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A 165-kW Open-Cycle OTEC Experiment

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ABSTRACT

The Solar Energy Research Institute (SERI) is developing a research experiment to establish the feasibility of producing significant amounts of net power from an open-cycle ocean thermal energy conversion (OC-OTEC) system. This experiment is sized at 165 kW_e gross and is adequate to evaluate turbine performance and system process interactions at a scale that can be extrapolated to projected commercial market entry system sizes of 5-15 MW_e.

RESEARCH ON THE EXTRACTION and conversion of the ocean thermal energy resource using an open-cycle process was initiated by DOE late in FY 1978 with the funding of a task to assess the feasibility of this technology to produce mechanical/electrical power cost-effectively. The original SERI studies, supported by results in subcontracted studies at Colorado School of Mines (1)*, the Westinghouse Corporation (2), and the University of Massachusetts (3), concluded that large-scale plants based on this technology could indeed be economically viable if the main assumptions in the studies were valid. A research program to develop data and analytical methods to refine and support these assumptions was defined and funded in the following technical areas beginning in FY 1980:

- Heat and mass transfer processes with seawater at low pressure
- Gas sorption kinetics in seawater and purge methods
- Low pressure turbine design and performance analysis techniques
- Vacuum and structural design and construction methods.

The research for the last five years was directed at obtaining data that could strengthen the assessment of the open cycle and provide a basis for system development should industry so decide. This research resulted in technical data and methods that were applied in a new system study by the Florida Solar Energy Center and Creare R&D, Inc., (4) that showed that all of the assumptions made in earlier feasibility assessments were conservative. The promise of available OC-OTEC indicated in those studies is even greater than first projected.

The overall conclusions derived from the research to date are that:

- Small-scale plants (5-15 MW_e) using the open-cycle OTEC technology can be economically viable in the near term.
- Open-cycle OTEC power modules in the 2-5-MW_e (net) range can be built today with little or no extension of the critical turbine and cold water pipe technologies.
- The critical issues relating to open-cycle OTEC feasibility are the coupling effects among heat and mass transfer, energy conversion, and fluid dynamics. These effects determine the ratio of power produced to system auxiliary power requirements. These issues can be explored at a geometry scale of approximately five.

The key results of the system study show that there is potential to produce power cost-effectively in relatively small plant sizes using open-cycle OTEC processes. This potential is realizable because steam production and condensation can be accomplished using compact and simple direct-contact heat transfer systems that operate with low hydraulic losses and because dissolved gases released from the seawater during the conversion process can be purged with minimum auxiliary power and with a minimum effect on

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*Numbers in parentheses designate references at end of paper.

heat transfer performance. These heat transfer and gas desorption results were verified in the laboratory using seawater.

The schematic in Figure 1 and the parameters summarized in Table 1 describe experimental and 10-MW_e plants operating in a land-based configuration with a temperature gradient of 22°C (40°F). The high risk technology items associated with the 10-MW_e system described in Table 1 are the large, low pressure turbine required (approximately 12 m in diameter) and the large diameter (5.2 m) cold water pipe required. Because open-cycle OTEC may be cost-effective at small plant sizes, it is possible to define an installation that utilizes multiple power modules using commercial components. Although using multiple double-ended steam turbines and clusters of smaller cold water pipes will cost more than using the optimum configuration in both cases, the premium is not significant enough to preclude this approach from entry level markets for the OTEC technology. A 10-MW_e plant uses multiple steam turbine modules with rotors from the low pressure stages of conventional power plants and multiple cold water pipe modules using 2.4-m-diameter polyethylene pipes deployed in an inverse catenary configuration similar to many discharge outfalls installed on both coasts of the United States.

Since there are potential solutions to the issues of component availability, performance, cost, and technical risk as factors in preventing the development of successful 5-15-MW_e OTEC systems, research can direct attention to the major factor that remains an uncertainty for plant designers--process coupling or interaction effects. These processes and the geometric parameters that influence them are shown in Table 2.

The thermodynamic performance of an open-cycle plant can be maximized by selecting optimum operating parameters such as seawater flow rate. A different optimization occurs if system cost parameters driven by things such as size and geometry are considered. Yet a third optimization occurs when the cost of the service is the selection criterion, and life and maintenance factors must be considered. All five of the major processes interact in a complex way in response to the variation of geometry and operating parameters.

It is clear that one cannot select a process operating parameter or hardware geometry on anything less than an overall system performance and cost criteria. It is not unusual for a designer to trade off heat transfer with hydraulic or pneumatic power to determine the optimum heat exchanger form factor and operating flow rates. This is especially true in OTEC plants where the water flow rates per kilowatt of power are significantly higher than they would be in a conventional plant. However, in addition to this interaction or process coupling an open-cycle plant has the following additional complicating interactions:

- steam side pressure losses, which are affected by duct sizes, mist elimination efficiency, and flow distribution and geometry in the heat exchangers

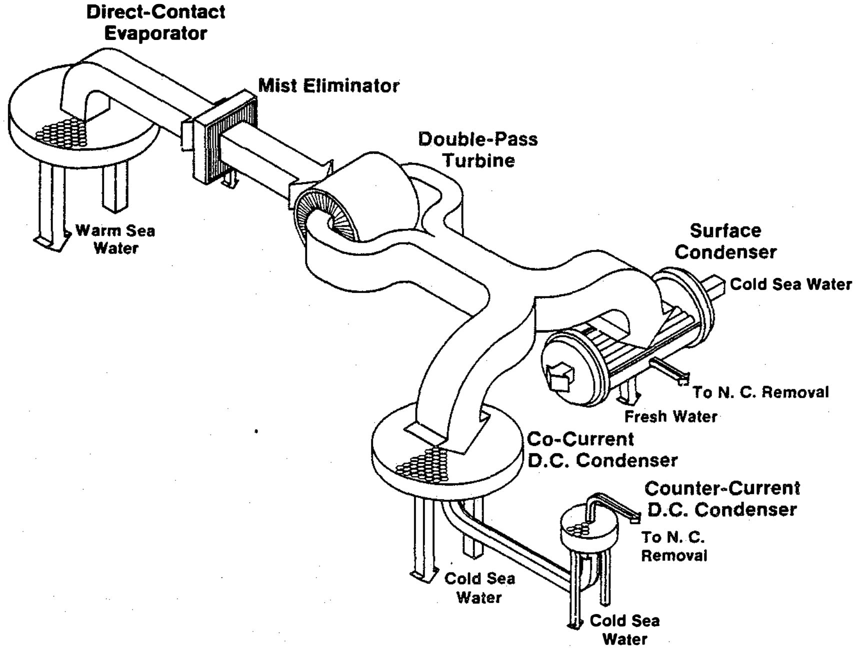


Figure 1. OC-OTEC System Schematic

Table 1. Comparison of an STF Open-Cycle Experiment and a Reference 10 MW_e Design

	Experimental System	10 MW_e
POWER SYSTEMS		
Turbine (double rotor)		
Diameter (m)	1.41	11.81
Gross power (kW)	165	13400
Vacuum vessel		
Evaporator area (m^2)	10.9	680
Condenser area (m^2)	6.9	480
Exhaust compressors		
Number of stages	3	6
Power requirement (kW)	29.6	1074
SEAWATER SYSTEMS		
Pipe diameters (m)		
Warm	0.762	5.07
Cold	0.762	4.58
Discharge	1.078	5.21
Pipe lengths (m)		
Warm	250	315
Cold	1675	2235
Discharge	500	615
Flow rates (kg/s)		
Warm	585	41300
Cold	410	29550
Barometric head loss (m)	3.75	0.0
Pumping power requirement (kW)	86.3	2310
NET POWER (kW)	49	10016

- air purge effectiveness, which affects heat transfer performance, hydraulic pumping requirements, and compressor cost and power
- turbine performance and life, which are driven by liquid and chloride content in the steam; steam fluid dynamic losses; air content; and fluctuations in seawater temperatures and the flow rate.

Because the variation of geometry and operating parameters does not affect the key processes independently but rather in a highly interactive fashion, these five, first order coupling effects and several additional second order effects need to be understood and quantified before successful commercial-scale plants can be designed and built. With this need in mind SERI, with DOE support, has set out to design, build, and operate an open-cycle experiment that permits study of these coupling effects and that is large enough to permit scaling to system sizes, representing market entry level for open-cycle plants. An earlier design for a 1-MW test facility is described in detail by Penney et al. (5). This experimental test facility will be built in two phases.

The experimental apparatus shown in Figure 2 is designed for installation at the Natural Energy Laboratory in Hawaii (NELH). This laboratory, located on the Kona coast of the island of Hawaii, was created by the state of Hawaii in 1974. A DOE Seacoast Test Facility (STF) has been operating at the laboratory since June 1981 when it became clear that a long-term integrated test facility was needed to support the OTEC industry and other ocean energy R&D. The STF has been used to conduct biofouling, corrosion, biocontrol, and other related tests. More recently it has been used to test such open-cycle OTEC processes as flash evaporation, contact condensation, and seawater deaera-

Table 2. Open-Cycle Processes and Geometric Parameters that Influence Them

Open-Cycle Processes	Influence Parameters
Conversion	Turbine geometry and steam flow rate
Heat and mass transfer	Heat exchanger geometry, seawater and steam flow, and noncondensable gas fraction
Steam fluid dynamics	Duct and heat exchanger geometry and steam flow rate
Seawater hydraulics	Heat exchanger and seawater pipe geometry and seawater flow rates
Noncondensable gas purge dynamics	Seawater/gas sorption kinetics, seawater process path, and compressor system design

tion. Design work is presently under way to upgrade the cold seawater (7°C) pumping capability from its present capacity of 1300 gpm to a projected 410 L/s (6500 gpm). The proposed system is designed to be consistent with the projected water pumping capability and consists of four major systems:

- Turbine/generator set
- Seawater evaporator
- Steam condenser
- System gas purge unit.

The sizing and design of this experiment is determined by the minimum size that permits valid scaling of the results to commercial size and by the minimum size and configuration that permits experimental study of the primary technical issue being resolved in the project--process coupling.

Three of these processes (heat and mass transfer, seawater hydraulics, and noncondensable gas purge dynamics) and their interactions are being studied and will be further explored in the first phase of the experiment development. The design of the experiment regarding the five key open-cycle processes are examined in the following sections.

HEAT AND MASS TRANSFER

The evaporator is designed after the methods described by Bharathan (6) and shown in Figure 3. It will have a field of 10-cm vertical spouts located on 0.7-m centers and will stand 0.5-m high. Our analysis, verified with single-spout experiments, indicates that this evaporator will produce 0.5 kg/s-m^2 of steam with a 3.1°C flashdown and less than a meter of hydraulic head loss.

The definition of the condenser is more tentative since research is still ongoing to define the preferred geometry and operating parameters. However, the configuration shown in Figure 4 represents a two stage concept

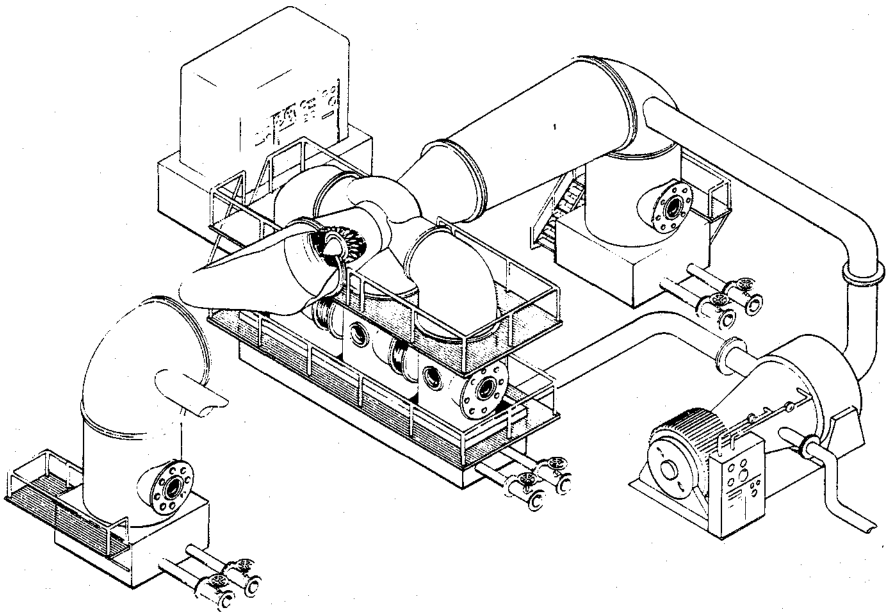
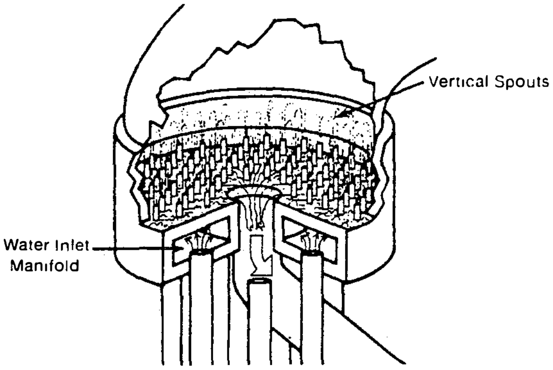


Figure 2. 165-kW Open-Cycle Experimental Apparatus



(4) Vertical Spouts

Figure 3. Vertical Spout Flash Evaporator

based on the analysis of Bharathan (7), which would be our present projection of the expected design. This design uses cocurrent flow in the first stage and countercurrent flow in the air-rich second stage. A matrix packing is used to provide the liquid/vapor contact with a volume ratio of 3:1 between the stages. We project that this device would condense 0.8 kg/s-m^2 of area with an entering temperature difference of 7^{o}C, which is typical of NELH cold seawater. The condenser enriches the air content of the vapor stream from 0.5% to 35%, thus minimizing air purge power requirements.

STEAM FLOW DYNAMICS

Flow velocity in the system ducting is kept below 50 m/s, and there is only one 180^o bend in the flow path to minimize steam fluid dynamics pressure losses. A Chevron-type mist eliminator provides water droplet separation with a minimum pressure loss. Pressure losses of less than 250 Pa are projected in the system based on experimental measurements. Smooth and gradual expansion and contraction exist at the heat exchangers and the turbine. Had these losses been avoidable, an additional 45 kW of power output theoretically could have been achieved.

SEAWATER HYDRAULICS

Head losses of less than one and two meters are experienced in the evaporator and condenser, respectively. Head loss in the cold water pipe varies with pipe diameter, as discussed in the turbine design description. Total hydraulic loss in the system on the cold stream for the design presented is 3.2 m. If the experiment is not maintained at the barometric level (for convenience in construction and operation of a research project), an additional head loss of 3.75 m is incurred to draw the water out of the condenser. This additional loss is easily overcome in a commercial design.

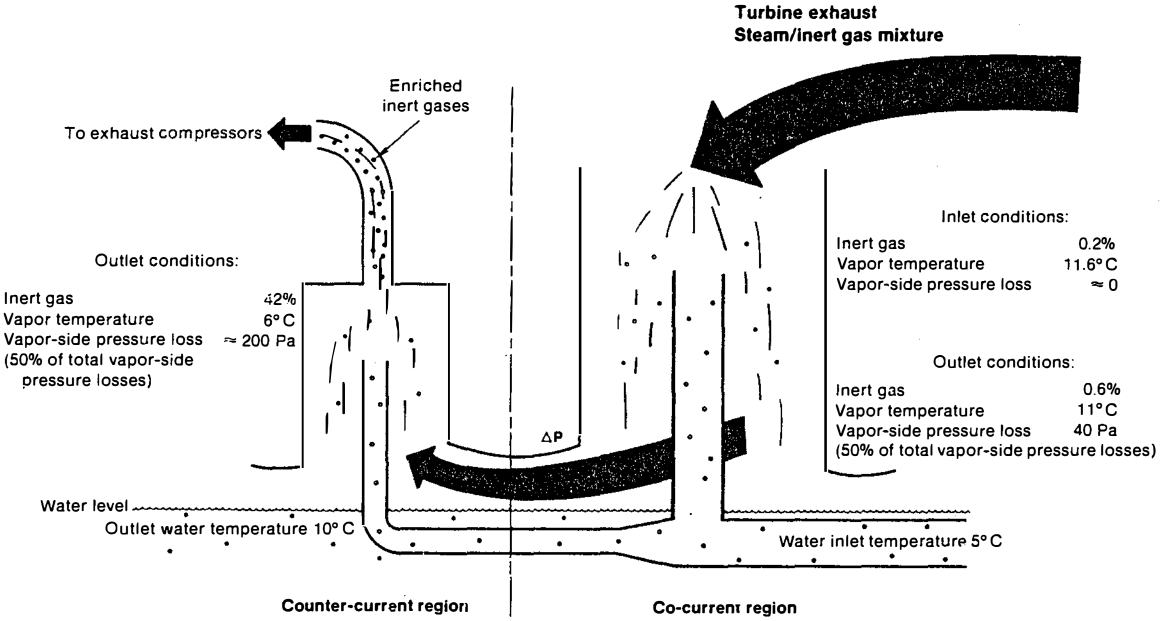


Figure 4. Two-Stage Direct-Contact Condenser

NONCONDENSABLE GAS PURGE DYNAMICS

Experimental seawater desorption studies indicate that up to 90% of the gas dissolved in seawater can be released before the seawater reaches either the evaporator or condenser. It is not yet clear whether this process is nucleated heterogenously (by process path) or homogenously (out of the bulk of the water). The purge system will vent and maintain the desired vacuum level in the experiment at both the evaporator and condenser pressure with consecutive stages in a multistage intercooled compressor. Such a design would minimize the flow through the low pressure compressor. An interstage cooler would remove the steam that must be pumped from the condenser, thus reducing condenser power requirements to a minimum.

THERMAL CONVERSION

The primary purpose of this experimental system is to evaluate the performance of a steam turbine operating at very low pressure with variable steam rate and enthalpy. More importantly, its purpose is to investigate the performance and control of a power system using such a turbine and operating with closely coupled processes. Table 1 shows that 5% of the power produced in an open-cycle OTEC plant is needed to purge the system of noncondensable gases (not including leakage into the system) and 20% of the power is needed to circulate seawater through the system. What the table does not show is that 25% of the theoretically available power is lost through unavoidable steam-side pressure losses in the flow path. These effects are because of the low pressure of the steam and the high rates of seawater circulation required. As the system is scaled to smaller sizes, the auxiliary power requirements become a larger fraction of the power produced until eventually they exceed the power produced.

Using analysis methods described by Parsons et al. (8), we show in Figure 5 the net power produced from an open-cycle OTEC experiment as a function of cold water flow rate with the cold water pipe as a variable parameter. From this analysis we concluded that a 76-cm (30-in.) diameter pipe delivering approximately 410 L/s (6500 gpm) is probably the smallest pipe size that could provide a meaningful ratio between gross power produced and the auxiliary power required to operate the plant. This flow rate will produce a gross power of 165 kW with auxiliary requirements as shown in Table 1. Operating at this scale provides a valid evaluation of the five major system process interactions. Figure 6 shows that the turbine wheel diameter to produce 165 kW for this system design is 1.40 m. The experimental turbine is just less than 1/4 scale of proposed full-scale size of 5.5 m. Although it is never possible to achieve complete physical similarity, this level of scale is typically used in the industry to accommodate thermodynamic and mechanical similarity. At this level rotor Mach number, isentropic velocity ratio, Reynolds number, moisture effects, blade dynamic response, and disc rim fixity can be scaled or corrections made to account for imperfect scaling (9).

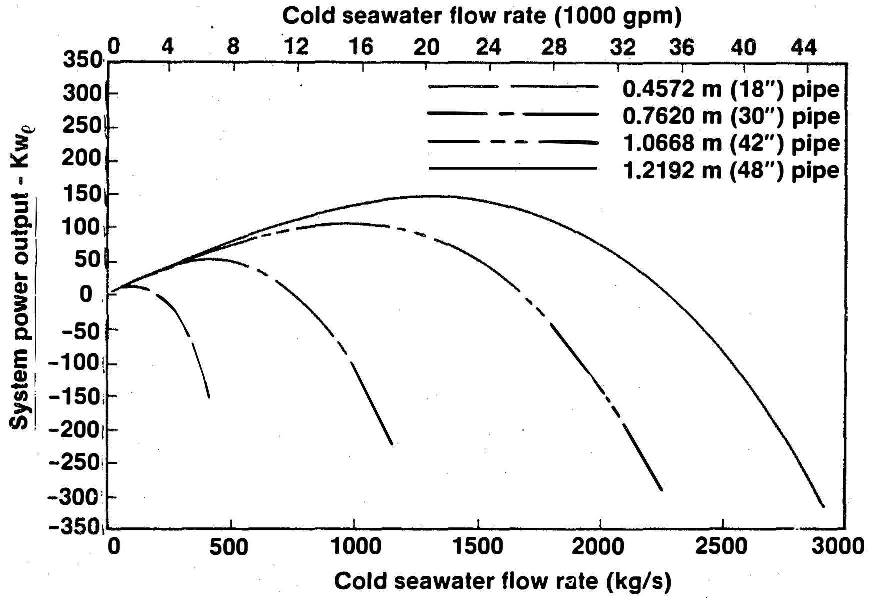


Figure 5. Open-Cycle OTEC Experiment—Projected Performance

CONCLUSION AND SUMMARY

The overall specification for the experiment is summarized in Figure 7. The temperatures, flow rates, and power rates associated with the major components are indicated on the drawing. What should be drawn from this summary and the associated discussion is that net power drawn from the plant has strong (and roughly comparable) sensitivity to auxiliary power demands created by each of the processes going on within the thermodynamic cycle. A departure in any one from the design value will influence the others and

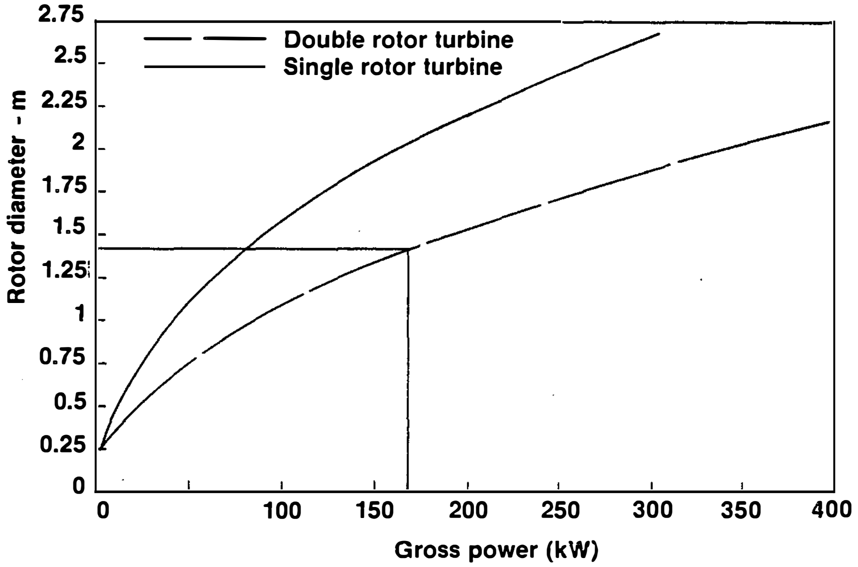
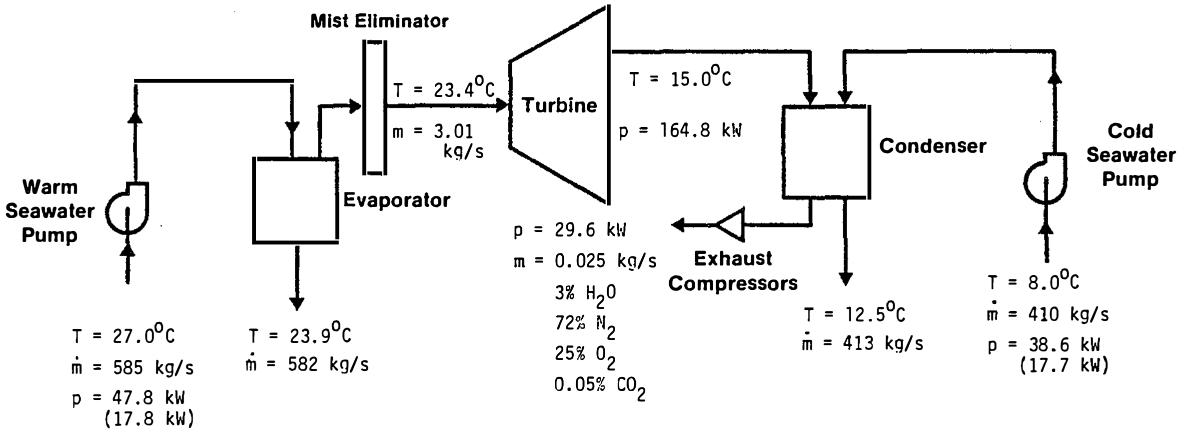


Figure 6. Turbine Test Article Design Choice—Open-Cycle OTEC Experiment



Net Power = 164.8 - 47.8 - 29.6 - 38.6 = 48.8 kW
(164.8 - 17.8 - 29.6 - 17.7 = 99.7 kW)

* Current design dictates a 3.75 m additional seawater head loss since the tank level is lower than barometric. Pumping power requirements for barometric level vacuum chambers are shown in parenthesis.

Figure 7. Open-Cycle OTEC Experiment Flow Diagram

have a compounded effect on power delivered.

The specifications for the 165-kW_e experiments are compared with the full-scale plant whose design is validated in Table 1. Experiment construction will occur in two phases. First, evaporator and condenser modules are in the form of three, 2.4-m (8-ft) diameter pressure vessels. Heat and mass transfer model validations will be completed with full-scale geometries. A turbine and additional heat transfer modules will be added in the second phase to permit completion of a cycle feasibility assessment. Completing this experiment will demonstrate the feasibility of the open-cycle process in addition to validating design methods and data necessary for assessing the viability of the technology. In addition, engineering data on the performance, cost, reliability, and maintainability of the hardware will permit us to definitively evaluate the cost-effectiveness of this approach as an energy supply option.

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