWECS ocean test platform were completed and received on October 20, 1982. As reported in the previous *Quarterly Report* (Ref. 1), the only practicable platform site identified was at the Naval Air Station, Pt. Mugu, Calif., and test planning and modeling studies continued on the assumption that this would be the most probable location. Concurrently, contract negotiations for the proposed PWECS hardware modifications and turbine testing continued with receipt of an initial NCEL proposal containing a statement of work and cost estimates. A meeting to discuss the latter effort was held at NCEL on October 6 (Ref. 2), and a subsequent NCEL draft proposal review meeting was held on October 29, 1982 (Ref. 3). A program status review for DOE was made on October 20 in which guidance and approval of the test planning were received. The revised NCEL proposal, received on November 29, included additional recommendations for the PWECS test. A meeting planned for January 1983 will finalize these test details.

Numerical model analyses continued in this quarter with completion of the model development, comparison of numerical predictions with a limited data set from an air-capture-chamber wave-tank model test, and a short parametric study of predicted power levels for a range of capture chamber geometry and wave resource parameter values. During this period, the plans for air-capture-chamber model tests in the USNA wave tank were reviewed with Prof. McCormick (Ref. 4), and APL provided him with the necessary test materials. In addition, a subcontract (APL Contract 601767-L, December 30, 1982) for a cost study to estimate PWECS commercial viability was negotiated and awarded to Gibbs and Cox. Finally, a paper describing work on PWECS at APL was prepared and presented (Ref. 5).

BACKGROUND

An experiment was conducted by the International Energy Agency (IEA) in 1980 off the coast of Japan on the barge *Kaimei* to assess the feasibility of several prototype ocean wave-energy conversion devices, each of which used a turbine driven by air that was alternately compressed and expanded (in a capture chamber) by the action of the wave field. The United States, as a member of IEA, planned to participate in the *Kaimei* experiment with the PWECS proposed by McCormick and designed at the Naval Ship Research and Development Center (NSRDC); however, the PWECS prototype could not be fabricated in time for the *Kaimei* experiment.

The PWECS prototype was assembled by the Solar Energy Research Institute (SERI) for DOE/DOET, and limited mechanical tests were conducted. The prototype PWECS, as assembled by SERI, consists of a base structure on which are mounted the counterrotating air turbines, main combining gearbox, magnetic clutch, generator, and a cabinet housing the controls (Fig. 1). SERI and its contractors also developed a preliminary numerical model of the thermodynamics of the PWECS capture chamber. Upon completion of the PWECS assembly, APL was requested by DOE/DOET to perform a systems analysis of the device, to plan for a proposed test on a bottom-mounted ocean platform, and to provide technical direction to NCEL, which will prepare for the test. As part of its systems analysis task, APL has analyzed the system’s mechanical components, modeled the dynamics of the system, and initiated a study by Gibbs and Cox of the commercial viability of PWECS.

TEST PLANNING AND SYSTEM STUDIES

The goals of the PWECS test program are to demonstrate the device’s performance, reliability, and efficiency and to assess its commercial potential. APL

Fig. 1 Component schematic of existing prototype wave energy converter. (82-4/54)

Fig. 2 Power output versus time: $A_t = 1.8292 \text{ ft}^2$; $l_0 = 10 \text{ ft}$; $\eta = 0.5$; $d = 10 \text{ ft}$; $C_D = 0.6$; $D = 20 \text{ ft}$; and $T_p = 6 \text{ s}$. (82-4/55)

examined the original design, and, as reported in previous *Quarterly Reports*, NCEL investigated possible test sites and air-capture-chamber concepts and estimated costs for construction and testing. The NCEL study (Ref. 6) concluded:

"A review of the data will disclose that there are no 'ideal' sites for deploying the PWEC in coastal U.S. waters. Although there is an adequate wave resource off the coast of Washington and Oregon, we were unable to locate a structure on which to mount the PWEC in these waters. Also, the construction and operating costs associated with working in these waters make sites

unattractive in light of the limited budget available. Cost constraints make it very desirable to locate a ready-made platform which is accessible by land such as a finger pier, breakwater, or causeway. Ideally, such a site would also be near a military base or other government facility to facilitate logistics support, data gathering, and security. The only facility which we have identified which fulfills these requirements is the Point Mugu Officers' Club Pier. The people at Point Mugu are enthusiastic about the project and have been very cooperative.

"Sketches of several options for mounting the PWEC are presented with summaries of the features (including typical cost) for each concept. Floating platforms are expensive because of the requirement to provide a large buoyant force and all off-shore platforms incur the added cost of logistic support via boat. Details on the costs are provided for each deployment alternative and environmental permitting processes are outlined.

"A review of the information presented indicates that the lowest cost deployment option is the Point Mugu Pier. At the present time there are plans to rebuild the pier out to the existing pierhead, but the Public Works Department at Point Mugu has expressed a willingness to modify their plans to accommodate the PWEC installation. The decision on whether or not the Point Mugu site is suitable for purposes of testing the PWEC centers on how much power the PWEC can be expected to generate at the site—a question which can only be answered by your performance modeling studies."

The APL systems analysis concluded that, for a "stand-alone" tower installation, a new self-supporting base and housing and added hardware components are needed; in particular, a flywheel, test and control instrumentation, systems to control the generator load and unit speed, a provision for emergency shutdown, and safety features are required for the ocean test. APL also requested that the new base with all components assembled be tested at NCEL and then transported to Point Mugu or another test location. Since the PWEC turbine is a unique design and since there are no experimental performance data, APL has requested that NCEL conduct a test to document the performance of the turbine for subsequent use in the numerical model. The NCEL proposal includes all of these items in its scope of work.

Since the waves, in any sea state, vary a great deal in height, period, and energy as a function of time, control of the energy extracted by PWEC is not feasible or desirable, except for possible partial throttling where conditions exceed the design. The resulting turbine output power will vary considerably with time (see Fig. 2). In order to generate power over a wide range of sea conditions, APL has recommended a control scheme in which the prime operating control parameter is the energy input, measured by shaft torque and speed sensors averaged over ten or more cycles. This will be used to control the generator load and speed.

A flywheel will provide the rotary inertia to absorb or supply energy to meet the change in energy content of succeeding waves as well as to damp out the speed oscillation that otherwise would occur in each wave cycle. For practical application and use of the output power,

site-dependent wave-resource, power utilization, and control studies are necessary. For test purposes, a DC generator would be recommended since its operation is stable over a relatively wide rpm range and the associated electrical load is easier to design and control. Alternatively, if the nonoptimum turbine efficiencies for constant-speed AC generation are determined to be acceptable and the generator is connected to a grid, no external control is required; but for stand-alone AC generation, the external load must be controlled by a time-averaged PWECS torque-speed signal. A variable load with a power dissipation capability in increments of approximately 0.25 kW is proposed in which individual resistor elements will be switched into or out of the combined load by a microprocessor-based control scheme. The maximum design load (time averaged) is now estimated at 100 kW. The modified power train, in conjunction with the control procedures, should allow power generation over a wide range of sea conditions.

The PWECS turbine is novel in that it uses a pair of counterrotating, single-stage impulse turbines mounted back-to-back; the direction of rotation of each turbine shaft remains unchanged with the change in airflow direction caused by the water column oscillation. In this design (by R. F. Latham), the inherent losses in the trailing (exit) stage from reverse flow through a nozzle and the effect of the counterrotating buckets were recognized, hence the selection of a high inlet nozzle angle (65°) and a relatively low design rotor speed (450 rpm).

The original design output was 125 kW for a 3-m-high (trough-to-crest) wave at the expected air-chamber-to-ambient-pressure ratio of 1.16. The first rotor was calculated to develop approximately 66% of the output power at these pressures, with the second rotor acting as an impulse-reaction stage. The airflow incidence angle and turbulence losses in the second rotor and exiting nozzles are difficult to quantify, but overall turbine efficiency has been estimated to be near 60% at the design velocities. On this basis, the counterrotating turbine design compares well with other unidirectional rotation devices that can accept bidirectional flow. While greater efficiencies can be attained with unidirectional airflow turbine designs, the losses in the large ducts and air valving required for airflow control, and their complexity and reliability, are major concerns.

The turbine performance characteristics test has been designed to substantiate some of these estimates; the resulting performance map will be used to incorporate "real" efficiencies and flow parameters into the numerical model. Sufficient data should be obtained from the test to construct a performance map such as shown in Fig. 3 and to determine the flow coefficients and efficiencies. A typical set of optimum power-speed curves is expected to result, from which an optimum operating line (dashed line) of the map can be stored in the microprocessor to control the load and speed.

To describe the hydrothermodynamics of PWECS, a numerical model (coupled model) has been developed, building on earlier work by SERI and McCormick. To verify the model, a wave tank test at the USNA of an air-capture chamber with orifice is planned. The test will measure internal and external wave height and phase,

Fig. 3 Expected form of turbine performance characteristics. (82-4/56)

Fig. 4 Resonance study for representative geometry: $Z_0 = H/2 = 2.5$ ft; $l_0 = 20$ ft; $d = 20$ ft; $D = 18$ ft; $A_1 = 2.5$ ft²; $C_D = 0.6$; and $\eta = 0.5$. (82-4/57)

capture-chamber pressures, temperatures, and airflow for a range of wave resource parameter values. The results will be compared with numerical predictions. The model will be modified as necessary to conform with the test results and will be used to estimate performance and determine initial control, limit, and safety settings for the at-sea tests of the PWECS prototype.

The PWECS turbine is driven by an oscillating water column, which can be designed so as to exhibit resonance. For a geometry representative of an at-sea installation, the numerical model also exhibits resonance as shown in Fig. 4, which plots amplification factors for varied frequencies. The resonance behavior was used to characterize the numerical model by comparing model predictions with

Fig. 5 Comparison of coupled model with USNA experimental data: (a) high damping: $A_t = 0.0055 \text{ ft}^2$; $D = 0.83 \text{ ft}$; $d = \text{variable}$; $\ell_0 = 6 \text{ ft}$; $C_D = 0.6$; $\eta = 0.5$; $Z_0 = 0.15 \text{ ft}$; and $R_t = 0$. (b) low damping: $A_t = 0.136 \text{ ft}^2$; $D = 0.83 \text{ ft}$; $d = 1.33 \text{ ft}$; $\ell_0 = 4.67 \text{ ft}$; $C_D = 0.6$; $\eta = 0.5$; $Z_0 = 0.15 \text{ ft}$; and $R_t = 0$. (82-4/58)

some experimental tank data from resonance tests of an oscillating water column. The comparison between the numerical predictions and experiments is shown in Figs. 5a and 5b. The figures show that, for the small throat area, which is the more highly damped case, the model underestimates the resonant frequency but gives reasonable estimates of the amplification factor. For the less damped case (Fig. 5b), the model gives good estimates of the resonant frequency but poor estimates of the amplification factor. The comparison between the predictions and experiment is discussed in more detail in Ref. 5. The overall qualitative agreement in the small orifice case allows us to make performance estimates.

An initial parametric study of the PWECS capture chamber and wave resource parameters was performed to provide power production estimates for the various geometries that will be considered in a study of the economics for commercial applications of PWECS. The primary parameters considered were chamber diameter, chamber freeboard, wave height, and wave period. The effect of chamber diameter on power for three different wave heights and two different periods is shown in Figs. 6a and 6b.

Fig. 6 Average power versus chamber diameter for coupled model: $T_p = 6 \text{ s}$ and 10 s ; $C_D = 0.7$; $A_t = 1.8292 \text{ ft}^2$; $\eta = 0.6$; $d = 10 \text{ ft}$; and $R_t = 0$. (a) $\ell_0 = 10 \text{ ft}$; (b) $\ell_0 = 20 \text{ ft}$. (82-4/59).

FUTURE PLANS

The modifications and additions to the PWECS assembly required for this test program are anticipated to be started by NCEL in the next quarter. The NCEL schedule indicates that the turbine air tests could be made five months from contract start. The air-chamber wave-tank-model tests are anticipated to be completed in the next quarter. The data from these model tests are critical to an evaluation of the present model predictions and, hence, "real life" performance—and also the concurrent cost study by Gibbs and Cox.

It is the intent, following the turbine characteristics tests, to assemble and check out the operation of an ocean platform "ready" PWECS assembly. Such ocean testing will be subject to the future availability of funding and the test site.

NOMENCLATURE

A_t	Turbine throat area
C_D	Turbine discharge coefficient
D	Chamber diameter
d	Draft
ℓ_0	Freeboard
H	Wave height

R_r Radiation damping
 T_p Wave period
 Z Chamber wave amplitude
 Z_0 Far-field height, single amplitude
 Δp Pressure difference across turbine
 η_t Turbine efficiency

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