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Quarterly Report

OCEAN THERMAL ENERGY

at The Johns Hopkins University Applied Physics Laboratory

APRIL – JUNE 1982

MASTER

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 Thermal Energy	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.

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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 30 June 1982.

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April-June 1982

OTEC PILOT PLANT CONCEPTUAL DESIGN REVIEW

Work in support of the OTEC Pilot Plant Program began slowly and was significantly less than anticipated in this period because of a delay in contract awards to General Electric (GE) and Ocean Thermal Corp. The Department of Energy (DOE) sent a contract to each company in late April.

APL meeting facilities and assistance were provided to DOE for its initial data transmittal meeting on 18 and 19 May. In this meeting, DOE and the technical advisory laboratories discussed their prior OTEC work and addressed areas that they anticipated would provide reviews and assistance in the development of each pilot plant design. Relevant supporting materials for the designs were reviewed for the contractors' benefit. An updated APL-OTEC bibliography (included herein) was provided from which selected items were requested by the contractors.

APL support task descriptions, schedules, and cost estimates were developed and submitted to the program director. The tasks are in two major categories: (a) review and analyses of contractor submissions and (b) evaluations and tests that may be necessary for assurance of design adequacy.

The initial Management Plan and Site Description documents submitted by the Ocean Thermal Corp. were reviewed; comments were provided to DOE.

The OTEC turbine design parameters previously developed by Westinghouse (W), Lockheed (LMSC), TRW, and GE were reviewed and summarized (Table 1) for the DOE program manager.

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Table 1

OTEC 10 MWe (net) turbine design parameters.

η(%)	Company	Fluid	Type	rpm	$\dot{w}$(lb/h)	P_{in}	T_{in}	P_{out}	T_{out}
83	W	NH_3	1 stage, double flow	3600	3×10^6	129.3	70.2	87.8	49.1
88	TRW (Elliot)	NH_3	4 stage, double flow	3600	2.75×10^6	133.4	72	90	51.6
87.6	LMSC (Rotoflow)	NM_3	Radial, inflow expander	3600	2.73×10^6	129.8	70.4	90.7	50.8
88	GE	R22	Axial	1800	9.962×10^6	140.3	71.8	96.7	48.6

Notes:
W Power Systems Development Contract (PSD)-1, San Francisco 1569-2, 4 Dec 1978
TRW PSD-2, Contract ET-78-C-01-3408, 10 Aug 1979
LMSC PSD-2, Design review, Jun 1979
GE PSD-2, Design review, 4 Jun 1979
W design at 80°F warm water, 40°F cold water (40° ΔT)
All others at 82°F warm water, 40°F cold water (42° ΔT)

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OCEAN THERMAL ENERGY CONVERSION §2
OTEC Energy Products ZY3COE
Support: DOE/DOET
W. H. Avery and D. Richards
April-June 1982

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. The present program is part of a broad effort to identify and rank the OTEC products and processes that can 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

Methanol can be made on OTEC plantships by the process shown in Fig. 1, which uses a coal slurry as the carbon source, together with hydrogen and oxygen produced on board the plantship by electrolysis of distilled seawater. This direct coal slurry approach eliminates the need for the on-shore coal pyrolysis plant previously discussed (Refs. 1 and 2), and it appears to offer better ecomonics.

At the request of the Energy Research Advisory Board of DOE, the cost of such OTEC methanol was compared with that of methanol produced by the same process on shore using electricity from a nuclear power plant for the water electrolysis. The results, shown in Tables 1 and 2, indicate that OTEC methanol could be

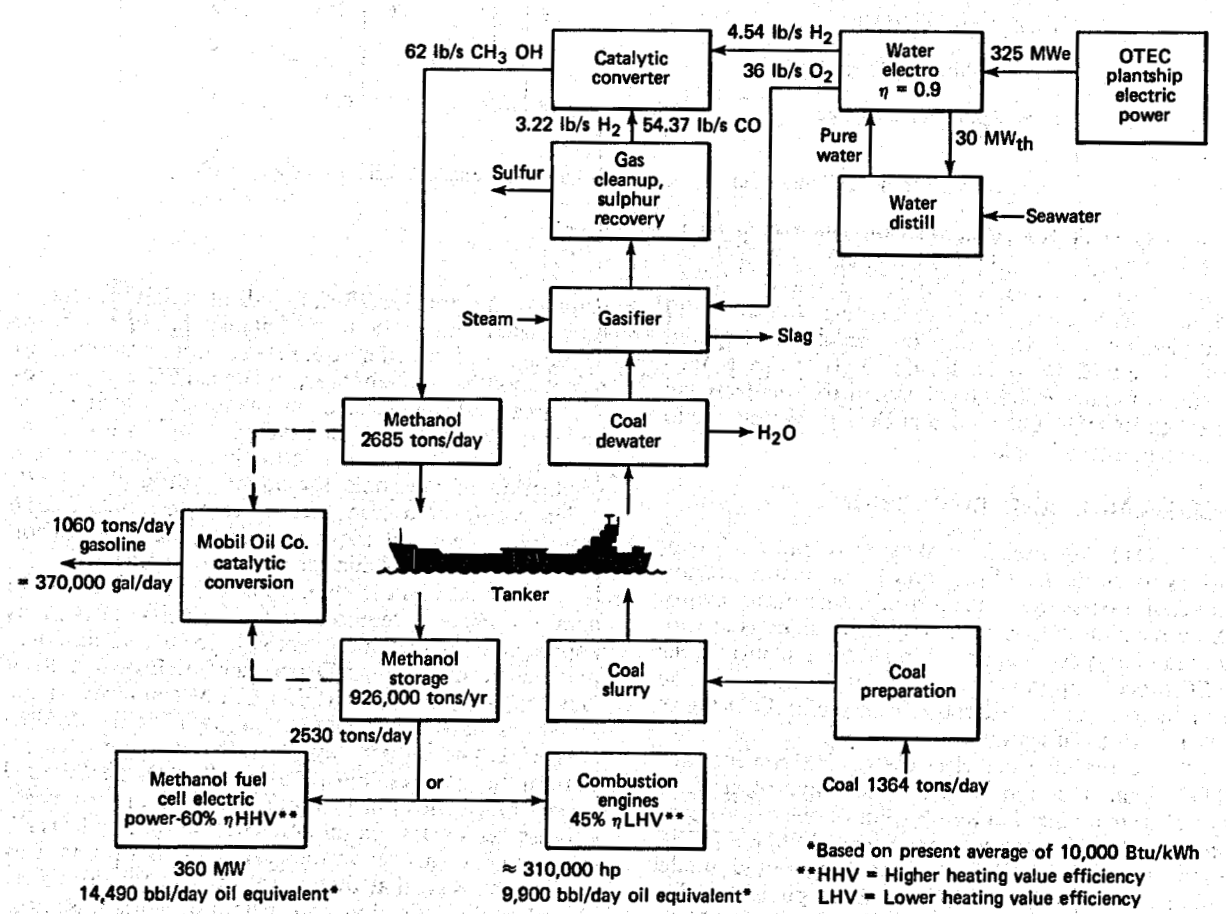

Fig. 1 OTEC methanol plantship fuel utilization. (82-2/37)

Table 1

Methanol cost for a land-based plant using electricity from a new (1990) nuclear plant. Industrial financing is used with 48% equity and a 46% federal income tax rate for two return-on-equity levels. Costs are in 1980 dollars.

Electricity cost from nuclear power plant producing 13.17% Return on Equity (ROE)

Bond interest	9%		12%		15%	
Plant investment (PI) ($/kW)	1500	2000	1500	2000	1500	2000
Fixed charge rate (incl. ROE)*	17.78%		19.12%		20.47%	
Annual fixed cost ($/kW)	267	356	287	382	307	409
Annual O&M cost, 1.8% of PI ($/kW)	27	36	27	36	27	36
Total annual cost ($/kW)	294	392	314	418	334	445
Hours/y operation	5000		5000		5000	
Power cost avg. ($/kW)	0.059	0.078	0.063	0.084	0.067	0.089

Adjacent methanol plant producing 20% ROE

Bond interest rate	9%		12%		15%	
Plant investment ($M)	232	355	232	355	232	355
Fixed charge rate (incl. ROE)*	22.8%		24.2%		25.7%	
Annual fixed charge ($M)	53	81	56	86	60	91
Annual O&M, 1.8%, 3.6% of PI ($M)	4	13	4	13	4	13
Annual power cost ($M)	159	210	170	226	180	240
Annual coal requirement (tons)	471,000		471,000		471,000	
Annual coal cost at $25 or $75/ton ($M)	12	35	12	35	12	35
Total annual cost ($M)	228	329	242	360	256	379
Methanol production (Mgal/yr)	280		280		280	
Methanol price at plant ($/gal)**	0.81	1.18	0.86	1.29	0.91	1.35

* Fixed charge rate also includes insurance at 1% of PI and state and/or local tax on plant of 2% of PI.

**Does not include distribution cost or taxes on retail sales.

sold at a much lower price (competitive with gasoline) while yielding a higher return on the smaller required equity of only 12.5% (with a Title XI government-guaranteed loan under Public Law 96-320) for the plantship vice a typical 48% equity for a nuclear power plant and an adjacent methanol plant.

BACKGROUND AND DISCUSSION

The OTEC process for making methanol yields over twice as much methanol per ton of coal as a methanol-from-coal process that gets most of the necessary hydrogen by reaction of approximately half of the coal with water (and oxygen from an air liquefaction plant). In the OTEC process, approximately 60% of the hydrogen and all of the oxygen needed come from the on-board electrolysis of distilled seawater.

The status of water electrolysis developments and OTEC plantship requirements for hydrogen (and oxygen) were reported in Ref. 3. Work done in the development of the original concepts for a 100 MWe OTEC ammonia plantship (Ref. 4), the design (and model testing) of a 40 MWe OTEC ammonia pilot plantship (Ref. 5), and projected scaling to 120, 240, and 360 MWe commercial plant sizes (Ref. 6) indicated that process arrangements, integration, packaging, product storage handling, and transfer are feasible for ammonia. In recent months, the emphasis in the OTEC energy product area has been placed on methanol, for which a large and stable market could be developed rapidly if the economics can be shown to be attractive. In contrast to the production of ammonia (or liquid hydrogen, Ref. 2), which requires no transport of raw materials to the plantship, methanol requires the shipment of carbon feedstock to the plantship for on-board gasification.

Methanol Plant Design. The effort to secure valid data on process requirements and costs of various approaches for methanol synthesis from coal disclosed that the Process Design Department of Brown & Root Development, Inc. (BARDI) recently completed a detailed design of a barge-mounted plant for the production of 2700 tons per day of methanol from offshore natural gas sources. Furthermore, BARDI has worked on slurry gasification in the TVA ammonia-from-coal process demonstration and on several aspects of OTEC ocean engineering on various OTEC design teams. Discussions showed that the group who did the aforementioned coal-gasification and methanol work was inter-

Table 2

OTEC methanol cost in 1990 based on 8th 325 MWe plantship. Title XI financing is used with 12.5% equity and 46% federal income tax for two return-on-equity levels.

20% Return on equity (ROE)						
Bond interest	9%		12%		15%	
Plant investment (PI) ($M), 0 or 0.33 contingency	724	963	724	963	724	963
Fixed charge rate (incl. ROE)*	12.51%		14.54%		16.71%	
Annual fixed cost ($M)	91	120	105	140	121	161
Annual O&M cost, 1.8% of PI ($M)	13	17	13	17	13	17
Annual coal requirements (tons)	471,000		471,000		471,000	
Annual coal cost at $25 or $75/ton** ($M)	12	35	12	35	12	35
Annual coal slurry shipment cost ($M), $10 to $30/ton	9	27	9	27	9	27
Annual methanol shipment cost ($M), $10 to $30/ton	9	27	9	27	9	27
Total annual cost ($M)	134	226	148	246	164	267
Methanol production (Mgal/yr)	280		280		280	
Methanol price delivered to port ($/gal)	0.48	0.81	0.53	0.88	0.59	0.96
30% ROE†						
Fixed charge rate (incl. ROE)*	13.35%		16.40%		18.63%	
Annual fixed cost ($M)	97	129	119	158	135	179
Total annual cost ($M)	140	235	162	264	178	285
Methanol price delivered to port ($/gal)	0.50	0.85	0.58	0.95	0.64	1.03

* Fixed charge rate also includes insurance at ½% of PI but no state or local tax on plantship or the port product-storage facility.

**Includes slurry preparation cost.

† All other numbers except those shown below are same as for 20% ROE.

ested in conducting an evaluation of the equipment and space requirements for an OTEC-methanol plant. Thus, it is expected that good cost estimates for the OTEC-methanol plant will be possible with modest efforts by BARDI and APL. Figure 2 is a simplified schematic of the on-board coal gasification to methanol process. BARDI experience will be used in determining OTEC-methanol process-equipment requirements, space, weight, and costs, as well as integrational requirements including feedstock and product handling. APL will provide project direction and coordination, advice on platform layout and arrangement, and OTEC power and electrolyzer systems installations. The resulting joint report should provide a relevant data base for cost estimation and for subsequent development of OTEC methanol plantships by private industry.

Coal (or Char) Slurry Combustion. For several years, a group led by R. H. Essenhigh of Ohio State University has been investigating the effects of composition, particle size, and burning conditions on the combustion of coal and coal char (Ref. 7). Recently he has studied the burning characteristics of coal-water and char-water slurries (Ref. 8). To profit from this work, a small program under APL sponsorship has been initiated at Ohio State to obtain data that will cover the range of conditions for gasification of coal or char slurries that would be used in the OTEC-methanol process.

Cost of OTEC-Methanol versus Nuclear-Power-Plant Methanol. At the request of DOE's Energy Research Advisory Board, the costs were compared for OTEC methanol and nuclear-power-plant methanol, both using a coal slurry and electrolytic hydrogen and oxygen as shown in Fig. 1. The results are summarized in Tables 1 and 2. Although the plant investment ($/kW of design output) used in the comparison is lower for nuclear than OTEC plantships, the significantly lower cost for OTEC methanol results from three factors:

1. The low plant factor of nuclear plants (0.57) based on experience (Ref. 9) compared to that projected for OTEC plantships (0.945). The OTEC plant factor is based on operating data for supertankers, which average two weeks down time per year, and on data for commercial refrigeration and cryogenic systems, which are similar to OTEC in basic components and operating temperatures. These typically have down times for maintenance scheduled at 3 to 5 year intervals. The Trane Corp. reports that one of its

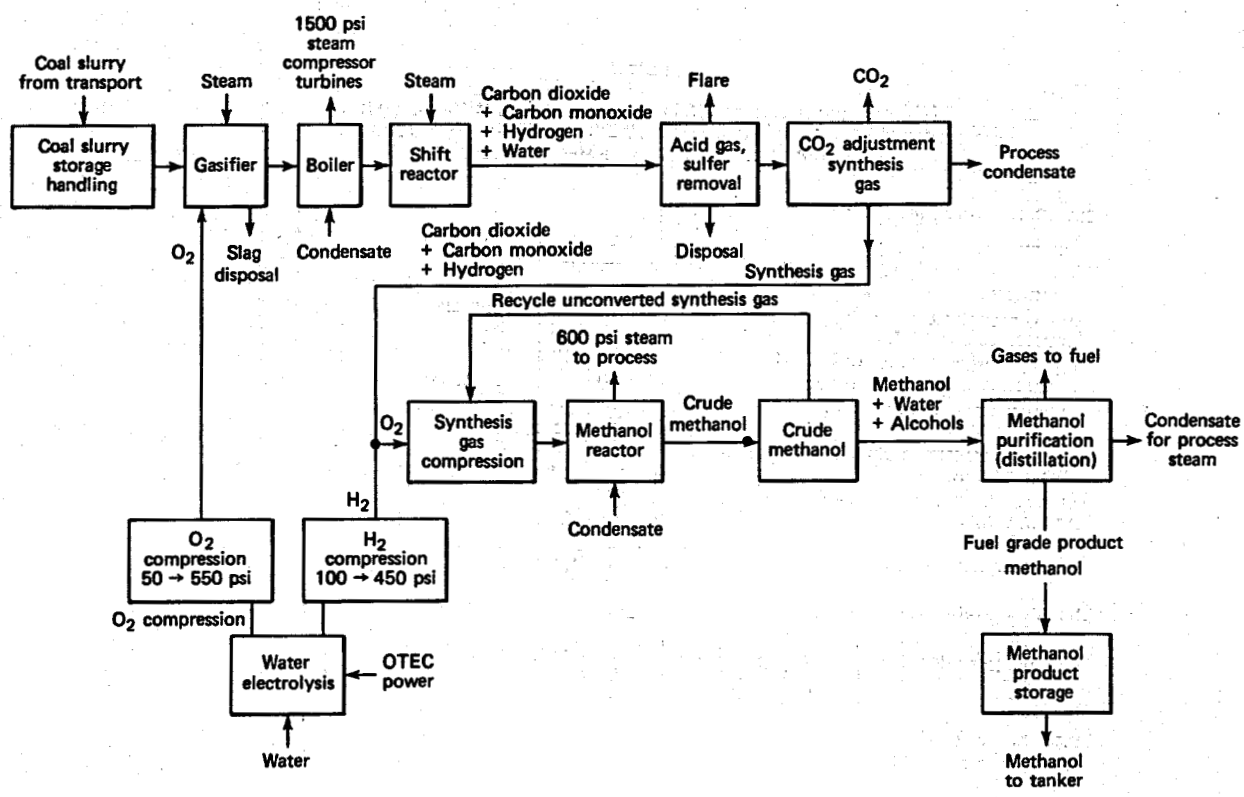

Fig. 2 Block diagram of methanol barge-mounted plant. (82-2/38)

cryogenic plants has operated continuously for 10 years with no down time.

2. No state and local taxes will be paid for OTEC.
3. Title XI of the law governing the Maritime Administration provides loan guarantees by the U.S. Government to assist U.S. Maritime construction. (This is not a subsidy. The Maritime Administration has consistently made a small profit, which results from the fee charged to loan applicants.) This permits the investor to receive a high return on his investment without a large markup of price over cost. OTEC plantships qualify for Title XI loan guarantees as provided in Public Law 96-320. Details of financing arrangements are discussed in Section 3 of the *Quarterly Report*.

FUTURE PLANS

The methanol plant design work by BARDI is to be completed in 1982. No FY 1983 funding from DOE for further OTEC energy products investigations is presently anticipated. Therefore, the subsequent APL work in this area will be limited to in-depth reporting of the work, to provide a firm base for future private development efforts on OTEC products.

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OCEAN THERMAL ENERGY CONVERSION §3
Technical Assistance/Commercialization
ZY3COE
Support: DOE/DOET
E. J. Francis April-June 1982

MANAGEMENT DECISION REQUIREMENTS FOR OTEC CONSTRUCTION

Technical development of components and engineering design of large-scale OTEC demonstration vessels and plants combined with project financing analysis in recent years have led to the conclusion that OTEC plants and plantships will produce electric power and energy products at costs competitive with power and products from other sources – coal, oil, natural gas, and nuclear. With innovative project financing and a favorable government regulatory climate, even the first private OTEC ventures present attractive business opportunities. Recent agreement by insurance companies to insure against the risks of below-contracted performance and tax credits recaptured by the government reduces risks to what appear to be attractive levels.

SUMMARY

Work during this period has been concentrated on the factors that management evaluates in making the "go-no go" decision, effective steps to increase the "go" side, and efforts to gain a better understanding of the process that must be carried through.

Results are presented in the context of a first large-scale (45.4 MW delivered) OTEC demonstration vessel for siting off the island of Oahu in the state of Hawaii. Other large-scale demonstration vessels and estimates for the first commercial-scale OTEC vessels are presented for comparison.

BACKGROUND

OTEC was not economically attractive until the end of the 1970's because of the earlier abundance of very inexpensive crude oil. However, the decade from 1970 to 1980 saw oil prices rise from $1.80 per barrel to $24 per barrel, a fifteenfold increase in price (Ref. 1) and a rise of 31% per year. This decade also brought a widespread realization that world oil supplies will not be plentiful much longer – perhaps 20 to 40 years – a major reason why oil prices will stay high or increase further in constant dollars. At today's oil prices, OTEC commercial-scale plants, even the very first ones, appear to be cost competitive. To prove this, it is widely recognized that the next step is to demonstrate costs and performance on large scale. These OTEC demonstration vessels will, by their first-of-a-kind nature, be high in cost and will require government and/or private industry incentives and subsidies. The supports are provided for a limited number of sites and demonstrations with U.S. built plants by Public Laws 96-320 and 96-223. Some of the pertinent estimates appear in Table 1. The financial management rates of return (FMRR) and net present values (NPV) (see Ref. 2 for definitions) for the Hawaii, Puerto Rico, and methanol cases seem to meet the profit thresholds of most U.S. construction companies for interesting potential projects.

The cost estimates used at APL for OTEC vessels are based on funded and contributed designs of three iterations of complete OTEC systems. The first was a conceptual design of a 100 MW OTEC vessel to produce ammonia on board, with substantial contributed effort by Sun Shipbuilding and Dry Dock Co., Avondale Shipyards, Inc., and others. The second and third iterations for 20 and 40 MW vessels, with a different set of industrial companies, produced drawings, documentation, and component tests at the level of detail of preliminary engineering designs, thus providing a reasonable basis for confidence in estimated costs. With modifications, these vessels could be moored off islands (e.g., Oahu, Hawaii, Puerto Rico, St. Croix, Jamaica) or the U.S. Gulf Coast, delivering electricity to on-shore utility grids by cable, or could be self-propelled in equatorial ocean waters in which the net power produced would be used on board for the manufacture of fuels, fertilizers, or metals for shipment to shore. The moored, offshore OTEC plants are environmentally good neighbors that can produce fresh water, improve fishing in the area around the plant, and provide food from mariculture, as well as electricity.

The cost estimates currently used at APL are taken or extrapolated from the third iteration engineering design of 40 MW (nominal) OTEC vessels for delivery of electric power to islands by cable and for on-board production of ammonia and were reported in 1980 (Ref. 3). The cost estimates are shown in Table 2. For OTEC methanol vessel cost estimates, a combination of costs extrapolated from the OTEC ammonia basic vessel and methanol plant costs based on data contained in Ref. 4 are used. It is expected that these costs will be updated about the end of 1982 when the current conceptual OTEC methanol work by APL and Brown & Root Development, Inc., is completed. As will be noted from the table, we expect decreases in cost per kilowatt on board as the size of OTEC vessels increases – from $5900 per kilowatt of average power delivered (total kWh delivered per year divided by the total number of hours in a year (8766)) at 40 MW (nominal) scale reducing to $3000/kW for the first 325 MW (nominal) scale (we call this commercial scale) moored vessel delivering electric power ashore to Puerto Rico by cable. For a moored OTEC vessel delivering electric power ashore to Hawaii, the estimated costs would be about 13% more than those for the Puerto Rico site because of the smaller temperature difference (38.5 versus 40.3°F) available off Hawaii, or $6650 and $3400/kW, respectively. For financial analysis, 10% contingency and 10% overall profit are added to the total Table 2 costs.

Large-Scale OTEC Demonstration. It is generally recognized in the United States and elsewhere that the next essential step in OTEC implementation is large-scale

Table 1

Typical OTEC vessel cash flow cases.*

OTEC Product	1982 Product Price	OTEC Vessel Cost, $1982 (millions)	Revenues, 1986-2010 ($billions)	Net Cash Flow, 1983-2010 ($billions)	FMRR†† (%/yr after taxes)
Delivered electric power Puerto Rico (51.4 MWe conservative case)	92 mills/ kWh	326 ($6400/kW)	4.4	1.1	32
Delivered electric power Puerto Rico (first 266 MWe)	92 mills/ kWh	960 ($3600/kW)	23.2	9.6	24
Delivered electric power Hawaii (45.4 MWe conservative case)	92 mills/ kWh	326 ($7200/kW)	3.9	0.8	30
Delivered electric power Hawaii (first 235 MWe)	92 mills/ kWh	960 ($4100/kW)	20.5	8.2	23
Methanol (60 MWe conservative case)	$295/ton or $0.98/gal	348 ($2200/ annual ton)	5.4	0.919	31
Methanol (325 MWe)	$295/ton or $0.98/gal	1,001 ($960/ annual ton)	32.5	12.2	25
Ammonia (325 MWe)	$260/ton†	980 ($2600/ annual ton)	11.7	2.9	18

* All cases are based on same assumptions, i.e., federal incentives except where indicated.
**Assumes technical correction to PL96-223 to include OTEC electric power delivered to United States, commonwealths, territories, or possessions.
† Competitive when U.S. natural gas prices are decontrolled.
††15% short- and long-term reinvestment rates.

demonstration at sea of OTEC performance and, as a result, documentation on large scale of actual OTEC costs. Table 3 presents the status of OTEC demonstrations as the author understands them to be as of June 1982. There are many factors that influence OTEC costs: the specific design, the available ocean temperature difference at the site, the option of delivery of electric power ashore or of on-board energy products processing plants, the specific companies doing the OTEC construction, the financing assumptions, insurance costs, legal fees, etc. These variables cause substantial variations in OTEC estimated costs and have led to confusion on the part of partially informed persons who have made quick comparative estimates between OTEC and other energy technologies. With well-documented large-scale OTEC demonstration projects, and careful presentation of their content and scalability, a good understanding of the commercial-scale potential and economic attractiveness of OTEC will be gained.

The U.S. Government has provided for support of OTEC demonstration vessels by provisions in Public Laws 96-320 and 96-223, in the form of government guarantee of private bond financing and business energy investment tax credits at the first OTEC site locations. These incentives appear to be adequate to attract private financing if the demonstration projects are properly designed, sited, and completed within the time allowed by the legislation. To qualify for U.S. Government support and to put together project financing, the OTEC project general partner or manager will need to obtain:

1. Long term take-or-pay contract for the power or product produced,
2. License (application fee $250,000),
3. Government loan guarantee (investigation fee 0.125 to 0.5% of bonds value),
4. Technological approval of demonstration from DOE, and
5. Approvals of unique construction facilities from EPA and state and local governments.

Under a tax syndication form of project financing, the general partner would be rewarded by some or all of the following:

1. Share of tax credits, loans, and cash flow,
2. Profit on construction costs, and
3. Management fees.

Our calculations indicate (see Table 1) a financial management rate of return (assuming 15% short- and long-term reinvestment rates) on the cash flow of the

Table 2

Estimated costs for acquisition, construction, and deployment of OTEC proof-of-concept/experimental and larger vessels.

	Puerto Rico Site Average ΔT = 40.3°F				Atlantic Ocean Site, Ammonia Average ΔT = 43°F			
Nominal size (MWe)	40	60	120	325	40	60	120	325
Power delivered to shore or process (MWe)	34.3	51.4	98.1	266	40.3	60.5	120.9	325
Platform system*	82.7	118.9	188.5	282.0	56.2	76.3	130.3	215.0
Hull structure	27.9	41.3			24.2	35.9		
Position control system	28.7	41.7			9.0	10.0		
Other equipment	26.0	35.9			22.9	30.4		
Cold water pipe system	11.3	11.3	22.3	40.0	11.2	11.2	22.3	40.0
Pipe system	8.0				7.8			
Screen	0.1				0.1			
CWP/hull transition	3.2				3.2			
Power systems	50.0	72.4	135.8	350.0	49.9	72.4	135.8	350.0
Evaporator and condenser systems	33.6	50.4			33.6	50.4		
Power generation, working fluid, controls, etc.	16.3	22.0			16.3	22.0		
Energy transfer system	27.4	28.8	30.2	50.0	30.3	42.5	76.0	160.0
Acceptance	1.1	1.3	1.7	3.0	1.1	1.3	2.1	3.0
Deployment services	25.0	32.0	49.4	60.0	13.8	15.2	26.9	35.0
Platform	1,1				1.5			
Power system	0.8				1.3			
CWP	11.2				10.9			
Discharge pipe	2.0				– –			
Electric cable	9.5				– –			
Industrial facilities			Treated separately					
Engineering and detail design	4.5	5.5	6.4	8.0	4.5	5.5	6.4	8.0
WBS 3.0 total	201.5	270.0	434.2	793.0	170.0	224.3	399.2	811.0
$/kWe on board	5875	5254	4423	2983	4142	3708	3308	2497

*Estimated costs in mid-1982 dollars (mid-1980 dollar estimates based on Ref. 3 costs and extrapolations therefrom, increased by 9% per year compounded). 10% allowance for overall profit and 10% contingency are added to get total estimated OTEC vessel costs used in financial analyses.

project that the general partner would share of 30.6% per year after taxes for Hawaii, plus 10% profit on the overall construction cost, plus 4% of overall construction costs, plus 1% of annual revenues in management fees. These returns are believed to be above the investment threshold for most large companies.

Cost Sensitivities. Input assumptions for a base case Hawaii OTEC vessel project delivering electricity to shore (which produces 30.6% per year after taxes on the total cash flow) and for an OTEC/methanol case that may be of interest to Hawaii are shown in Table 4. Detailed design and construction for these cases is assumed to take place between 1984 and 1986 with the start of operations estimated to be 1 Jan 1987. Taking the Hawaii base case, we have calculated sensitivities to the following increases in costs, following the procedures used in Ref. 5. We have also calculated sensitivities to changes in interest rate, changes in inflation rate, and changes in the negotiated price paid for delivered electric power. The results appear in Fig. 1. The effects, taken separately, for reasonable maximum errors in the cost estimates are listed below:

Table 3

Status of OTEC demonstrations, June 1982.

Site	MWe	Construction Team	Status
Nauru	2.5–10	Toshiba, Japan	100 kW, 1-yr test completed, 2.5 MW under construction
Hiroshima area	0.05*	Kyushu Electric Power, Japan	Completed, in test
Kumezima, Okinawa	3	Japan	Under construction
Agunishima, Okinawa	1	Japan	Under construction
Palmyra Atoll	50	Project Energy	Concept; NH_3 and mariculture
Hawaii (mini-OTEC)	0.05*	Lockheed	Completed, out of use
Hawaii (OTEC-1)	1	Global Marine	Completed, out of use
Hawaii	40	GE	Conceptual design
Hawaii	40	Ocean Thermal Corp.	Conceptual design
Guam	10–40	International Energy Enterprises	Concept; capital formation and license
Puerto Rico	40	Brown & Root	Concept; in litigation
Puerto Rico	50	Maryland Ocean Thermal Corp.	Concept; capital formation, no contract
St. Croix	12.5	OTEC International	Concept; contract capital formation
Jamaica	10	Sweden	Concept
Tahiti	3.5	France	Concept
Martinique	?	France	Concept

*Gross power rating; all others are net power.

	FMRR at 15%/15%
Base case, Hawaii.	30.6%
50% increase in hull costs	30.0%
200% increase in CWP and deployment costs	28.0%
200% increase in cable system costs	28.9%
200% increase in mooring system costs	28.1%
50% increase in equipment costs	28.9%
100% increase in O&M costs	29.4%
7% inflation rate (vice 9%)	28.1%
15% interest rate (vice 13%) on Title XI bonds	26.3%
Reduction to 90 (vice 120) mills/kWh 1985 power payments	25.9%

Commments on some of these results are in order. Since the concrete hull requirements are well understood, an increase as large as 50% is unlikely. Since the CWP is a first-time item, 200% is considered a possible but very high cost increase percentage. Similar considerations apply to cable costs and mooring costs. Equipment costs were considered to increase no more than 50% since most equipment is off-the-shelf. O&M costs were considered to increase up to 100% over estimates. The inflation rate was assumed to decrease to as low as 7% per year. Increased Title XI bond interest rates of up to 15% per year were considered. Reduced payments for the electric power produced were also plotted, down to as low as 90 mills/kWh (in 1985). The results show the effect of cost increases or overruns in major components assuming that the other components come in as estimated. The cumulative effect, if all of the items listed were degraded simultaneously by 25% of the range presented, would be to reduce the estimated FMRR to 25.9%.

Perception of Risk and Insurance. As stated in the previous *Quarterly Report*, there is a general perception that the construction, operation, and ownership of an OTEC vessel is a high risk undertaking because of its substantial cost, its unique elements, and the uncertainties associated with government regulations, approvals, and tax incentives (see Ref. 5 for a more detailed discussion). The two largest elements of risk are design and recapture of tax credits. The first risk is that the general partner, for unexpected reasons, may not complete and deliver a working OTEC plant. The second is that the tax

Table 4

Input assumptions, OTEC demonstrations.

	60 MWe (nom.) Power at Hawaii	60 MWe (nom.) Methanol Delivered to U.S. Coast
Construction costs ($M)	227	293
Selling price (mills/kWh or $/ton)	78.0	248
Annual production (MWh or tons)	360,000	157,000
Average cost per crew member ($)	40,600	40,600
Transportation costs (mills/kWh or $/ton)	0	17.70
Coal costs $/ton of CH_3OH ($20.50/ton of coal in slurry)	0	8.765
Supply boat charter costs ($)	365,000	162,500
Boat stevedore costs ($)	10,000	10,000
Ships chandler costs ($)	25,000	25,000
Land transportation costs ($)	25,000	25,000
Miscellaneous costs ($)	25,000	25,000
Cost per inspector ($)	60,000	60,000
Auxiliary fuel costs ($)	30,000	60,000
Cost per manager ($)	60,000	60,000
Miscellaneous logistics costs ($)	50,000	50,000
Crew air travel costs ($)	0	408,000
Stores costs ($)	140,000	350,000
NOAA application fee ($)	250,000	250,000
Annual legal fees during construction ($)	500,000	500,000
Members of crew	30	40
Number of crews	1	2
Number of inspectors	0	0
Number of managers	5	5
Number of years for construction	3	3
Number of years to depreciate	5	5
Depreciation rate, declining balance	1.75	1.75
Years to pay back debt	25	25
Days of working capital	120	120
Year of operations start	1986	1986
Final year of cost projections	2011	2011
Insurance (% of plant investment)	0.5	0.5
Maintenance materials costs (% of plant investment)	1.0	1.0
Training cost factor (% of crew cost)	5.0	5.0
Annual inflation rate (%)	9.0	9.0
Real price escalation rate (%)	0	0
Interest rate on debt (%)	13.0	13.0
Interest rate on bank loans (%)	N/A	N/A
Contingency on construction cost (%)	10.0	10.0
Profit added to construction and contingency costs (%)	10.0	10.0
Tax credits, net effect (%)	22.5	22.5
Percentage of construction cost in year 1 (%)	10.0	10.0
Percentage of construction cost in year 2 (%)	40.0	40.0
Tax rate on earnings (%)	46.0	46.0
First year production realized (% of rated)	65.0	65.0
Private debt portion of construction cost (%)	87.5	87.5
Government subsidy (%)	0	0
Brokerage fees (%)	0.8	0.8
Title XI investigation fee (%)	0.125	0.125
Stock brokerage fee (%)	2.0	2.0
Tax package sale rate (%)	100.0	100.0
During construction, Title XI fee (%)	0.375	0.375
Operating, Title XI fee (%)	0.75	0.75
General manager fee (% of plant investment)	4.0	4.0
General manager fee (% of revenues)	1.0	1.0
Government subsidy ($M)	0	0
Number of years of government subsidy	0	0

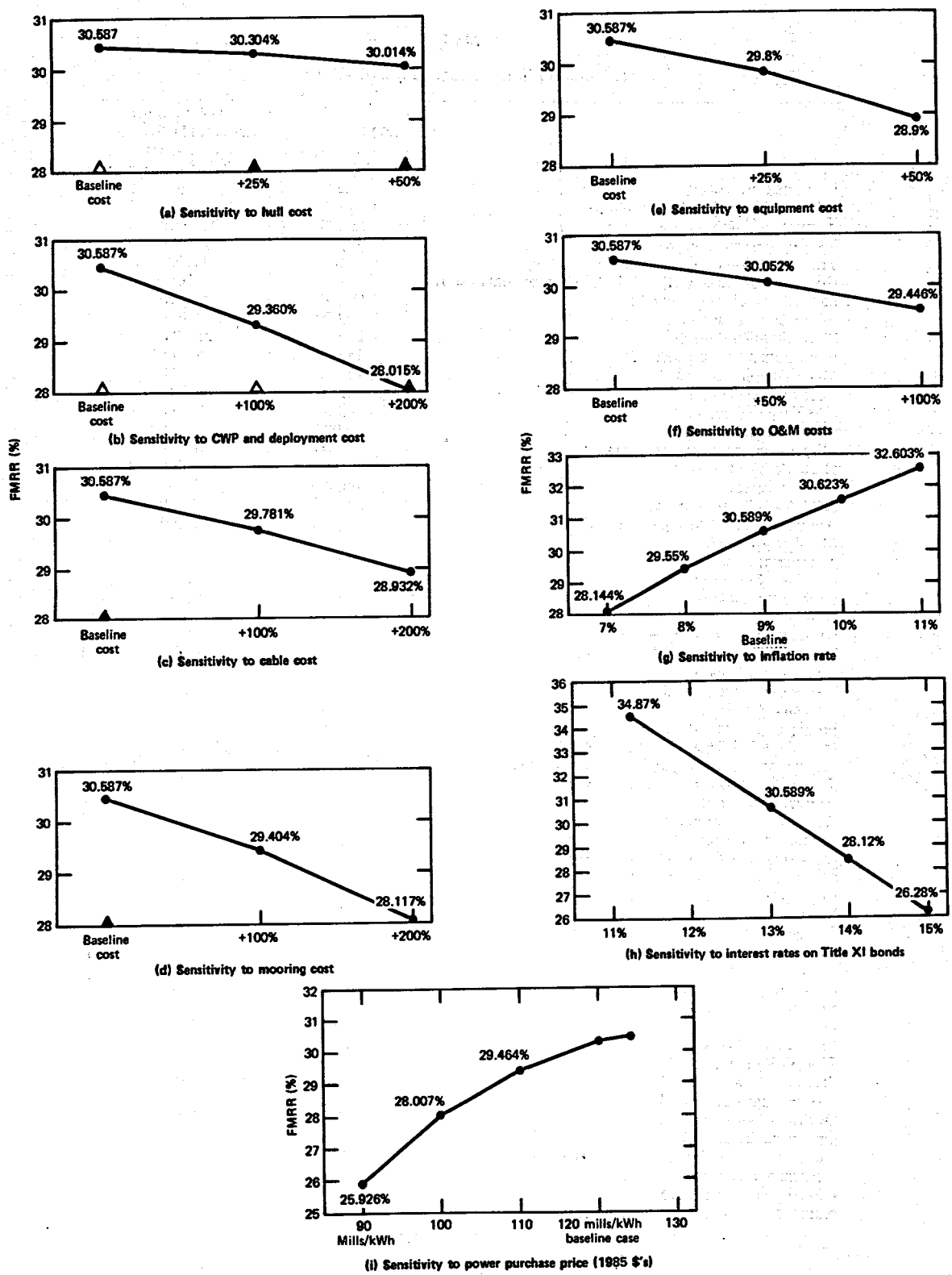

Fig. 1 Cost sensitivities in terms of financial management rate of return (FMRR) at 15% short- and long-term reinvestment rates for a moored plant at Oahu, Hawaii, with a nominal capacity of 60 MWe and an average delivery capacity of 45.4 MWe. (82-2/48)

Table 5

Summary of total equity capital contributions needed for a total OTEC base case project (Hawaii, 45.4 MW) and amounts (millions of current-year dollars) at risk for each year.

Year	Equity Needed	Elements of Risk: Cumulative Cost Design	Tax Credits Recapture, Cumulative: %	Tax Credits Recapture, Cumulative: Cost
1983	$3.0	$3.0	--	--
1984	4.85	7.85	100	$9.0
1985	21.2	29.05	100	47.3
1986	28.8	57.85	100	99.6
1987	--	--	100	99.6
1988	--	--	80	79.7
1989	--	--	60	59.8
1990	--	--	40	39.8
1991	--	--	20	19.9
1992	--	--	--	--

credits, both investment and business energy investment credits, which together make up a substantial portion of the attractiveness of an OTEC project to investors, may be recaptured because of the cessation of operations indefinitely during the first five years of operation.

A summary of equity, design risk, and tax credit recapture risk amounts for the Hawaii baseline OTEC demonstration project appears in Table 5.

An exploration of the possibility that one or more insurance companies or groups of companies could insure against the design risk and against the tax credit recapture possibility is in progress, with successful results. To date, at least one group of U.S. insurance companies has agreed that the risks are insurable and that they would underwrite the coverage (Ref. 6). Other investigations are in progress, so far without negative response. The cost of the insurance coverages is being estimated (Ref. 7).

CONCLUSIONS

Increases in oil prices in the 1980's have led to the expectation that OTEC commercial-scale vessels, even the very first ones, will be economically competitive. This competitiveness must be verified by a few large-scale OTEC demonstration vessels, which will require incentives or subsidy. These incentives, put in place by Public Laws 96-320 and 96-223, appear to be sufficient so that large-scale demonstration OTEC vessels for the delivery of electric power or methanol to Hawaii provide attractive opportunities for private investment.

The sensitivity to a series of potential cost overruns to the potential for a profitable all-private investment OTEC vessel for Hawaii has been examined, with positive conclusions. Further, insurance coverage for the two largest perceived elements of OTEC risk – the design risk that the project will not be completed and the risk of tax credit recapture caused by unexpected calamitous problems in the first five years of operations – is now available. While all of the questions have not been answered, it is time for private industry to decide to make an application for a U.S. license to build, deploy, and operate OTEC on large (40 to 60 MWe) demonstration scale.

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OCEAN THERMAL ENERGY CONVERSION §4
Geothermal-OTEC Hybrid Plants
(GEOTEC) ZY3COE
Support: DOE/DOET
G. L. Dugger, L. L. Perini, and D. Richards
April-June 1982

HYBRID GEOTHERMAL–OTEC (GEOTEC) POWER PLANT PERFORMANCE ESTIMATES

At shoreline locations where conventional Ocean Thermal Energy Conversion plants are not feasible, because either no warm seawater exists or it is impractical to attain a cold deep water source, but where a moderate quality (120 to 200°C) geothermal water resource is available, there can be advantages in combining OTEC and geothermal binary cycle technologies. Hybrid GEOTEC plants could be particularly attractive at locations having modest power demands (10 to 40 MWe) now met by oil fired plants. The previous *Quarterly Report* (Ref.1) addressed potential U.S. Navy sites for GEOTEC systems and single binary cycle GEOTEC performance including heat exchanger sizes. Some continued work on the single binary cycle is reported here, but the major effort this quarter was on further development of the computer program for dual binary cycles and on comparative evaluations of isobutane-ammonia and steam-ammonia systems.

SUMMARY

Single Cycle Requirements. Earlier work (Ref. 2) showed that ammonia has significant advantages over R22, propane, or isobutane, so ammonia was chosen for these single cycle examinations. Figure 1 shows the effect on geofluid and seawater flow rates of the geofluid reinjection temperature (T_{inj}) at given resource temperature (T_{GF}) levels for a net power output of 10 MWe. For each case, the "pinch" temperature difference (the minimum ΔT between geofluid and the working fluid) is set at 10°F. This type of plot, done here for a seawater temperature (T_{SW}) of 41°F (5°C) and a drawdown depth (Z_d) of 328 ft (100 m), shows that the required seawater flow ($\dot{w}_{SW}$) increases rapidly as T_{inj} is reduced below some optimal value for a given geofluid temperature. This must happen because the condenser temperature must be reduced as T_{inj} is reduced, and hence the seawater ΔT through the condenser must be reduced. Insofar as the GEOTEC power cycle is concerned, this figure illustrates that, for the T_{GF} range of 250 to 392°F (121 to 200°C), a T_{inj} of 160 ± 10°F will be best. Any further heat extraction from the geofluid should be done in a separate geothermal heating applicaton (e.g., heating of buildings).

The geofluid requirement in Fig. 1 increases by a factor of 3 as T_{GF} drops from 392 to 250°F and another

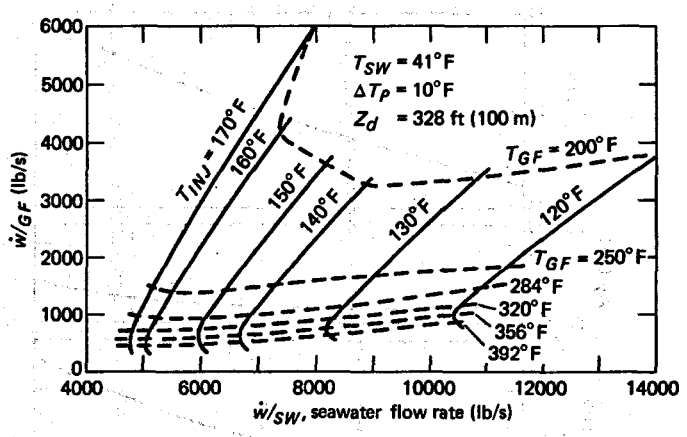

Fig. 1 Flow requirements for single cycle GEOTEC plants using ammonia and delivering 10 MWe (net) power. (82-2/39)

factor of 2.5 for a reduction of T_{GF} to 200°F. If the average flow rate per production well is 1000 gpm (143 lb/s or 65 kg/s), this means that for 10 MWe (net) power, three production wells and two reinjection wells would suffice with 392°F geofluid, but 23 production wells and 12 or more reinjection wells would be needed with 200°F geofluid. Fortunately, at one of the sites being considered (Adak Island, Alaska), present indications are that the geofluid temperature available along one fault line should be near 356°F (180°C).

Dual Binary Cycle Investigations. A pair of working fluids not previously considered is fresh water (steam) for the higher temperature loop A and ammonia for the lower temperature loop B in a dual binary cycle. It was decided to compare the water-ammonia pair with isobutane-ammonia for a geofluid temperature of 356°F (180°C) and a reinjection temperature of 158°F (70°C). In prior work on dual binary systems, we had treated the power split between the loop A and loop B turbines as an independent parameter, but the computer program logic has been changed to eliminate the loop A condenser (which used seawater cooling) and to accomplish all of the condensation of the loop A fluid by heat exchange with boiling loop B fluid in the interloop heat exchanger. The optimal ΔT between the fluids in this heat exchanger was found to be near 15°F (8.3°C), and this value was used in the results presented in Figs. 2 through 5. For these figures, as in Fig. 1, T_{SW} = 41°F, Z_d = 328 ft, and the heat transfer coefficients for the seawater biofouling film and the geofluid scale are 2000 and 400 Btu/ft^2-h-°F, respectively.

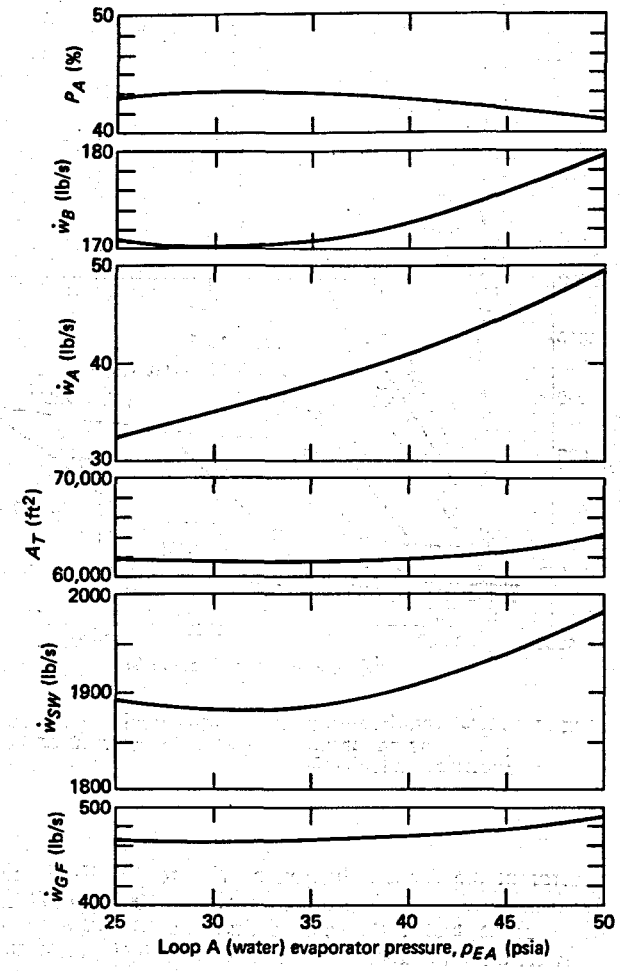

Fig. 2 Effect of loop A evaporator pressure on performance of water-ammonia dual binary cycle performance with p_{CP} = 190 psia, T_{GF} = 180°C, and 100 m drawdown. (82-2/40)

In Figs. 2 through 5, the following parameters are plotted: the percentage of the 10 MWe (net) power that is provided by turbine A (percent P_A, from water or isobutane); the fluid flows in loops A and B ($\dot{w}_A$ and $\dot{w}_B$, lb/s); the total surface area for all heat exchangers (A_T, ft^2, including evaporator A, interloop heat exchanger, evaporator B, and condenser B); and the seawater and geofluid flow rates ($\dot{w}_{SW}$ and $\dot{w}_{GF}$).

Figure 2 shows the effect of evaporator pressure in loop A (p_{EA}, steam) on the foregoing parameters for the water-ammonia pair with a loop B condenser pressure (p_{CB}, ammonia) of 190 psia. Considering all of the effects, it appears that p_{EA} should be in the 30 to 40 psia range. Less than half of the power will come from loop A. Figure 3 shows the effects of p_{CB} for p_{EA} = 40 psia. Here a stronger effect on $\dot{w}_{GF}$ may be seen, and it appears that the optimum P_{CB} may be in the 120 to 140 psia range, in which case only 33 to 37% of the power would be taken from loop A.

Figures 4 and 5 are for isobutane-ammonia. It appears from Fig. 4 that the isobutane evaporator pressure should be near 380 psia. However, Fig. 4 was for an ammonia condenser pressure of 220 psia, and Fig. 5 indicates that p_{CB} should be lower, in the 120 to 140 psia range.

Comparison of the water-ammonia results with the isobutane-ammonia results indicates that the latter combination requires about 20% less geofluid flow and 40 to 50% less seawater flow but about 35% more heat exchanger area than the water-ammonia system. The water evaporator (steam boiler) is much smaller than the isobutane evaporator, and its shell would be much lighter because of the very modest steam pressure. However, the advantages in geofluid and seawater flows for the isobutane-ammonia system appear to outweigh the heat exchanger consideration.

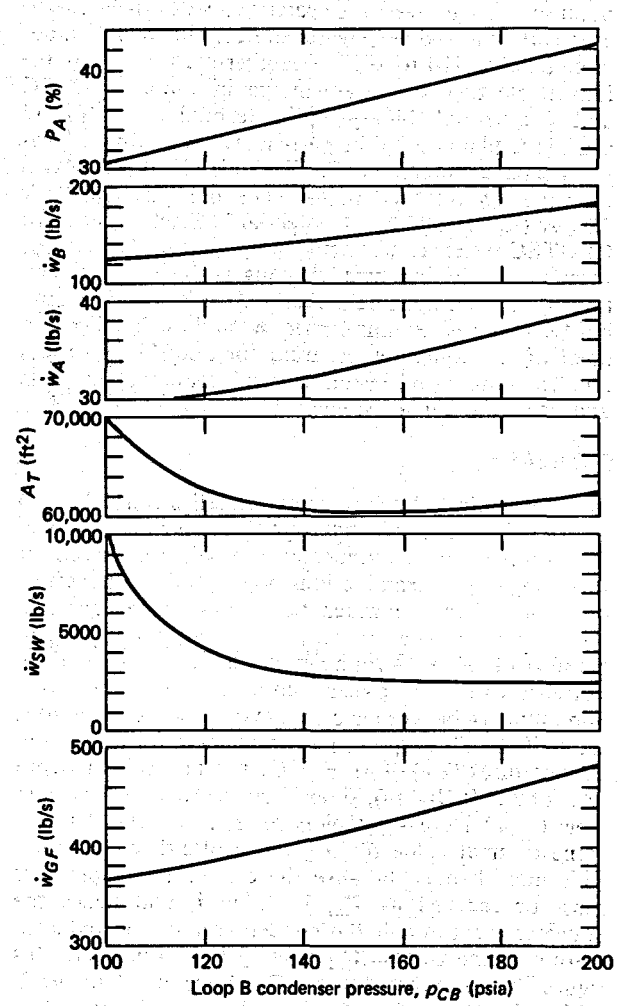

Fig. 3 Effect of loop B (ammonia) condenser pressure on water-ammonia dual binary cycle performance with p_{EA} = 40 psia. (82-2/41)

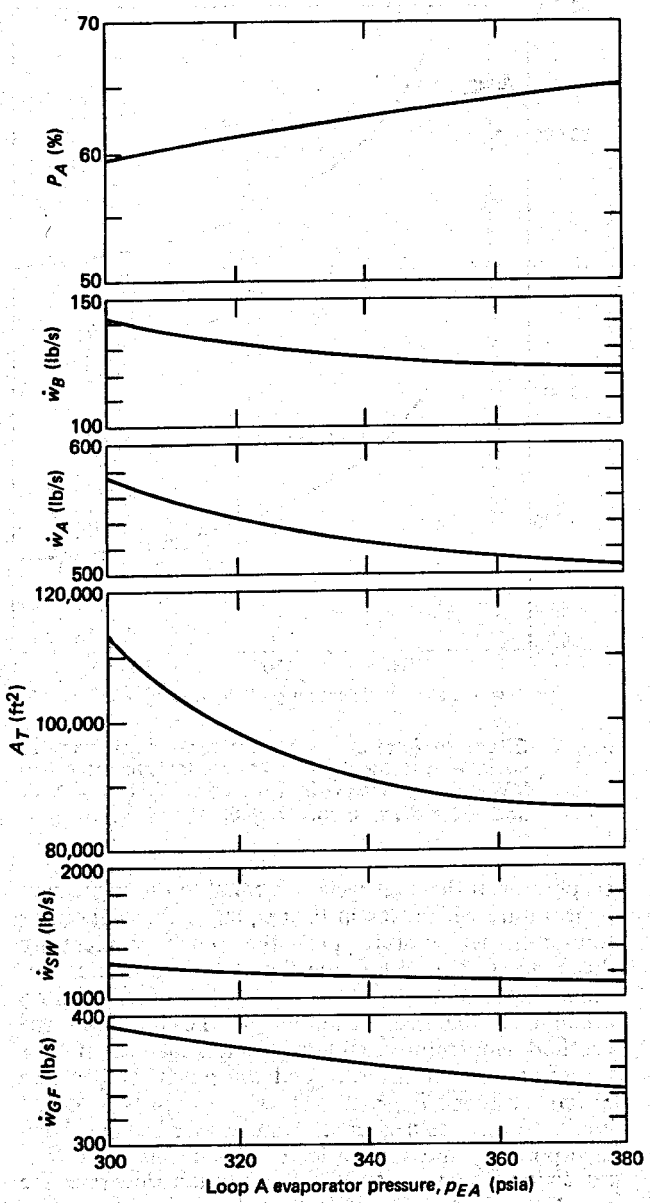

Fig. 4 Effect of p_{EA} on isobutane-ammonia dual binary cycle performance for p_{CB} = 220 psia. (82-2/42)

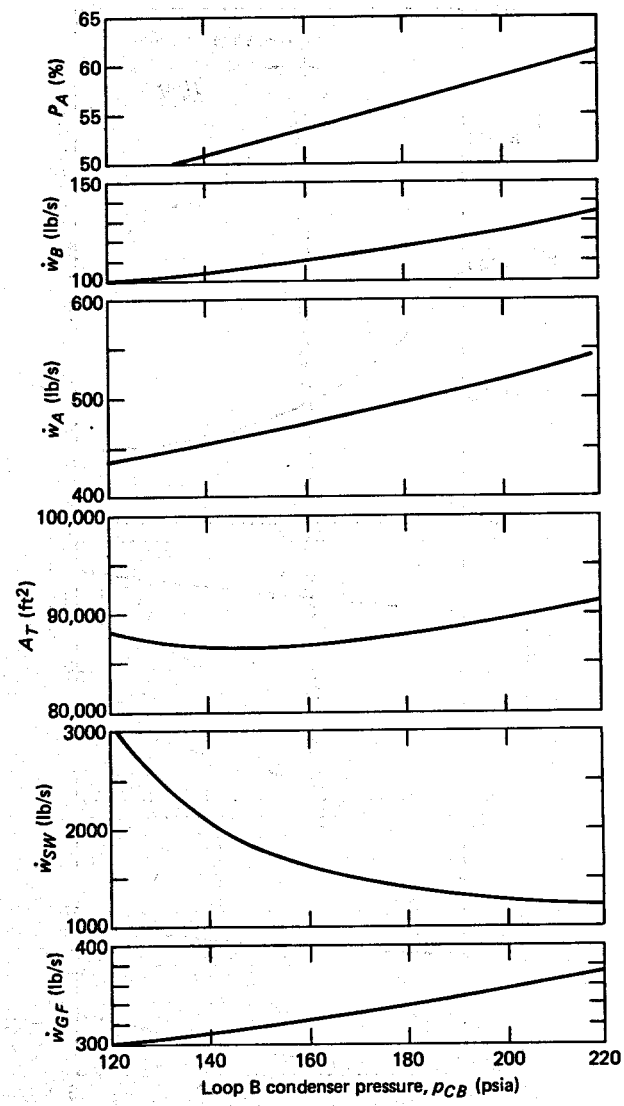

Fig. 5 Effect of p_{CB} on isobutane-ammonia dual binary cycle performance with p_{EA} = 320 psia. (82-2/43)

BACKGROUND AND DISCUSSION

An assessment of known information about geothermal resources at potential military station sites (Ref. 1) indicated that the Naval Air Station at Adak Island, Alaska (in the Aleutians chain) and the Naval Magazine at Lualualei, Oahu, Hawaii, appeared to be the most attractive, in that order. Considerable resource assessment has already been done at Adak, and another assessment trip will be made by Navy and JHU/APL representatives in July-August 1982 and reported subsequently. Water samples from gradient holes and warm springs have indicated a T_{GF} near 180°C at Adak. A major fault line apparently cuts across Mt. Adagdak, Andrew Bay, and Mt. Moffett. It is hoped that enough wells can be located within a reasonable distance from a GEOTEC power plant near the shoreline to generate approximately 10 MWe (net). With 180°C geofluid this should be possible, provided also that the flow rates available from wells of 4000 to 6000 ft depth are adequate (on the order of 1000 gpm or 65 kg/s per well). However, if T_{GF} proves to be much lower, there could be serious problems in attaining 10 MWe.

Last quarter, it was shown (Ref.3) that the temperature of the seawater available for cooling and the drawdown depth in the geothermal wells will have substantial effects on the required geofluid flow and gross power generation needed to get 10 MWe (net) for a given T_{GF}. The figures presented here are all for T_{SW} = 5°C, the approximate annual average value for

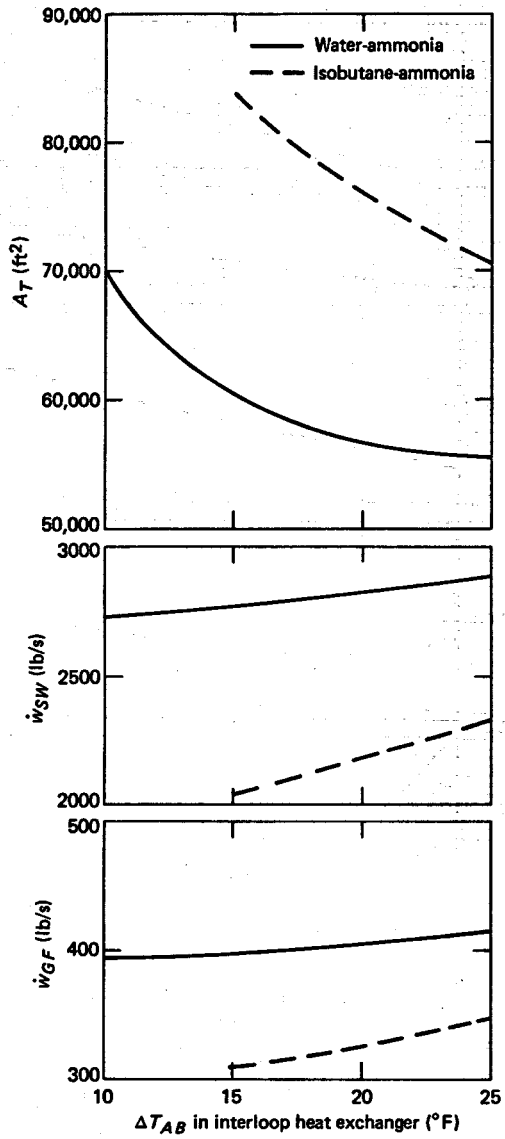

Fig. 6 Effect of the temperature difference between the working fluids on the performance of dual binary cycles producing 10 MWe (net) power with T_{GF} = 180°C, T_{SW} = 5°C, and 100 m drawdown. (82-2/44)

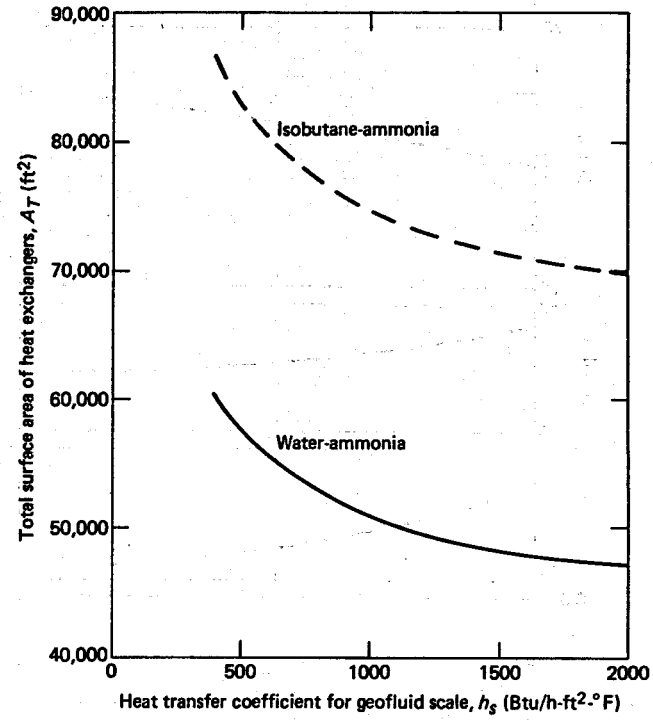

Fig. 7 Effect of geofluid scale on total heat transfer surface area for dual binary cycles producing 10 MWe (net) power with T_{GF} = 180°C, T_{SW} = 5°C, and 100 m drawdown. (82-2/45)

Adak, and for a drawdown depth of 100 m. The latter may be optimistic, since drawdown depths of 200 m or more have been experienced in some wells for binary plants.

Some further refinements in the computer program have been made. A 20 ft (6 m) head loss is now included for the geofluid or seawater through each evaporator or condenser. The turbine-generator efficiency is now divided into an 86% thermodynamic efficiency (nonisentropic expansion), 97% mechanical efficiency, and 98% generator efficiency. It had been assumed previously that the geofluid exit temperature from the evaporator of the single cycle or the loop B (ammonia) evaporator of the dual cycle was equal to the reinjection temperature which was in turn equal to the evaporator saturation temperature plus the pinch temperature difference (ΔT_p). While the liquid heatup of the ammonia upon entering the evaporator was taken into account in the heat requirement, the fact that the geofluid temperature could drop to less than the sum of the saturation temperature and the pinch temperature difference [e.g., $T_{inj} < (T_{EB} + \Delta T_p)$] in providing that liquid heatup was neglected. That feature has now been incorporated, and since a lower T_{inj} means more heat extraction from the seawater, the seawater flow rates are a bit lower than previously indicated.

For the dual binary systems, the effect of the temperature difference ΔT_{AB} between the two fluids in the interloop heat exchanger was investigated. Figure 6 shows how the total heat exchanger area (A_T) decreases as ΔT_{AB} is increased, while $\dot{w}_{GF}$ and $\dot{w}_{SW}$ increase slightly. On balance, it is presently judged that 15°F will be near the optimum in a plant cost trade-off analysis, and that value was used in Figs. 2 through 5.

The scale effect from the geofluid on the insides of the tubes in the evaporators can also be substantial. For Figs. 2 through 5, it was assumed that the scale heat transfer coefficient (h_s) would be only 400 Btu/ft²-h-°F, while a seawater biofouling film coefficient (h_f) of 2000 Btu/ft²-h-°F could be maintained in accord with OTEC experience. Figure 7 shows that, if the geofluid is of better quality so that a higher h_s can be maintained, the

heat exchanger area will be significantly reduced. The water sample data from Adak (Ref. 1) suggest that the geofluid there may be comparable to seawater, so $h_s = 2000$ may be achievable.

FUTURE PLANS

Studies of the dual binary cycle parameter variation are continuing and will be extended to a geofluid resource temperature range of 100 to 200°C. Results for single and dual binary cycle systems at equal resource temperatures will be compared, and specific equipment cost factors will be added in the computer program to obtain preliminary cost comparisons and gross cost estimates. For a specific "baseline" resource temperature, heat exchanger design requirements will be developed for the several heat exchanger regimes to permit more detailed costing, and conceptual plant layouts will be developed. Further program modifications to evaluate specific components, e.g., steam (or isobutane) and ammonia superheaters and preheaters, will be made to refine the plant design. A subcontract award to an experienced power plant design consultant is planned with the aim of attaining detailed generic baseline designs and cost estimates that can be used as starting points for site-specific designs for GEOTEC plants.

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OCEAN ENERGY TECHNOLOGY §5
Technology Base and Commercialization
ZY3COE
Support: DOE/DOET
D. Richards and F. Weiskopf April-June 1982

SUPERVISION OF TESTING OF PNEUMATIC WAVE ENERGY CONVERSION SYSTEM

The use of ocean waves to produce power has often been proposed in the search for renewable energy sources. Although many technically feasible systems have been devised, economically attractive systems of general applicability have not been demonstrated. In a novel pneumatic wave energy conversion (PWEC) concept by M. McCormick of the U.S. Naval Academy (USNA), counterrotating turbines are coupled to a wave-compressed air supply in a way that produces unidirectional rotation of an electric generator. Wave tank tests at small scale at USNA demonstrated the principle, and Prof. McCormick estimated that construction costs and resulting power costs will be attractive at megawatt scale. A PWEC system of nominal 125 kWe size has been constructed and has undergone mechanical and electrical testing to determine rotary inertias, torques, and resistances under DOE/DOET support. At-sea tests by the Naval Civil Engineering Laboratory (NCEL), Port Hueneme, Calif. have been proposed, and APL has been tasked by DOET to oversee this testing program.

SUMMARY

A meeting was held at NCEL on 28, April 1982 to define the parameters and statement of work for an initial at-sea-test feasibility study by NCEL, in which NCEL would evaluate the suitability of existing platforms or structures and seek sites with average wave heights of 1.2 to 1.8 m (4 to 6 ft) and wave periods of 6 to 11 s. Their investigation would also include preliminary analyses of air-chamber/platform structures, test requirements, and cost estimates for the program. In developing the test program, APL is tasked with evaluation of the PWEC design, definition of test requirements, analyses of data, and program direction; NCEL will define the site platform and will construct the test installation, instrument it, conduct the test program, and record and reduce the test data for analysis.

Our preliminary analyses have been based on the modeling results reported in Refs. 1 and 2, which were derived from a 6 s period, sine-wave oscillation of the water column surface. Nominal conditions were: a water-plane to turbine-throat area ratio (A_w/A_t) of 200:1, an air chamber height above the water level (ℓ_0) of 6 m, an internal wave height (Z_0) of ± 1.5 m, a nozzle discharge coefficient (C_d) of 0.6, and a turbine efficiency of 0.5. The effects of A_w, ℓ_0, Z_0, and C_d on peak chamber pressure changes (Δp's) were examined, with the results shown in Fig. 1. In brief, we presently judge that the air chamber height and the chamber diameter should each be near 6 m. A preliminary platform concept is shown in Fig. 2.

BACKGROUND AND DISCUSSION

The development and construction background of the existing PWEC unit were discussed in the previous *Quarterly Report* (Ref. 3). The prototype unit was constructed so that it could be bolted to the deck of the Japanese barge test vessel, *Kaimei*, over an air chamber. The unit has been in the possession of the Solar Energy Research Institute (SERI) in Golden, Colo. At this time only the turbine and gear increaser are fully assembled, and limited tests have been conducted as noted. Modeling studies have been made of the combined oscillating water column/air turbine as reported in Refs. 1 and 2. A somewhat modified model is being developed by APL in which the actual wave and energy effects will be simulated.

Installation Test Design Criteria. Peak chamber pressure changes (Δp's with respect to ambient pressure) based on modeling data of Ref. 1 are plotted against turbine power in Fig. 1. Within interpolation reading error, a distinct conformance is seen except for two cases in which changes were made to the discharge coefficient. It was stated (Ref. 1) that changes in turbine efficiency had slight influence, but no data were presented.

Assuming that the model results are representative of actual Z_0 effects and that the discharge coefficient and turbine efficiency are near the assumed values of 0.6 and 0.5, respectively, the Δp curves can be used to give the requirements for given power outputs. However, these curves do not take into account the effects of irregular waves, water mass (including added mass), draft, or resonance effects. Nevertheless, some qualitative judgments can be inferred for air chamber and test installation design. The peak *allowable* pressures are obviously critical parameters for both turbine control and air chamber design.

Each turbine is stated to be designed for 125 kW at 450 rpm (max 205 kW at 552 rpm), with a step-up gear box rated at 125 hp for each turbine drive shaft; the generator output is 150 kW at 1200 rpm with a capability of 275 kW at 1800 rpm (safe speed limit). For the assumed values and machine rating limits, a probable maximum operating pressure of ± 13.8 kPa (2 psi) and peak allowable pressure of ± 20.7 kPa (3 psi) are tentatively proposed as design criteria for turbine Δp. Without venting, air chamber pressures could exceed ± 3 psi, depending on the design (survival) wave and chamber dimensions and the height (see Fig. 1). Thus, relief ports and positive isolation of the turbine are required.

The data show that air chamber height is the most important dimension, and the test installation chamber height should be near the 6 m nominal design value (≈ 20 ft) for the SERI model. This height, which is dependent on siting, should provide adequate interior clearance from higher waves or amplified water column level and

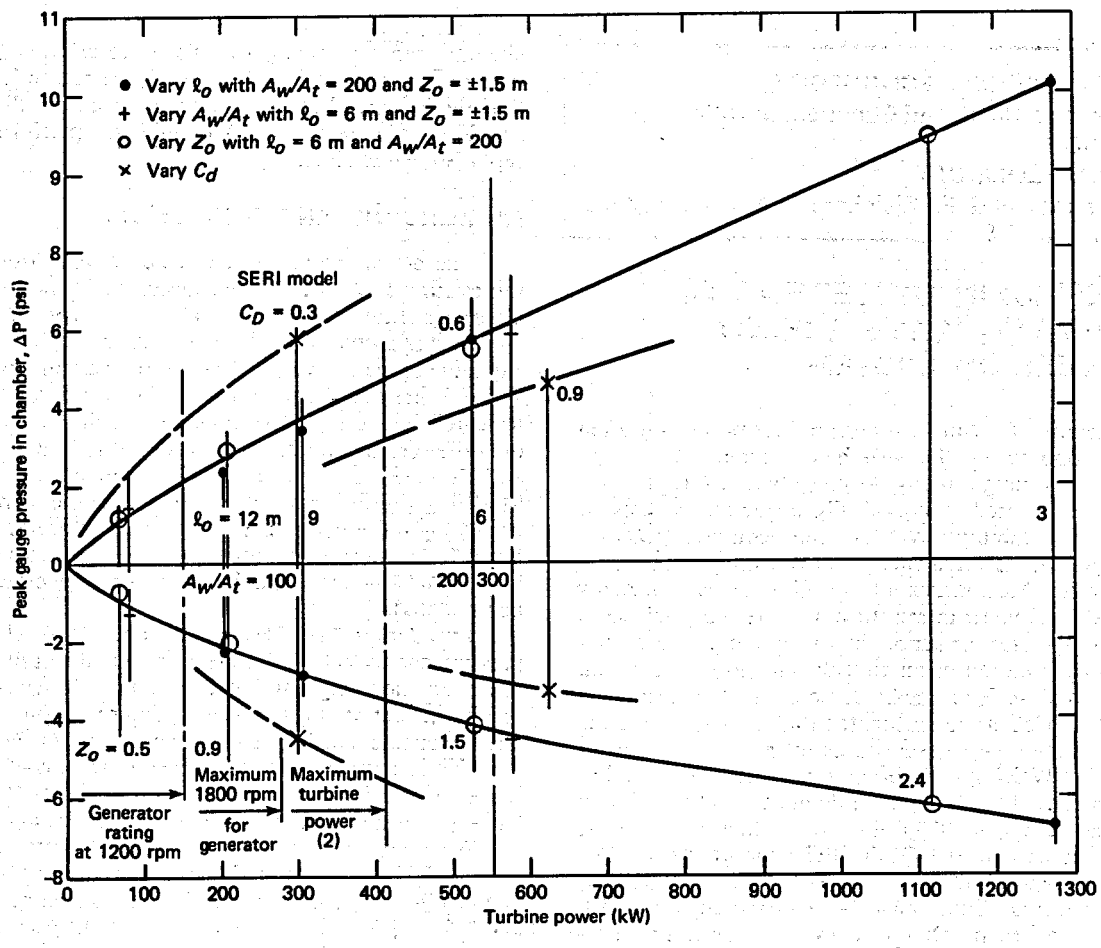

Fig. 1 Turbine output power versus peak gauge pressure in chamber. (82-2/46)

from wave or spray impact on the prototype PWEC assembly. A water spray (droplet) eliminator could also be provided at a top outlet. The maximum (survival design) wave for the site, however, will govern the design for both air chamber pressures and platform forces. An area ratio near 75:1 (≈15 ft diameter) would appear adequate for $Z_0 \simeq 1.5$ m. A larger ratio is desirable to attain meaningful power output at the normally much lower expected wave heights; this will increase the structural and relief requirements of the chamber and the platform forces.

On the basis of the above preliminary installation criteria, a possible platform air chamber installation has been developed, as shown in Fig. 2. Specific comments are:

1. A fixed mounting (relative to sea level) is desired, leading to installation on a tower or tension-leg-moored semisubmersible. In either case, the forces and loads will be high and will require substantial structural support. (Pressures of ±3 psi will produce a ±75,000 lb force at 15 ft diameter or ±140,000 lb at 20 ft diameter). A used oil tank or similar vessel might be used for the air chamber with some stiffening and modifications if necessary.
2. The ability to tune by adjusting air chamber height would be possible with standard offshore rack and pinion arrangements but is probably too complex and costly. The possibility will be evaluated when a site is determined.
3. The air chamber pressures given in Refs. 1 and 2 are thought to be higher than will actually be attained, and the model Z_0 of ±1.5 m would require a wave height near 3 m. Available sites will probably have lower wave design conditions, so that a larger area ratio will be required.

Prototype PWEC Design and Platform Installation. The PWEC unit was inspected in early July, and discussions of probable site conditions and the testing program were held with NCEL and SERI personnel, including review of the APL study of PWEC construction drawings, turbine data, and the 1/4-scale model tests in the USNA wave tank (Ref. 4). The APL examination led to the following conclusions:

1. The actual turbine nozzle area computed from drawing dimensions is 1.7 m^2 versus 2.32 m^2 in Latham's original calculation (reduced by changes in turbine design development).
2. Airflow is estimated to be near 50 lb/s at pressure ratios of 1.16 to 1.2 (2 to 3 psi Δp) and an average power of 125 kW, depending on actual turbine losses and overall discharge coefficient.
3. The turbine must be rigidly supported to a structural base to prevent significant deflection under differential air pressure (± 3 psi $\approx \pm 6500$ lb) on the inlet bellmouth area, and diagonal L-plate stiffeners must be added to the existing turbine mounting place if it is retained.
4. A bellmouth-to-air-chamber seal is required for the proposed installation (Fig. 2), which will impose a collapse loading on the bottom turbine air inlet. Chamber pressure > 3 psi will deform the 1/8 in. spun aluminum bellmouth, which must be strengthened.
5. The triple shaft turbine/gear box/generator assembly must be rigidly mounted to a platform structure stiffened against torque-induced torsional oscillation-vibration. The existing support platform is inadequate.
6. Interpolation of the air mass flow curves (Fig. 8 of Ref. 1) scaled to ≈ 150 kW (peak) output, assuming a direct relationship between turbine power and mass flow, results in large speed oscillations. For the rotary inertias quoted in Ref. 2 (turbine-gearbox ≈ 3 kg-m^2, generator ≈ 4 kg-m^2), the estimated variations are $\pm 36\%$ or ± 7.2 rps at 20 rps (1200 rpm) and $\pm 17\%$ or ± 2.5 rps at 30 rps (1800 rpm). These variations depend on wave period and to some extent on loading. Additional flywheel rotary inertia to reduce these oscillations should be added. There is space on the turbine side of the gearbox to add an overhung 400 lb wheel with a radius of gyration of approximately 9 in. (insufficient to reduce oscillations to about $\pm 5\%$ or less at 1800 rpm), but this would require changes in the center shaft and possibly in the bearing as well as gearbox stiffening and support. Therefore, it is recommended that a flywheel be mounted between the gearbox and the generator.
7. A check for radical failure (i.e., shaft seizure or blade jamming) indicates that a 1 s impulse torque could be 2.5 to 4 times normal at 1200 to 1800 rpm generator speed (assuming no motoring*) and may not cause structural damage. A flywheel conceivably would cause major damage or radical failure, but it may be possible to disengage the existing electric clutch via a reverse torque limit sensor.
8. Turbine and gearbox housings are made of welded aluminum bolted to steel, with a direct sea path connection. The addition of an impressed-current corrosion protection system seems advisable.

*Motoring occurs when the generator or flywheel drives the turbines, which happens when the airflow is reversed (no airflow). In the case of turbine stoppage, the high reverse torque can be used to disengage the flywheel or generator.

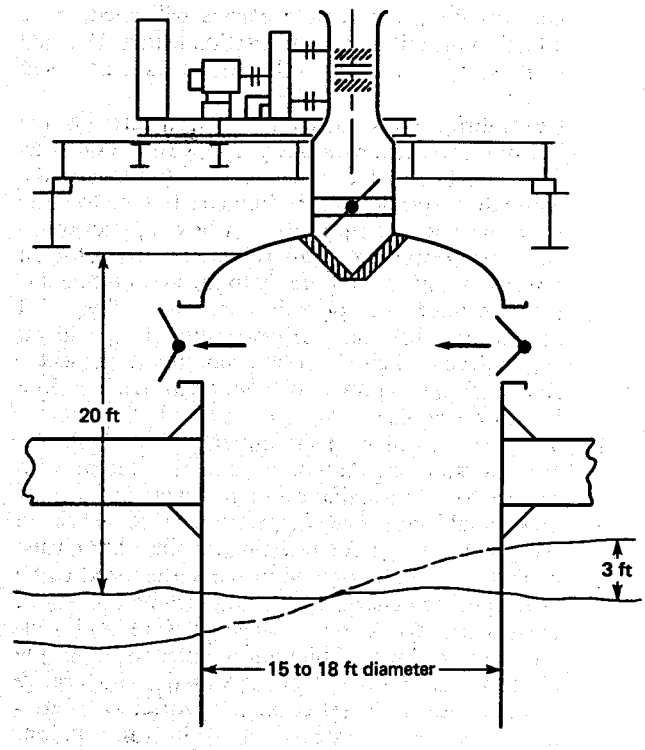

Fig. 2 Conceptual PWEC installation on tower structure. (82-2/47)

9. The generator load bank was to be provided on *Kaimei*. For the proposed NCEL tests, a variable resistive load bank is required. Reference 1 notes that the generator voltage regulation is linear with rpm and proposed three resistance levels for wind tunnel load tests to 90, 125, and 150 kW at 1200 rpm. It was subsequently learned that the existing generator is rated 125 kW, 50 Hg AC at 1200 rpm. For the probable speed-load control for optimum efficiency, a DC generator would have better control capability.
10. The original control concepts were described as: start-up breakaway motoring via an electric clutched worm gear drive motor, dropping out at rpm level A; gear drive-generator electric clutch closes at rpm level B; generator load applied at rpm level C; air chamber vent 1 opens and closes at rpm level D and/or preset pressures; and air chamber vent 2 (and 1) opens and guillotine closes at rpm limit E, requiring manual reset. With the now proposed platform installation, the existing vents and guillotine are not required, and a combined pressure-speed-generator load control system is necessary. A key control element is a fast-acting pressure (and speed) response to an extreme wave of a series requiring air chamber vent opening and turbine valve closing (or throttling). For the proposed air chamber/turbine inlet, a butterfly valve with a pneumatic actuator and platform control air supply is required; hydraulic or electric actuators are too slow. It is assumed the existing controls can be adapted with

little modification or addition. Additional logging of controls data and remote alarms will need to be added to the initial instrumentation listing. Detailed controls system design will require data as noted below.

11. Gear lubrication is via an oil-immersed bath. For the bottom turbine, the output gear tips run in oil at its fill level, but in the upper turbine (reversed), the entire drive spiroid must be immersed. Similarly, the lower output gear tip in the gearbox supplies oil to the upper gears. For long-term unattended testing, a separate spray-type oil supply to each gear element is recommended to provide positive oiling and monitoring. The necessary pressure, flow, and oil supply level switches can be connected to present a single remote alarm and shutdown signal before loss-of-oil damage.
12. With the turbine inlet butterfly valve closed, the sea state should not be a major factor with respect to safe installation or removal, but a shaft lock should be provided, particularly for work on the generator and for resetting turbine stator vane angles. Automatic operation sequences need to be developed and checked prior to machine operation, particularly for overspeed-overpressure and runaway protection. Minimum maintenance on the platform is desired, and the major imperative would appear to be selection and protection of controls, electrical systems, and instrumentation. Problems with the turbine would necessitate its removal for shop maintenance.

FUTURE PLANS

A detailed PWEC design information and description report including present assembly equipment and controls, ratings, and details is being assembled by the SERI contractor (to be completed by September).

APL will model the proposed installation, validate the SERI work, and extend the present understanding for test installation design requirements. APL will coordinate and review the platform and installation requirements, including controls and instrumentation, with NCEL when sufficient platform and site data are available. The PWEC structural support requirement and proposed stiffening design will be checked when further turbine and modeling data are available. A preliminary turbine air test using an industrial blower is proposed to obtain turbine and system characteristics and to proof system operation, instrumentation, and controls prior to actual platform installation.

NCEL will review and propose means to effect the PWEC modifications and additions discussed and will propose test requirements as they are developed further. A review of the site-wave data investigation will be held in August at which time it may be possible to select a platform design and further define the test requirements and costs.

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President's Office		President's Office	1
Provost's Office		R. P. Longaker	1
Energy Research Institude		J. L. Katz	1
Center Metro Plan. & Research		J. C. Fisher	14
Whiting School of Engineering		V. D. Vandelinde	1
Geography and Environmental Engineering		M. G. Wolman	1
Earth and Planetary Sciences		O. M. Phillips	1
Univ. of Hawaii	Honolulu, HI	J. Craven, Dean Marine Programs	1
Univ. Maryland	Cambridge, MD	Vaughn Center for Environmental and Estuaries Studies, Horn Point	1
Univ. Maryland	College Park, MD	Library	1
Univ. Maryland	Princess Anne, MD	Library	1
Univ. Puerto Rico	Mayaguez, Puerto Rico	D. S. Sasscer	1
Univ. Utah Res. Inst.	Salt Lake City, UT	D. Foley	1
Univ. Virginia	Charlottesville, VA	S. F. Singer	1
COMPANIES			
Basic Resources Corp.	New York, NY	J. Yaffo	1
Bethleham Steel Corp.	Baltimore, MD	E. Schorsch	1
Ebasco Services	New York, NY	W. Mott	1
Ebasco Services	Newport Beach, CA	M. S. Jones, Jr.	1
EBL Engineers, Inc.	Salisbury, MD	R. H. Stratemeyer	1
EG&G Idaho, Inc.	Idaho Falls, ID	E. DiBello	1
General Electric Co.	Schenectady, NY	D. Lessard	1
Lockheed Missile and Space Co. Inc.	Sunnyvale, CA	R. Fuller	1
	Washington, DC	F. Naef	1
Sea Solar Power	York, PA	J. H. Anderson, Jr.	1
The Mitre Co.	McLean, VA	R. Manley	1
TRW	Redondo Beach, CA	J. Snyder	1
		A. Griffin	1
VSE Corp.	Alexandria, VA	P. Walsh	1
		J. Obradovich	1