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Quarterly Report

OCEAN ENERGY SYSTEMS

at The Johns Hopkins University Applied Physics Laboratory

JANUARY — MARCH 1983

MASTER

THE JOHNS HOPKINS UNIVERSITY ■ APPLIED PHYSICS LABORATORY

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THE JOHNS HOPKINS UNIVERSITY ■ APPLIED PHYSICS LABORATORY
Johns Hopkins Road, Laurel, Maryland 20707

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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.

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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 and preliminary design activity of industry teams that are designing a shelf-mounted offshore OTEC pilot plant that could deliver power to Oahu, Hawaii. In addition, the Laboratory is now taking part in a program to evaluate and test the Pneumatic Wave-Energy Conversion System (PWECS), an ocean-energy device consisting of a turbine that is air-driven as a result of wave action in a chamber. This *Quarterly Report* summarizes the work on the various tasks as of 31 March 1983.

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GEOTEC PLANT PERFORMANCE USING STEAM/AMMONIA DUAL-BINARY CYCLE

For near-ocean sites where a geothermal water resource with a temperature in the 100 to 180°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 the possible use of a GEOTEC plant at a U.S. Naval Station is the Naval Air Station at Adak Island, Alaska. This report presents the latest cycle analysis results for plants using the steam/ammonia dual-binary cycle with steam and ammonia superheaters. The present cost estimate for a 10-MWe (net) power plant at Adak—\$4150/kWe—is given in detail. A conceptual arrangement and a description of the plant at Adak are included.

SUMMARY AND CONCLUSIONS

Figure 1 is a simplified schematic diagram for the dual-binary plant as analyzed herein. It is the same as that

analyzed in Ref. 1 except that superheaters are added ahead of the turbines to increase the turbine exit quality to 98% (or to the highest value achievable while maintaining a pinch (minimum) temperature difference, ΔT_p , of 5.5°C between the two fluids in each superheater and evaporator). It is assumed that superheating occurs at constant pressure, equal to the evaporator pressure. The geofluid flows inside the tubes of shell-and-tube heat exchangers through the superheater and evaporator of loop A and then through the superheater and evaporator of loop B. Figure 1 shows the optimal conditions for a geofluid temperature, T_{GF} , of 180°C when fresh water is used as the working fluid in loop A and ammonia is used in loop B. The two loops are coupled through an interloop heat exchanger, with ammonia inside the tubes. All of the heat exchangers are horizontal; the evaporators are pool boilers.

For the superheaters, the vapor-side (shell-side) heat transfer coefficient, h , is calculated for turbulent flow normal to staggered tubes using the following equation:

$$hD/k = 0.33(G_{\max} D/\mu)^{0.6} (\mu c_p/k)^{1/3}, \quad (1)$$

Fig. 1 Cycle diagram for 10-MWe(net), steam/ammonia, dual-binary GEOTEC plant at Adak, Alaska. (83-1/45)

Table 1

Comparison of dual-binary steam/ammonia cycle with and without superheat.

	Super-heat	No Super-heat
Geofluid flow (kg/s)	158	167
Seawater flow (kg/s)	981	1044
Steam flow (kg/s)	16	18
Ammonia flow (kg/s)	48	57
Total heat exchanger areas (m ²)	6444	5776
Quality, steam turbine exit	0.97	0.93
Quality, ammonia turbine exit	0.98	0.88
Gross power (MWe)	11.0	11.1
Thermal efficiency (%)	11.1	10.5
Cost (\$M)	41.5	41.0

Conditions:

$$T_{GF} = 180^{\circ}\text{C}$$

$$\text{Drawdown} = 100 \text{ m}$$

$$T_{SW} = 5^{\circ}\text{C}$$

$$P_N = 10 \text{ MWe}$$

$$T_{inj} = 80^{\circ}\text{C}$$

Fig. 2 Estimated costs of 10-MWe(net), steam/ammonia, dual-binary GEOTEC Plant at Adak, Alaska. (83-1/46)

where D is the tube's outside diameter and k , μ , c_p , and $G_{\max}$ are the vapor thermal conductivity, viscosity, specific heat, and mass flux, respectively, all evaluated at the average temperature in the superheater. The $G_{\max}$ values assumed herein are 73,200 and 220,000 kg/h-m² for steam and ammonia, respectively.

Shown in Table 1 are the effects of superheating the steam and ammonia. The results are presented for the nominal case and estimated cost factors for Adak. This amount is twice as much as the cost would be in the lower continental states (CONUS) for installed plant equipment (described later) and three times the CONUS cost for wells. The cycle performance is improved by superheating; flow requirements are reduced throughout (5.4 to 15.8%), and overall thermal efficiency is improved. The turbine exit qualities are increased from 93 to 97% and from 88 to 98% for steam and ammonia, respectively. However, the total costs are essentially the same because of the required increase in the total heat exchanger surface area when superheaters are added.

Figure 2 shows cost estimates for the steam/ammonia dual-binary plant at Adak as functions of T_{GF} and the geofluid reinjection temperature, T_{inj} . The optimal (lowest cost) value of T_{inj} increases as T_{GF} increases. For $T_{GF} = 180^{\circ}\text{C}$, the estimated cost is \$41M, whereas for 120°C it is \$82M. These cost estimates are based on \$269/m² (\$25/ft²) for all heat exchangers, \$300/kWe (net) for turbine-generators, \$150k/production well for geofluid pumps, and \$1M/production or reinjection well for drilling, casing and housing. Table 2 shows the cost breakdown for the CONUS and Adak cases with the nominal Adak temperatures.

Figure 3 shows the geofluid and seawater flow requirements as functions of T_{GF} for the steam/ammonia system. For each value of T_{GF} , the optimal value of T_{inj} (see Fig. 2) has been selected for the plot in Fig. 3. If flow rates per well of approximately 65 kg/s (1000 gal/min) are attained, it appears that two or three production wells will be needed for 10 MWe, and the seawater flow will be about six times the geofluid flow. A conceptual plant arrangement will be discussed later.

BACKGROUND AND DISCUSSION

In addition to T_{GF} , T_{inj} , and the seawater inlet temperature ($T_{SW} = 5^{\circ}\text{C}$ herein), the computer program that we have developed takes as inputs the following parameters: the pinch temperature difference, ΔT_p , for each heat exchanger; the drawdown depth, Z_d , in the geofluid production wells (100 m herein); the booster (feed) pump pressure needed to keep the geofluid from flashing (related to T_{GF}); the geofluid and seawater velocities in piping systems (2.1 m/s herein) and heat exchangers (2.4 m/s); the seawater elevation head (6 m herein); the geofluid and seawater pressure drops (6 m per heat exchanger); the thermodynamic properties of the working fluids; the component efficiencies; and the desired net power output from the plant (10 MWe herein). An iterative procedure is used to establish the flow rates (and the associated pumping power requirements) that yield the desired net power. Frictional losses in the geofluid and seawater distribution systems will be small with the 2.1 m/s velocity and are assumed to be covered by the aforementioned head losses. The geofluid flow rate per well is assumed to be 64.7 kg/s (1000 gal/min). The number of reinjection wells needed is assumed to be one-half the number of production wells.

Table 2
Estimated costs (1982 \$) for steam/ammonia
GEOTEC plant.

Equipment costs	\$k
Heat exchangers (\$25/ft ²)	2130
Turbine-generator (\$300/kW)	3305
Seawater pumps	21
Geofluid pumps (\$150k/production well)	378
Pump A working fluid	19
Pump B working fluid	22
A. Equipment cost subtotal	5875
Misc. building costs	
Piping, valves, etc. (0.10A)	587
Electrical (0.070A)	411
Structural steel (0.020A)	118
Instrumentation (0.025A)	146
Insulation (0.015A)	88
Painting (0.010A)	59
Buildings (\$5/ft ² heat exchanger)	426
B. Misc. building costs subtotal	1835
C. Total equip. and building cost (A + B)	7710
Field installation (0.35C)	2699
D. Total installed cost	10409
Engineering and management (0.12D)	1249
Interest during construction (0.18C)	1387
E. Total plant and equip. cost, CONUS	13045
F. Total plant and equip. cost, Adak (2 × CONUS)	26090
Wells and piping	
Production wells (\$1000k/well)	2520
Reinjection wells (\$1000k/well)	1260
Geofluid piping, valves, insulation	724
Injection piping, valves	398
Seawater piping, valves, and intake	226
G. Total well and piping cost, CONUS	5128
H. Total wells and piping cost, Adak (3 × CONUS)	15384
I. GEOTEC plant cost, CONUS (E + G)	18174
J. GEOTEC plant cost, Adak (F + H)	41475

Conditions:

$$T_{GF} = 180^{\circ}\text{C}, T_{SW} = 5^{\circ}\text{C}, T_{inj} = 80^{\circ}\text{C}$$

Shown in Fig. 4 are the cost effects of changing the values of various input parameters: well productivity, heat exchanger specific cost, drawdown, net power, brine scale factor, and seawater temperature. To obtain smooth curves for comparison purposes, we have calculated all well-field costs assuming that fractional wells could be used; in practice, whole numbers will apply (and breaks will appear in curves), but the flow rate will also vary from well to well. The cost is affected strongly by well productivity; a 40% reduction in well productivity causes a 26% increase in total cost. Small changes in the net power requirement cause proportionate cost changes (no change in specific cost, \$/kWe). Heat exchanger costs and well drawdown are important cost items – a cost saving of 14% can be realized if the heat exchanger costs can be

reduced from \$269/m² (\$25/ft²) to \$86/m² (\$8/ft²), where the lower value may be achievable with aluminum, plate-type heat exchangers. The well drawdown would be a function of the well characteristics at the Adak site. We have assigned a nominal value of 100 m; however, if the drawdown is 200 m, the greater pumping head and lower pump efficiency, which increase the parasitic power requirement, would cause a 10% cost increase. The costs are not very sensitive to changes in the brine scale factor or the seawater temperature (2.2 to 7.8°C).

These preliminary results suggest that a GEOTEC plant at Adak, where all power now is generated by burning jet fuel, should be attractive if a T_{GF} in the 150 to 180°C range can be attained together with an adequate flow rate to generate 10 to 12 MWe net power. For example, with a fixed charge rate of 15%, an annual operating and maintenance cost of 3%, and 90% availability, a \$4100/kWe plant's electricity cost would be 0.18 [(\$4100/kWe)/(8766h × 0.90)] = \$0.093/kWh. This is comparable to costs now being experienced by island utilities that depend on imported oil. As noted earlier, this cost could be reduced by perhaps 14% by using aluminum heat exchangers. Better technology for well drilling may permit savings comparable to our assumed \$3M/well for Adak. These cost estimates are based on simplified algorithms and the use of constant \$/m² heat exchanger costs. Obviously, refinement is required to take into account the cost differences among the several types (superheaters, evaporators, and condensers) as well as computed rather than assumed pressure drops.

PLANT DESCRIPTION

Let us now consider some plant construction and arrangement aspects that probably will apply to a site such as Adak. The plant will be located on a level site near sea level, near the wellfield, and accessible by heavy road vehicles. The geofluid supply wells (Fig. 5) are assumed to be dispersed up to several kilometers from the plant, so that a collector-piping transport system can run alongside the access roads between the well and the plant. The seawater cooling (condensing) system intake and discharge locations are assumed to be a few kilometers apart. Electrical power transmission at the required voltage will interface with and connect to the existing primary distribution system. A portion of the existing generating system will be retained to provide the power for the GEOTEC plant for start-up for emergency use when the GEOTEC plant is shut down.

Figure 6 is a simplified layout depicting the major components of such a plant. The actual plant might look different following detailed study of optimum equipment arrangements in order to use practical preassembled shipment modules, but it would comprise the basic elements shown. Since weather conditions at Adak could severely affect construction and assembly time, we assume that a completely prefabricated, insulated, modular building would house most of the plant. The building would be assembled quickly on a prepared foundation. It would include a control room and an overhead crane to service all but the largest components. The major equipment elements and auxiliary assemblies – including work-

Fig. 3 Geofluid and seawater requirements for 10-MWe (net) GEOTEC plant using steam/ammonia, dual-binary cycle. (83-1/47)

Fig. 4 Effects of parameter changes for steam/ammonia, dual-binary plant with $T_{GF} = 180^\circ\text{C}$, $T_{inj} = 80^\circ\text{C}$, and $T_{SW} = 5^\circ\text{C}$. (83-1/48)

ing fluid storage, treatment, and transfer systems, vacuum, instrument air, etc. — would be skid-mounted on integral foundation supports, with all piping, mechanical

connections and controls, and instrumentation in place and sealed. All instrumentation, controls, and electrical connections would also be preassembled as much as possible and run to connection points for quick assembly. Wherever possible, a sealed, inert, dry gas fill as well as water vapor absorbents would be used for protection during transportation following factory cleaning and checkout.

Road transportation limits probably would dictate the maximum dimensions and weight permissible for a module, but we assume each module to be skidded sequentially into the building to a preplanned location, bolted to the building floor, and quickly interconnected via prepared piping spool pieces etc. Pressure-leak testing and system continuity checking would be necessary, but all major proof tests and capacity-performance checks would be completed at the factory. We also assume that, with the exception of the wells and essential concrete structures, all exterior work including piping, electrical conduits and supports, pumps, intake screens, etc. would be prefabricated to minimize assembly time at the site.

In Fig. 6, geofluid from the supply wells enters the plant in a single pipe and is boosted to a pressure sufficient to prevent its flashing to steam at any point in the geofluid circuit. Whether this pressure will suffice to eliminate the need for reinjection well pumps would be determined by the geologic permeability of the wells. A pressure-surge tank is provided to damp the pressure spikes that could occur in the long pipelines because of well start-up or shutdown. The tank contains pressurized gas over a sealed floating liquid level. Normally, the plant load would determine the number of supply wells on-line, with geofluid flow uncontrolled except as necessary to maintain pressure requirements and possible performance balancing, as will be discussed later. The geofluid enters the superheater (single pass) and then the evaporator (two pass) of loop A. In the heat exchangers, the geofluid or seawater is inside the tubes (and the working fluid is in the shells) to minimize possible corrosion or scaling problems and cleaning requirements.

The loop A evaporator has a baffled section in the bottom (cold) geofluid pass to initially heat up the loop A condensate, which then enters the remaining bottom pass length before rising to the top (hot) geofluid pass. The evaporator is a pool boiler with convective heating in the bottom pass and major steam generation in the top pass. The steam passes through a cross-flow baffled superheater before entering the loop A steam turbine. A turbine inlet valve and a bypass control the pressure in each loop at start-up/shutdown and during transients, with the individual turbine-generator load share most probably determined by inlet-vane settings under microprocessor control. The loop A (steam) turbine exhausts to the shell of a condenser in which the loop B ammonia condensate flows in the tubing. A single-pass condenser is used, and a percentage of the ammonia is evaporated in the heat exchange process, with the ammonia exiting via two-phase flow. The steam condensate is pumped from the condenser hotwell by a standard vertically mounted multistage condensate pump back to the evaporator via condensate control and treatment systems. The loop A cycle pressures are such that a booster (boiler feed) pump

may not be necessary. Hot-well level controls, water make-up, vacuum, noncondensables removal, and most other loop A equipment are standard designs for steam plants.

The loop B (ammonia) power cycle receives the rejected heat from the loop A condenser (i.e., the interloop heat exchanger); the partially vaporized ammonia then flows to the loop B evaporator and the superheater. The ammonia evaporator is a pool boiler; geofluid flows in an upper (hot) pass and lower (cold) pass after first flowing through a single-pass superheater. Ammonia vapor leaves the evaporator shell through a droplet eliminator and then through the cross-flow baffled superheater, as in the loop A cycle. The ammonia from the turbine is exhausted to a condenser where cold seawater flows through the tubes in a lower and then an upper pass. The condenser water system uses a conventional intake structure and equipment and a vertical mixed-flow cold water pump fitted for salt-water service; condensed ammonia is pumped to the loop A condenser to complete the cycle. A single, multistage, vertical, ammonia condensate pump is shown with an intermediate condensate surge tank and a booster pump to provide the required evaporator feed pressure. Dual pumps (one standby) are desired for all auxiliary systems. Ammonia cycle pressures are much above atmospheric pressure throughout; thus, following initial inert gas purge and ammonia charge, noncondensables should not be a problem, but provision would be made for their removal.

Miscellaneous equipment including level controls, bypass-fill, drains, etc. are not shown but would be typical of ammonia plant standards, as is the turbine expander. Ammonia leakage would be to the atmosphere or to other cycle fluids, and suitable equipment would be installed to detect and monitor leakage. Welded tube to tube-sheet designs would be preferred to minimize or prevent interfluid leakage. An ammonia removal system would be required in the case of the loop A cycle condensate.

For plant start-up, a gradual warm-up via supply-well control and geofluid bypass is envisaged, with seawater flowing to the loop B condenser; the loop B (ammonia) cycle would be started first, bypassing the turbine. The geofluid bypass shown across loop A would permit part-load operation of loop B alone and possible balancing of the performance between each cycle on full operation. Once ammonia begins to flow through the loop A condenser, that system can be started; for each cycle, when sufficient working fluid flows and pressures have been reached via turbine bypass control, the turbines can be started and brought up to rated speed, and the generators can be phased in and connected. The plant output load can then be controlled by using turbine control valves and adding supply well pumps.

Geofluid discharge from the loop B evaporator is shown going to reinjection wells, but it may be feasible to extract additional heat for space heating or domestic uses, providing the solids remain in solution. Thus, for example, if the temperature of the injectant leaving the plant is 80°C, as indicated in Fig. 1, a further 30°C heat extraction to about 50°C reinjection temperature could

Fig. 5 Typical supply well. (83-1/49)

represent near 20 MW of thermal energy to a hot-water heat distribution system. Evaluation of this possibility is warranted.

FUTURE PLANS

Similar dual-binary cycle calculations will be made with isobutane and ammonia as the working fluids. Prior calculations (Ref. 2) had indicated that this combination would require slightly less geofluid flow but larger heat exchangers than the steam/ammonia system. Further effort will be devoted to heat exchanger design, and we will concentrate efforts on potential cost reductions that could make plants with low geofluid temperatures (100 to 130°C) cost competitive.

With regard to a possible plant at Adak, the Naval Weapons Center is presently negotiating a modest sub-contract with an industrial team to carry the conceptual

Fig. 6 Concept for GEOTEC plant arrangement. (83-1/50)

design and cost estimate for a GEOTEC plant at Adak to the next level of detail and accuracy. A report on the resource assessment at Adak is also in preparation by NWC. The Navy may fund and conduct further exploratory drilling. One possible conclusion of this work is that the Navy would issue a Request for Proposal for construction of a GEOTEC plant by a private company that would sell the power to the Navy.

REFERENCES

1. G. L. Dugger, L. L. Perini, and D. Richards, "Hybrid Geothermal-Ocean Thermal Energy Conversion (GEOTEC) Power Plant Analysis and Cost Estimates," presented at the 5th Miami Conf. on Alternative Energy Sources, Miami Beach (13-15 Dec 1982).
2. Section 4, *Quarterly Report, Apr-Jun 1982*, JHU/APL OQR/82-2.

OTEC METHANOL

The use of slowly cruising plantships to produce synfuels and energy-intensive products makes the tropical oceans ($\pm 20^\circ$ latitude) a virtually unlimited, renewable resource for world energy needs. Conversion to chemical energy of only 0.05% of the heat absorbed in these waters at the ocean's surface would produce a fuel supply equivalent to the oil consumption of the world in 1980. The present program is part of a broad effort to identify and prioritize OTEC products and processes that could have a significant effect 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

The conceptual design of a 160 MW, OTEC methanol-from-coal plantship based on a design by Brown and Root Development, Inc. (BARDI) was documented in prior *Quarterly Reports* (Refs. 1 and 2); a joint APL-BARDI presentation of the work and results was given to a DOE and OTEC support contractor audience on January 19, 1983.

In this report, further details of the BARDI process design are presented, and an estimate of OTEC methanol plantship capital and product costs is given.

Also reported in Ref. 1 were the initial process optimization studies based on the use of the Rockwell molten-salt-bed gasifier in place of the Texaco gasifier of the BARDI study. In this quarter, preparations were initiated to issue small design-study contracts to Rockwell, Inc. and Ebasco Services, Inc. for a more detailed investigation of an OTEC methanol plantship using the Rockwell gasifier. APL's preliminary capital and product cost estimates show that OTEC methanol will be competitive with alternative processes for methanol from coal or from natural gas (at decontrolled prices).

BACKGROUND AND DISCUSSION

As previously reported, the BARDI study resulted in a 1000-ton/day methanol process plant layout occupying an 84-m-long section at the center of the plantship, with two 80-MWe OTEC power systems, one fore and one aft of the process plant, each with a nominal 12.2-m-diameter cold water pipe. An artist's rendering of the design (Fig. 1) and the process block flow diagram (Fig. 2) are repeated from Ref. 1.

The coal is ground on shore to the required gasifier size, slurried to 70 to 75% by weight in water, and shipped to the plantship where it is pumped to on-board storage. The coal slurry would be pumped by a system such as the Marconaflo process used in the transfer of iron ore slurry. The coal is gasified by reaction with oxygen from OTEC water electrolysis to produce synthesis gas. This is a mixture of carbon monoxide and hydrogen that, after removal of carryover solids, acid gases, and excess CO_2 , is compressed with the OTEC hydrogen and cycled through a catalytic converter to produce methanol. Storage is provided for the feedstock and the product, including the by-product and supplies for process needs, on a 28-day transshipment cycle.

Detailed diagrams and material balances were developed, equipment weights, sizes, and cost quotations were obtained for the system layout, and estimates were presented in the final BARDI report. For the process work, Illinois No. 6 coal (industry standard) was used as the design feed. Although several different processes could be used for each step of the overall scheme, BARDI and APL agreed to use the Texaco process for coal gasification and coal slurry preparation, the Selexol process for H_2S and COS removal, the Stretford process for sulfur removal, and the Lurgi process for methanol synthesis. All of these processes have been commercially proven. The Texaco gasifier is a pressurized (3.1 MPa) down-feed slagging design that requires a coal-water slurry feed, producing no oils, tars, or phenols. A waste-heat boiler at the gasifier outlet generates high-pressure steam for the turbines that drive the large syngas compressors; the excess steam is let down to medium (synthesis reactor steam) pressure.

In the process, part of the synthesis gas passes through a shift reactor to make additional hydrogen via the reaction $\text{H}_2\text{O} + \text{CO} \rightarrow \text{H}_2 + \text{CO}_2$. This flow is adjusted to maintain the relationship $(\text{H}_2 + \text{CO}_2)/(\text{CO} + \text{CO}_2) \geq 2$ by volume in the total synthesis gas. The combined flow then undergoes processes in which acid gases are removed (excess CO_2 and sulfur). Crude methanol includes approximately 15% water from the reaction $3\text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$, plus some higher alcohols and light ends. Those are removed by distillation. The waste organics may be used as fuel or flared. Sodium hydroxide (NaOH) is added to the product (and also the coal slurry) to control pH, so that alloy steels are not required for storage and transport. The NaOH is removed with higher alcohols on distillation to fuel grades. Syngas, including added OTEC hydrogen, is compressed from a near 2.75 MPa entering gas pressure to the 6.9 MPa reactor pressure. The Lurgi reactor temperature is controlled by boiling water outside the reactor tubes. The water, along with the excess steam

Fig. 1 160 MW methanol plantship. (83-1/51)

Fig. 2 Flow diagram of the BARDI process. (83-1/52).

Table 1

Plantship capital costs (in mid-1980 dollars).

Component systems	40 MW	Scaling Factor	Explanation of Factor	160 MW
Platform system	\$20.4M	Size ^{0.8}		\$62M
Hull structure	—	\$/m ²		28
Added structure for CH ₃ OH plant	7.6	2.25	Side area	17
Position control system	2.1	NA	BARDI estimate	6
Platform support system	6.4	NA	BARDI estimate	6
Outfit and furnishings	0.1	1.0		0.4
Seawater systems	4.5	4 ^{0.93}	Experience factor	16
Cold-water pumps and motors	5.2	4 ^{0.93}	Experience factor	19
Warm-water pumps and motors	0.5	1.0		2
Biofouling and corrosion control				
Subtotal	46.7			156.4
Cold-water pipe system				
Pipe system	6.6	2 × 40 / 30	Weight ratio	18
Screen	0.1	2 × 40 / 30	Weight ratio	0.3
CWP/hull connection	2.7	2 × 40 / 30	Weight ratio	7
Subtotal	9.4			25.3
Power system				
Evaporator system	14.3	4 ^{0.93}	Experience factor	52
Condenser system	14.0	4 ^{0.93}	Experience factor	50
Working fluid system	3.1	4 ^{0.85}	Experience factor	10
Purge system	0.4	4 ^{0.85}	Experience factor	1
Power generation	7.0	4 ^{0.93}	Experience factor	25
Auxiliary systems	0.6	4 ^{0.93}	Experience factor	2
Instrumentation and control	1.6	4 ^{0.93}	Preliminary estimate	6
Biofouling and corrosion control	1.0	4 ^{0.93}	Preliminary estimate	2
Subtotal	42.0			148
Methanol system				
Gasification		1.0	BARDI estimate	94
Synthesis		1.0	BARDI estimate	30
Distillation		1.0	BARDI estimate	9
Utilities		1.0	BARDI estimate	29
Electrolyzers (Teledyne)			BARDI estimate	40
Power conversion (Seward)		4 ^{0.95}	Experience factor	18
Subtotal				219
Deployment				
Platform	0.9	1.0		4
Power system	0.7	1.0		3
Cold-water pipe	9.4		Weight ratio	25
Subtotal	11.0			32
Industrial facilities	3.7		Cost ratio	17

Component systems	40 MW	Scaling Factor	Explanation of Factor	160 MW
Engineering and detail design	3.3		Cost ratio	15
Total costs*		Design cost	Design cost + 30% contingency	
160-MW CH ₃ OH plantship With interest during construction (14.8%** of P.I.)		\$613M \$703M	\$796M \$914M	

*Does not include facilities for coal preparation that are amortized in coal price.

**13% interest, 10% first year, 40% second year, 50% third year.

Table 2

OTEC methanol costs (in mid-1980 dollars).*

	Without Contingency (M\$)	With 30% Contingency (M\$)
Estimated plantship investment	703	914
Fixed cost for 345 days/yr operation**	42.7	55.5
Operating costs		
Crew 100 @ \$65,000/yr	6.5	8.5
Catalysts and materials	6.0	7.8
Shipping CH ₃ OH @ \$10/ton	3.5	4.6
Shipping coal @ \$10/ton (750 ton/day)	2.6	3.4
Coal costs @ \$45/ton	11.7	15.2
Subtotal	30.3	39.5
Total annual cost	73	95
Methanol cost, includes nominal 14% return on equity	0.17/l (0.64/gal)	0.22/l (0.83/gal)

*Methanol output 1000 tons/day = 345,000 tons/year = 4.31×10^8 l/yr (1.14×10^8 gal/yr).
For ITC = 0.10, real fixed charge factor = 0.0608.

**Based on DOE/EIA 03651-1 financial assumptions. Nominal cost escalation, 9.1%. Nominal cost of debt, 13%, 30-year plant life, MARAD loan guarantee, and 12.5% equity. The real fixed charge factor includes taxes on 14% return on equity.

from the gasifier, is used for process and equipment drive needs including pumping, water distillation, and possible supplemental electric power generation. Other methanol reactor designs are claimed to operate with little or no CO₂ but are yet to be investigated. Excess heat (steam) is used in a final distillation process to produce 99% fuel-grade methanol and a small amount of lower alcohols, which are stored for shipment.

This simplified process description omits a discussion of intermediate and subsidiary process steps. For the gasifier and methanol synthesis, specific process equipment has been used in plant sizing and costing; all estimated by-

products, waste streams, and auxiliary systems have been accounted for, including cooling water, makeup water distillation and treatment, standby power, and storage and handling for sulfur (32 tons/day), and gasifier slag and waste, which are pumped for transport for on-shore sale, disposal, or treatment.

METHANOL FUEL COSTS

BARDI's cost estimate, including contingency for the on-board process plant, is \$161.4 million (1980 \$), which would produce 1000 tons/day of fuel-grade 98% methanol from 750 tons/day of coal shipped as a slurry. While much of the design data and costs was developed for the land-based processes, our estimates have included those 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. Cost estimates in mid-1980 dollars are developed by scaling the costs for the 40-MW pilot plantship (Ref. 3) to

a 160 MW plantship using scaling and learning factors that are judged to be appropriate (listed in column 3 of Table 1).

The estimate of delivered cost to port shown in Table 2 indicates that OTEC methanol can be made competitive via the process optimization discussed earlier. Costs highly competitive with proposed land processes can be attained with significantly less environmental effect because of the much reduced coal consumption per ton of product.

REFERENCES

1. Section 2, *Quarterly Report, Oct-Dec 1982*, JHU/APL OQR/82-4.
2. Section 2, *Quarterly Report, Jul-Sep 1982*, JHU/APL OQR/82-3.
3. J. F. George and D. Richards, *Baseline Designs of Moored and Grazing 40 MW OTEC Pilot Plants*, Vol. 1A, *Detailed Report*, Vol. 1B, *Engineering Drawings*, JHU/APL SR 80-1A and -1B (Jun 1980).

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, Oahu, Hawaii. An OTEC Pilot Plant Program Management Office has been set up with C. Castellano as Program Manager. The Energy Technology Engineering Center 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, Lawrence Berkeley Laboratory, and Argonne National Laboratory. The working group, formed from these organizations, monitors the progress on the two contracts; APL is a participating member of the group.

SUMMARY

Considerable progress toward completion of the concept designs was demonstrated by both contractors this quarter. The draft final reports (9 month deliverables) were due February 17, 1983, essentially completing this phase of the design program; proposals for the Phase II - Preliminary Design were due February 28, 1983. Report submissions that were reviewed and on which comments were made are listed in Table 1.

APL participated in program management and interim design review meetings at the General Electric Company (GE), Schenectady, N.Y., January 26-28, 1983, and in the draft final design reviews by GE and the Ocean Thermal Corp. (OTC) at DOE February 16 and 17, 1983. The competitive-proprietary aspects of the designs restrict discussion of substantive details, as was noted in Ref. 1.

APL funding requirements for continued program support through the Phase II - Preliminary Design completion (September 1984) were submitted. As requested by the Program Manager, estimated support costs were provided for either one or two Phase II awards.

DISCUSSION

The reports and studies on the site descriptions, design and operational data sets, and site specific environmental assessments by both contractors were extensive and included descriptions of the physical and dynamic, chemical and biological, and oceanographic and geophysical conditions at the site. The conceptual design reports are similarly comprehensive and voluminous.

Many reviewers expressed opinions that the physical plant arrangements required further study and op-

Fig. 1 GE-OTEC tower-mounted pilot plant. (212113)

timization, and that resistance to or protection from the 100-year design wave were major concerns. Descriptive details of the long down-slope cold-water pipe systems and deployment methods were also limited at this concept stage, and little comment was offered except that much more work was required, including knowledge of bottom geology and operations. The estimated total costs were near \$8000/kW (1982 \$), more than 30% higher than the estimates for a moored vessel design. This was felt to be an item of significant concern.

Figure 1 is an artist's rendering of the GE tower-mounted plant. The submerged heat exchangers, pumps,

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	1-6-83	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	1-6-83	11-29-82
16	9b	Interim report, Cost Assessment	•	11-29-82
17	11b	Interim report, Operational and Maintenance Plan	1-6-83	11-29-82
18	12b	Interim report, Commercialization Plan	•	11-29-82
19	13b	Interim report, Preliminary Test Plan Long Lead Item List	1-6-83	11-29-82
20	15b	Interim report, Preliminary System Interface Integration Criteria	1-6-83	11-29-82
21	3d	Final report, Site Specific EA	—	—
22	4b	Interim report, Plan Site/Design Specific EIS (Environmental Impact Statement)	—	—
23	10b	Interim report, Physical Model Test Plan	•	12-8-82
24	1c	Draft final report, Conceptual Design of OTEC Concept	3-14-83	3-11-83
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	3-14-83	3-11-83
30	10c	Draft final report, Physical Model Test Plan	—	3-11-83
31	11c	Draft final report, Operation and Maintenance Plan	—	—
32	12c	Draft final report, Commercialization Plan	—	3-11-83
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	—	—

*At Design Review Meeting of January 28, 1983.

Fig. 2 Ocean Thermal Corp. 40 MWe OTEC pilot plant. (83-1/53)

and piping are supported inside the tower structure. The GE design incorporates the Trane Co. brazed, zinc-coated, aluminum plate-fin heat exchangers in 16 battery modules for the condensers and a similar number for the evaporators. In-line pumps with submerged drive motors supply warm or cold water to groups of heat exchanger batteries. The condensers are located above the evaporators to minimize pumping of the working fluid although this is not as critical with ammonia as it was with R-22. For topside maintenance, automatic isolating valves and piping disconnects permit removal of the heat exchangers by a removal tool. The structure has grown larger in overall dimensions and in member size. The major concerns expressed have been on the overall complexity, underwater installation and maintenance, possible recirculation (reinjection) of discharged water, and wave loadings.

The plant concept by OTC shown in Fig. 2 uses the same equipment layout and plant concept previously described. Each 5 MWe shell and (titanium) tube heat exchanger (two evaporators and two condensers), with its seawater pump, is paired with 10 MW net turbine generators. The plant structure is now self-protective - incorporating a seaward-facing perforated wave barrier (Jarlan wall) that will be floated out and sunk onto a prepared bottom in which the cold, mixed-discharge, and warm-water channels and piping have been set. Warm water

intake is from the landward side through conventional trash racks and traveling screens, to which warm cooling water discharge from the Hawaiian Electric Co. (HECO) Kahe Point generating plant is connected to increase the thermal gradient. Sand carried through the HECO plant may deposit in the warm water channels. (Condenser tube erosion has been a problem that has apparently been resolved by the titanium retubing.) Many reviewers expressed reservations on the compactness of the equipment layout, possible maintenance difficulties, and safety. Design wave effects were also a concern.

For each design, assuming Phase II contracts are awarded, specific model tests and long lead item development tests will be developed, as has been identified in this phase.

FUTURE PLANS

OTEC pilot plant management support is expected to continue at the present level or less, depending on the number of Phase II awards, through September 1984.

REFERENCES

1. Section 1, *Quarterly Report, Oct-Dec 1982*, JHU/APL OQR/82-4.
2. Section 1, *Quarterly Report, Jan-Mar 1982*, JHU/APL OQR/82-1.

SUPERVISION TESTING OF PNEUMATIC WAVE ENERGY CONVERSION SYSTEM

Wave energy conversion has been the objective of increased international efforts in the past decade. Of the concepts that have survived initial examination, the U.S. prototype Pneumatic Wave Energy Conversion System (PWECS) is a leading design contender. Small-scale systems are feasible in many locations where there is a need for power. From the development of these small systems will come the knowledge necessary to determine the prospects for large-sale wave energy (multimegawatt) power. To date, the work and the proposed test program have the aim of providing the essential information for some of these energy conversion applications. The effective commercial conversion and utilization of the energy available from ocean waves requires a demonstration of their practicality and reliability as well as the essential data for economic evaluation of the oscillatory water-column pneumatic-turbine concept.

APL was asked by DOE/DOET to conduct systems analyses of the PWECS and to supervise a proposed ocean-platform-mounted test program. Funding and sites for such an ocean test are as yet uncertain.

SUMMARY

Contract negotiations with the Naval Civil Engineering Laboratory, Port Hueneme, Calif. (NCEL) for PWECS hardware modifications and turbine testing were completed in January 1983, and NCEL was to start work in February 1983 (Ref. 1); however, NCEL withdrew from the agreement in early February. Using the product of those negotiations and the results of on-going analysis work, APL is preparing a revised statement of work for dissemination as a Request for Proposal to qualified sources.

Analyses of the PWECS continued with the expansion of the numerical model to include the dynamics of the PWECS power train. Limited parametric studies were also made to determine probable flywheel size, and the code was modified to include the capability of forcing the model with digitized real-world wave height data taken off Pt. Mugu, Calif. Using this version of the model, a limited parametric study was completed of output power with variations in air chamber geometries and wave resource parameters.

The first air-chamber-orifice model tests were completed at the U.S. Naval Academy (USNA) in mid-March; further model tests have been scheduled for April. The early test data have been reduced and compared with the model predictions. Moderate agreement was found in

internal wave height, but strong disagreement was indicated in peak chamber pressures.

The first part of the economics costing study by Gibbs & Cox, Inc. was completed. The better U.S. coastal sites were identified on the basis of wave power, annual mean variation, and average-to-peak (survival) wave heights.

BACKGROUND

In recent times, many schemes have been proposed to convert ocean surface wave energy to mechanical or electrical power. M. McCormick (of the USNA) gives a good summary in Ref. 2. One of the more straightforward approaches is to drive a turbine with an air supply that is alternately compressed and expanded by an oscillating water column driven by the passing surface wave field. Programs at the U.K. National Engineering Laboratory (Ref. 3) and in Japan also use this approach.

The PWECS, proposed by M. McCormick and designed at the Naval Ship Research and Development Center, was intended as the United States' contribution to an international experiment on the Japanese barge *Kaimei* in 1980 (Ref. 4), but it was not built in time. The design output of the PWECS was 125 kW at an expected ratio of air chamber to ambient pressure of 1.16 in 3-m-high (trough-to-crest) waves. The prototype, designed to be mounted on the deck of the *Kaimei*, was assembled by the Solar Energy Research Institute (SERI) (Ref. 5), and limited mechanical tests were conducted. It consists of a base structure on which are mounted the counter-rotating air turbines, main combining gearbox, magnetic clutch, generator, and a cabinet housing the controls. SERI and its contractors also developed a numerical model of the thermodynamics of the PWECS air capture chamber.

On completion of the PWECS assembly, APL was requested to plan and prepare for a proposed test on a bottom-mounted ocean platform. APL's systems analyses and review of the mechanical design of the prototype PWECS resulted in recommendations for improving the structural integrity of the prototype; adding a flywheel to the power train to reduce speed fluctuations; and redesigning the electrical system, controls, and protective/safety equipment.

As part of the systems analyses, a numerical model of the dynamics of the PWECS was developed, and tests were defined to document the performance of the counter-rotating turbines. Model tests of the air chamber orifice were designed to obtain data to validate the numerical model. APL contracted with Gibbs & Cox, Inc. to conduct a cost study to estimate the commercial viability of PWECS. This study will identify potential sites for PWECS installations, estimate the cost of such

Fig. 1 Schematic of PWEC air-test stand. (83-1/54)

Legend:

$H = 3 \text{ ft}$ ———	$T_p = 15 \text{ s}$	$A_t = 1.8292 \text{ ft}^2$ —▽
7 ft - - - - -	$C_D = 0.7$	3.6584 ft —◇
11 ft - · - · -	$\eta_t = 0.6$	5.4876 ft —□
	$d = 10 \text{ ft}$	7.3168 ft —△
		9.1460 ft —○

Fig. 2 Average power versus chamber diameter for (a) 10 ft freeboard and (b) 20 ft freeboard. (83-1/55)

installations (and the expected average annual power production using the APL numerical model predictions), and estimate the expected cost in mills/kWh of PWEC-generated power for the different sites.

TEST PLANNING SYSTEM STUDIES

The goals of the PWEC test program are (a) to demonstrate the performance, reliability, and efficiency

of the design and (b) to assess its commercial potential. Examination of the prototype design resulted in proposed modifications that would enhance the reliability and improve the performance of the device. The modifications were incorporated into a statement of work that was prepared jointly by APL and NCEL. It included a test designed to document the characteristics of the counter-rotating turbines that convert the energy in the compressed air to mechanical power. The turbines are of a unique design, and no experimental data on their performance exist. The performance data will be used to design the control procedure to optimize the operation of the device and will also be used in the numerical model to predict the power generated for various air chamber geometries and wave resource parameters. Although the scope of the test has not changed, the instrumentation and test modes have undergone several revisions from those discussed in Ref. 1.

The final version of the turbine performance test specification calls for the turbine to be mounted on a new base configured as shown in Fig. 1. However, for the performance test, neither the flywheel nor the clutch will be installed. The turbines are mounted on the new base with the gearbox and a test brake approximately 10 ft above ground and the air ducts and equipment installed beneath and to the side of the base. The air will flow through the turbines from below, with vertical discharge. Mechanical power will be converted to electrical power by a DC generator and absorbed by a resistive load bank or, alternatively, by a noninstrumented friction brake. Turbine output power will be measured by turbine shaft torque and rpm. It will be used to generate a performance map of output power for various rotation speeds and air-flow at constant pressure differentials across the turbines.

Unfortunately, NCEL withdrew from the program for reasons that included overcommitment on existing projects, reassignment of key personnel to other projects, and the uncertainty of an ocean test program. As a result, the statement of work and scope will be revised so that proposals can be requested from other qualified sources in the next quarter.

The numerical model couples the dynamics of the oscillating water column to the thermodynamics of the air capture chamber (Refs. 1 and 6) but has several limiting assumptions involving the ratios of wave height to chamber freeboard and capture-chamber diameter to wavelength. The net result is that the model probably overpredicts the displacement of the oscillating water column surface and consequently the peak pressures and peak power. Nevertheless, the model was used to perform a parametric study of generated power as a function of the geometric and wave resource parameters that characterize the problem. The geometric parameters of interest are the capture chamber diameter, draft, freeboard, and throat area of the turbines. The wave resource parameters are the wave period, wave amplitude, and water depth. The results for a range of chamber diameters, two values of freeboard, five turbine throat areas, and several wave heights and for fixed values of wave period, chamber draft, and water depth (50 ft) are shown in Fig. 2. The predicted values of power are considered to be overestimates but are representative of the performance under ideal conditions.

The dynamics of the PWECS power train were included in the numerical model in order to size the flywheel and to simulate system operation when driven by real-world data. The model includes the time-dependent torque output from the turbines; the moments of inertia of the turbine/gearbox combination, flywheel, and generator; and the loss torques of the gearbox and the DC generator. The resulting equation is:

$$\frac{P}{N} = \frac{BA^2N}{RE} + T + \frac{dN}{dt} (I_{TG} + I_G + I_F),$$

where

- P = instantaneous output power of the turbine (lb-ft/s);
- N = generator-shaft rotation rate (rad/s);
- I_{TG}, I_G, I_F = moments of inertia of turbine/gearbox combination, generator, and flywheel, respectively (slugs-ft²);
- T = loss torque of turbine/gearbox combination (ft-lb);
- R = load resistor value (1 ohm);
- A = proportionality constant between generator shaft rotation rate and output voltage ($V = AN$);
- $B = \frac{550 \text{ ft-lb/s}}{746 \text{ W}}$;
- E = assumed turbine efficiency (50%).

The model was run for a set of geometric and wave resource parameters that was used in the parametric study. The instantaneous power and shaft speed are shown in Fig. 3. Unregulated speed and power are assumed to be possible, and the resulting mean (M) and standard deviation of the rotation rates are 1641 and 24 rpm. A limited parametric study of flywheel size versus standard deviation was conducted for a range of geometric and wave resource parameters; the results are shown in Fig. 4. Those values indicate that a flywheel weighing approximately 1000 lb with a 1-ft radius of gyration (31 slugs-ft²) will smooth the rpm fluctuations to a standard deviation of less than 5% of the mean rotation rate.

The model was also modified to include the capability of using digitized time histories of real wave-height data to provide the forcing term in the model. As described in past *Quarterly Reports*, four time histories of wave height data taken off Pt. Mugu were digitized and processed to provide a 0.02-s-interval time history from which the mean has been extracted. The distribution of wave heights and zero crossing periods for the first of these segments is shown in Fig. 5. The model was executed for this wave-data time segment; sliding boxcar averages (boxcar width = 0.839 min) of the output power and rotation rate are shown in Fig. 6. Again, no speed or power output regulation is considered, and oscillation about the mean similar to that shown in Fig. 3 will occur for each wave.

Fig. 3 Instantaneous power and generator-shaft rotation rate versus time into working period. (83-1/56)

Fig. 4 Variation of standard deviation as a percentage of mean rotation rate with flywheel moment of inertia. (83-1/57)

Fig. 5 Percentage distribution for (a) wave height and (b) wave period, Pt. Mugu data segment. (83-1/58)

Fig. 6 Averaged power and generator shaft rotation rates versus time, Pt. Mugu data segment. (83-1/59)

The first experimental model tests of the PWECS air-chamber-orifice were conducted in the USNA high-performance towing tank. This first test consisted of 36

runs, and, for each run, time histories of the surface displacement of the far-field-wave-amplitude oscillating water column, the chamber pressure, and the air velocity at the chamber exit were measured. Preliminary comparison of the experimental data and the numerical model predictions indicates that the model is in qualitative agreement with the experimental data with regard to surface displacement of the oscillating water column but is in serious disagreement with regard to the peak pressures. The disagreement between the numerical model and experimental data will be investigated in future tests.

FUTURE PLANS

During the next quarter, proposals will be requested for modifications to and testing of the PWECS. If work can begin as soon as contract negotiations are complete, it may be possible to complete the turbine performance tests by the end of this calendar year. Further model tests at the USNA will also be completed in the next quarter, and the numerical model predictions and the experimental data will be compared. As a result of the studies, the numerical model will be modified to obtain system performance predictions that seem reasonable.

NOMENCLATURE

A_t	Turbine throat area
C_D	Turbine discharge coefficient
D	Chamber diameter
d	Draft
l_0	Freeboard
H	Wave height
M	Mean generator-shaft rotation rate
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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2. M. McCormick, *Ocean Wave Energy Conversion*, John Wiley, 1981.
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