Systems Aspect of Ocean Thermal Energy Conversion

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Solar energy conversion using an ocean-driven heat engine occupies a special place on the systems engineering horizon. In addition to the concept's proven technical feasibility, conditions in the field of OTEC research are such that systems innovations can be readily and profitably implemented. A team led by TRW Systems Group has synthesized a baseline design for an ocean thermal energy conversion (OTEC) plant of 100-MWe output, with initial cost of $2100/KW delivered at the busbar, a cost that could be reduced considerably through the application of new technology and proposed refinements in baseline subsystems. It has been projected that a per-kilowatt cost of $1100 for a functioning OTEC plant could be realized within the next two decades if a vigorous research and development program is carried out.

Introduction

POTENTIAL shortages of fossil fuels and the growing cost of nuclear fission power plants have stimulated a growing interest in the vast undepletable resource of solar energy. One method of harnessing solar energy, originally conceived by D'Arsonval in 1881,[1] is to operate a heat engine using the warm surface waters in the tropic oceans as a high-temperature reservoir and the colder waters existing at greater depths as a low-temperature reservoir. Recently, several investigators have developed conceptual designs and cost data for such ocean thermal energy conversion (OTEC) power plants.[2-5]

OTEC power plants use ocean water for collection and storage of solar energy and are able to operate continuously without the variation in output associated with photovoltaic and direct conversion methods. A section view of the closed binary cycle OTEC power plant developed through a joint effort of TRW, Global Marine Development, Inc., and United Engineers and Constructors[5] is shown in Fig. 1 with characteristics summarized in Table 1.

A Rankine cycle is employed utilizing warm surface seawater to evaporate the ammonia working fluid. Ammonia vapor from the evaporator drives a turbine-generator and is then condensed by heat exchange with cold water pumped from a nomial depth of 4000 feet. The floating OTEC plant is maintained at a desired location by using the cold and warm water exhausts as thrusters for dynamic positioning. With a temperature difference of 40°F the cycle efficiency is about 3.5%.

Our studies indicate that economic viability of OTEC plants may be achieved through engineering development within a decade. Since OTEC plants may be constructed in quantity to a standard design, their potential for deployment in such numbers as to significantly augment the national energy supply by the year 2000 is enhanced. This paper deals with two related aspects of OTEC system development: the potential for application of classical system engineering and management techniques and the incentive to advance OTEC technology.

Many promising innovations in energy recovery, conversion, and delivery systems (e.g., oil shale and coal gasification) are now prevented from being realized on a broad scale by the sociopolitical environment into which these innovations must fit. New legislation, with its implied delay and unpredictable outcome will be necessary.

In contrast, the OTEC system is relatively free from such impediments to progress. OTEC plants do not compete for land use or present a major waste management problem; no regulations constrict their architecture or engineering (save for those that apply to any ocean-based system, for reasons of safety and insurability). OTEC systems thus resemble military or space systems programs, in which exploitation of advancements in design, configuration, and technology are largely a function of technical performance and economic viability.

A monolithic arrangement, whereby decision making is centralized, independent, and conducive to new ideas, is therefore envisioned for OTEC plant development and construction. Within this framework, systems engineering and management are given the initiative to be effective, and new technology is incorporated on the basis of technical and economic merit.

OTEC Power Cost

The cost of electric energy generated onboard an OTEC includes only the capital invested in the plant and normal operating and maintenance expenses as itemized in Table 2. No fuel cost results from the use of the ocean temperature gradient which is replenished by the enormous solar energy

Table 1 OTEC baseline power station characteristics

ITEM	DESCRIPTION
100 MWE DELIVERED POWER	4 MODULES (25 MWE EACH)
HULL	340-FOOT DIAMETER, 170 FEET HIGH, 110-FOOT DRAFT, DISPLACEMENT = 212,000 LONG TONS
COLD WATER PIPE	50-FOOT DIAMETER, 4000 FEET LONG, FIBERGLASS REINFORCED PLASTIC
WORKING FLUID	700,000 GALLONS OF AMMONIA
CONDENSER (FOUR UNITS)	SHELL AND TUBE – SHELL: 50-FOOT DIAMETER, 55 FEET LONG TUBES: 65,400 TITANIUM TUBES, 43 FEET LONG, 1.5 INCHES OD
EVAPORATOR (FOUR UNITS)	SAME AS CONDENSER EXCEPT 75,900 TUBES
TURBINE/GENERATOR (FOUR UNITS)	15-FOOT DIAMETER, 38 FEET LONG, VERTICAL SHAFT, DIFFUSER MOUNTED ON CONDENSER
WARM WATER PUMP (FOUR UNITS)	AXIAL FLOW, DC MOTOR DRIVE LOCATED IN EVAPORATOR EXHAUST PIPE
COLD WATER PUMP (FOUR UNITS)	AXIAL FLOW, DC MOTOR DRIVE LOCATED AT CONDENSER INTAKE PIPE
WORKING FLUID PUMP (FOUR UNITS)	CENTRIFUGAL, DC MOTOR DRIVE LOCATED IN HOT WELL EXHAUST LINE

Presented as Paper 75-615 at the AIAA/AAS Solar Energy for Earth Conference, Los Angeles, Calif., April 21-24, 1975; submitted Aug. 11, 1976; revision received July 25, 1977.

Index category: Ocean Thermal.

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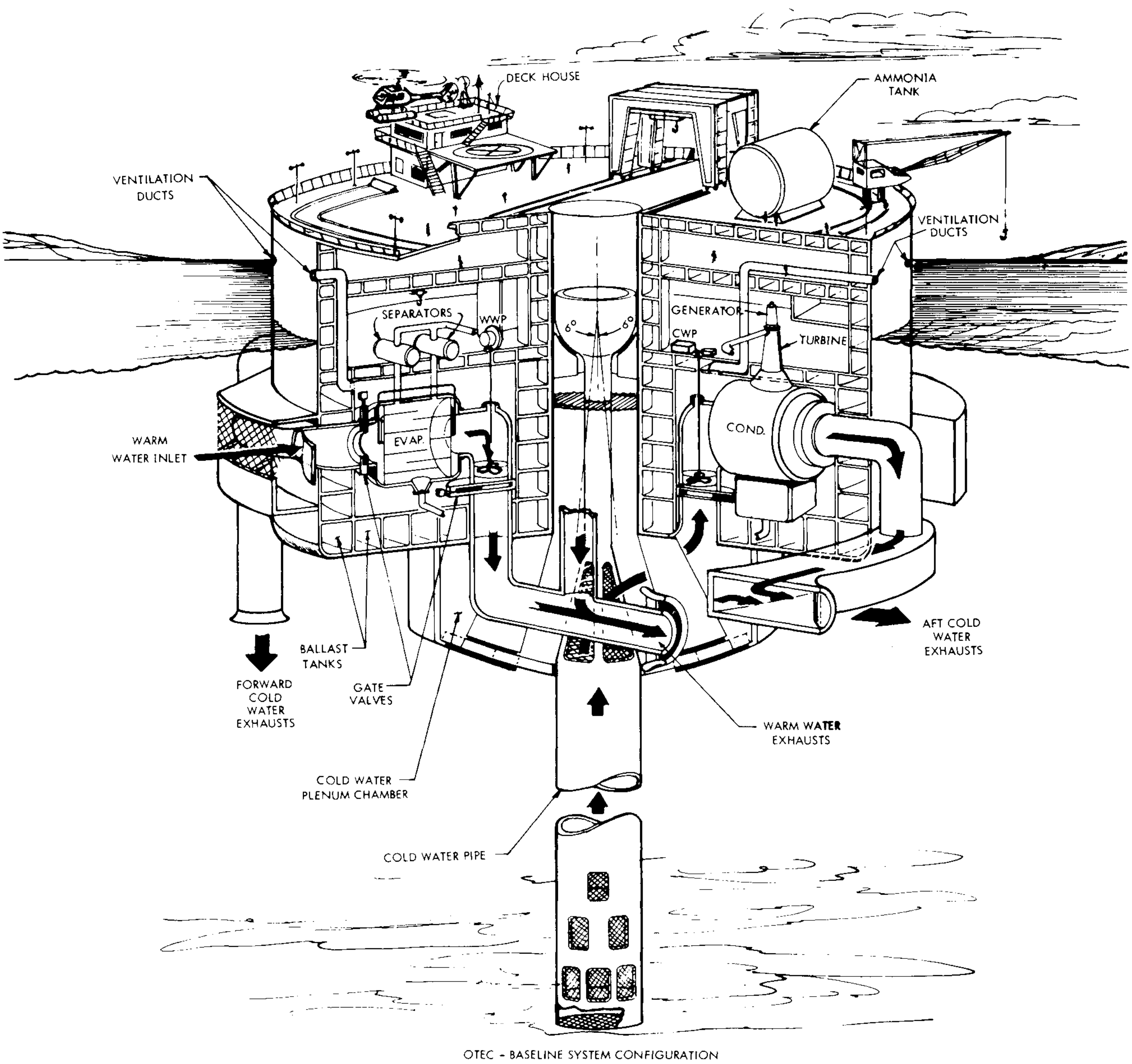


Fig. 1 Sectional view 100-MWe OTEC baseline.

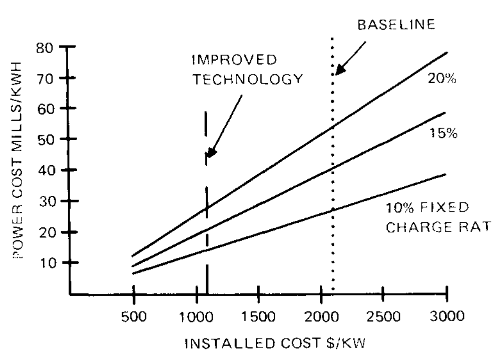


Fig. 2 OTEC power costs.

flux received by the vast surface area of the tropic oceans. The cost of electric energy is a function of both capital investment and operating expenses and is shown in mills ($\$ \times 10^{-3}$) per kilowatt hour (kWh) in Fig. 2. Power costs are a strong function of both the total plant investment and the annual fixed charge for capital. The annual fixed charges are typical of financing either as a municipally owned (10%) or privately owned utility (15-20%), and include a rate of return on equity and debt financing, depreciation and administrative expenses, insurance, and taxes (for private ownership only). The baseline OTEC requires an initial investment of approximately $2100 per kilowatt (peak) in 1975 dollars, and with financing as a privately owned utility (annual fixed charge for capital of 15%) results in an electrical power cost of approximately 50 mills/kWh.

As may be seen in Table 2, the most expensive OTEC components are the evaporator, condenser, cold water pipe, and basic hull. Potential reductions in cost may reduce the capital cost of 100 MWe OTEC to approximately $1100 per installed kilowatt at the busbar. The resulting range of power costs from 17 to 25 miles per kWh is illustrated in Fig. 2. The potential cost reductions will be discussed next.

Discussion of Cost Leverage Items

In our investigations of methods for reducing cost of OTEC energy, we have focused on the following high leverage items: heat exchangers, platform, cold water pipe, and system design and optimization.

Heat Exchangers

To reduce the cost of heat exchangers a) the fabrication cost (per unit surface area) must be lowered and b) the per-

Table 2 Estimated TRW 100-MWe OTEC power plant costs ($ Millions)

(A) CAPITAL COST		
PLATFORM		50.50
HULL	44.10	
OUTFIT AND FURNISHINGS	4.90	
AUXILIARY SYSTEMS	1.50	
POWER PLANT		95.27
EVAPORATORS	40.11	
CONDENSERS	39.72	
TURBINES	3.65	
GENERATORS	3.44	
INSTRUMENTATION AND CONTROL	1.18	
OTHER	7.17	
ELECTRICAL DISTRIBUTION		4.00
TRANSFORMERS	1.72	
PLANT ELECTRICAL	2.28	
WATER SUPPLY AND DISTRIBUTION		31.38
COLD WATER PIPE	19.79	
PUMPS AND DRIVES	6.56	
PIPES AND MISCELLANEOUS	5.03	
TOTAL DIRECT	181.15	
DEPLOYMENT		0.96
CONSTRUCTION OVERHEAD		28.08
TOTAL CAPITAL COST		210.19
(B) OPERATION AND MAINTENANCE		
CREW		0.67
LOGISTICS		0.26
MAINTENANCE AND INSPECTION		1.54
MISCELLANEOUS AND OVERHEAD		0.70
TOTAL OPERATIONS COST ANNUALLY		3.17

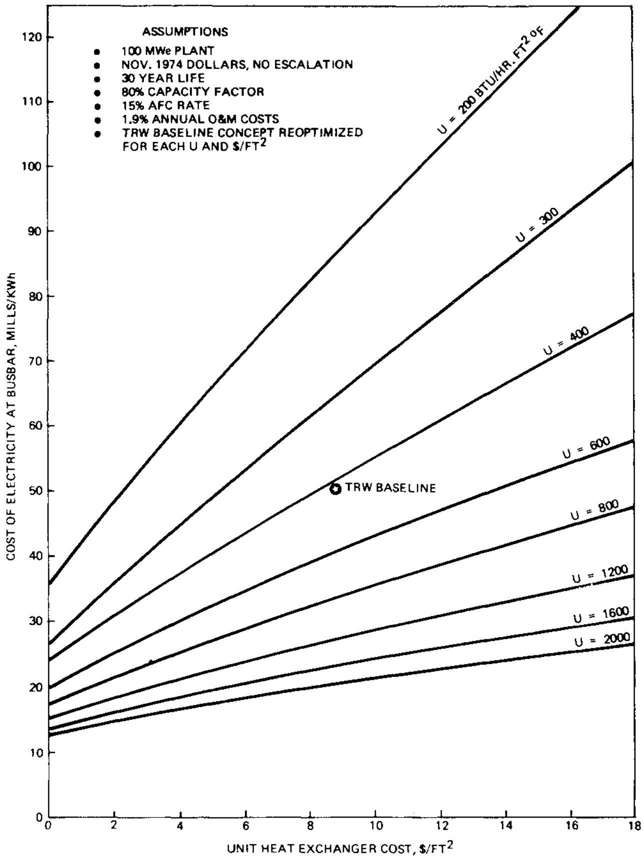


Fig. 3 Effect of heat exchanger unit cost and performance on energy cost.

formance must be improved relative to todays state-of-the-art. Figure 3 illustrates the dependence of energy cost on these two parameters.

If aluminum can be qualified as tube material and meet the requirement for a 30-year plant life, a significant cost reduction would result. ERDA-funded research[6] aimed at improved performance indicates that the overall heat-transfer coefficient (evaporator or condenser) may ultimately be enhanced from the 400-450 Btu/hr-ft^2-°F range considered state-of-the-art to 700-900 Btu/hr-ft^2-°F. Figure 3 indicates that this could result in a busbar cost reduction from 50 mills/kWh to about 25 mills/kWh for aluminum tube exchangers assuming \$6/ft^2 versus \$9/ft^2 for titanium.

Another area being pursued vigorously by ERDA is biofouling control. In Figure 4 we have shown how the direct capital cost of the TRW baseline depends on the assumed fouling factor. This figure is for plain tube heat exchangers i.e., no heat transfer enhancement. The effect of increased fouling factor would clearly be much more pronounced for advanced heat-transfer concepts.

Platform Design

As shown in Table 2, the platform is the second largest cost item. The selection of an optimum hull configuration depends strongly on environmental constraints (wind, waves, and currents), energy usage requirements, operation and maintenance requirements, and power plant design. The TRW team evaluated 15 different hull configurations belonging to one of three major categories: surface floating vessels, semisubmersible vessels, and spar-buoy-type vessels.

These fifteen designs were compared in a matrix evaluating each of the designs for a series of operational and design requirements. However, we did not trust an evaluation of general design configurations without establishing sizes and investigating how the necessary heat engine components can be arranged in the available hull spaces. Therefore, we chose

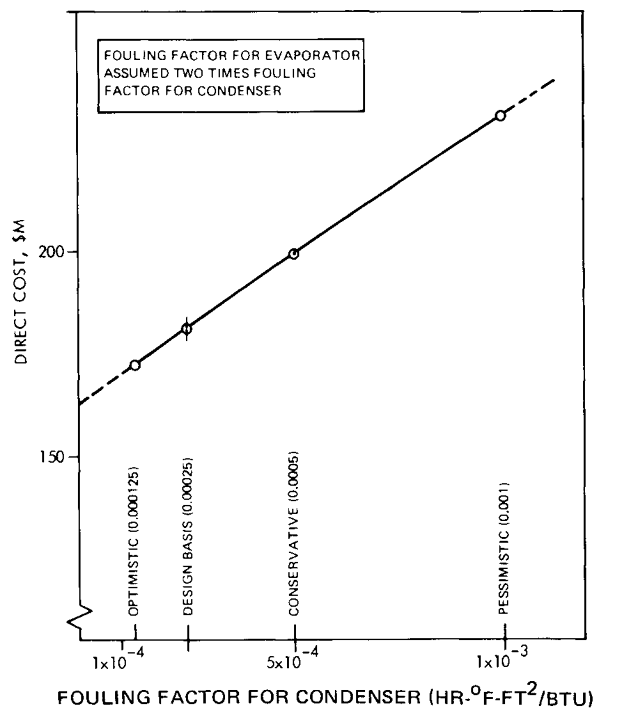


Fig. 4 Effect of fouling factor on direct costs.

to base a comparison on two different methods:

1) A matrix for 15 general designs, rating each of them according to a series of requirements.

2) A comparison of sizes and potential layouts for the leading candidate designs of each of the three basic configurations.

Both methods were used to select the most favorable vessel configuration for the baseline design. The list of evaluation criteria is shown in Table 3.

Important Evaluation Criteria

The importance of each of the criteria is different and was accommodated by a weight factor. (The difficulty in assigning weight factors to the criteria is acknowledged and ultimately reflects the judgment and experience of the investigator.) The following three criteria were considered of special importance: reliable support of CW pipe by vessel, maintainability of vessel structure, and maintainability of heat engine components. These are marked with an asterisk in the evaluation matrix shown in Table 4. The comparison of rating totals shows a preference of configurations of the surface vessel group over the semi-submersibles and the sparbuoy-type vessels.

To compare configurations quantitatively, we selected two candidates from the surface vessel group and one from each of the others for further evaluation: cylindrical surface vessel, rectangular surface vessel, double cylindrical hull semi-submersible, and pressurized detachable module spary buoy. After developing a workable arrangement for each, we performed a structural analysis to estimate the weight and cost of each vessel. Results of the weight and cost analysis are given in Table 5. Detailed studies[5] concluded that the cylindrical and rectangular surface vessels were the leading candidates.

These configurations maintain onboard energy utilization as an option. TRW selected the cylindrical surface vessel for the baseline 100 MWe design. However, for plants of greater size, the rectangular surface vessel (barge) appears, from present thinking, to be better from a module packaging viewpoint.

Having selected a hull shape and construction material (we favor concrete), the cost per kilowatt of the platform may be reduced by increasing the total plant size and by decreasing the hull envelope by improved packaging of power plant components. Figure 5 illustrates the effect of increasing plant size for a barge-shaped structure, for which extrapolation of data from the shipbuilding industry is possible. The effect of improved packaging is shown in Figure 6. A reduction in hull diameter from 340 ft to 300 ft lowers the direct cost of the hull by approximately $12 million.

There is a high potential for cost savings in decreasing the hull size by improving the arrangement of the components. The TRW baseline design using tube and shell heat exchangers inside a pressure-proof hull is certainly not optimal from a packaging point of view, but was selected to facilitate maintainability, ease of repair, and accessibility to these

Table 3 Evaluation criteria

EASY CONSTRUCTION OF VESSEL
EASY INSTALLATION OF HEAT ENGINE IN VESSEL
EADY DEPLOYMENT OF VESSEL
EASY CONNECTION OF CW-PIPE TO VESSEL
RELIABLE SUPPORT OF CW-PIPE BY VESSEL
FAVORABLE SEAKEEPING CAPABILITY
FAVORABLE HABITABILITY AND WORKING CONDITIONS
EASY TRANSFER OF CREW, MATERIALS AND CONSUMABLES
MAINTAINABILITY OF VESSEL STRUCTURE (DRY DOCKING)
ACCESSIBILITY OF HEAT ENGINE (HE) COMPONENTS
MAINTAINABILITY OF HEAT ENGINE COMPONENTS
LEVEL REQUIREMENTS OF HE-COMPONENTS RELATIVE TO SEA SURFACE
LEVEL REQUIREMENTS OF HE-COMPONENTS RELATIVE TO EACH OTHER
COMPLIANCE WITH EXISTING REGULATIONS
LOW INSURANCE RATES
CAPABILITY OF DETACHING AND RE-ATTACHING OF CW PIPE IN EMERGENCY CASES
CAPABILITY OF REPAIR IN CASE OF COLLISION
FAVORABLE MOORING CAPABILITY
FAVORABLE DYNAMIC POSITIONING CAPABILITY
CAPABILITY OF PLANT CAPACITY INCREASE BY IMPROVEMENT MODIFICATIONS

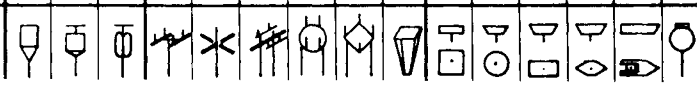
Table 5 Weight and cost summary

	WEIGHT*		COST (M$)	
	STEEL (M LBS)	CONCRETE (CU YDS)	STEEL	CONCRETE
CYLINDRICAL SURFACE VESSEL	76	72,500	72	49
RECTANGULAR SURFACE VESSEL	87	64,600	82	45
SEMI-SUBMERSIBLE	65	–	62	–
SPAR BUOY	86	–	81	–

*WEIGHT DOES NOT INCLUDE THE COLD WATER PIPE.

Table 4 Evaluation of 15 vessel configurations

REQUIREMENTS FOR EVALUATION OF VESSEL CONFIGURATIONS:		VESSEL CONFIGURATIONS: Spar Buoy			Semi Submersibles						Surface Vessels					
Requirements:	Weight:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Easy Construction of Vessel		1	1	3	6	6	6	3	6	1	9	8	10	10	10	5
Easy Installation of Heat Engine in Vessel		2	2	2	4	4	4	4	4	1	10	10	10	10	10	8
Easy Deployment of Vessel		2	2	2	6	5	5	6	5	1	8	8	9	10	10	7
Easy Connection of CW-Pipe to Vessel		1	1	1	4	5	4	5	4	10	4	4	4	4	10	4
Reliable Support of CW-Pipe by Vessel	*	1	1	1	5	5	5	5	5	10	9	9	10	10	10	9
Favorable Seakeeping Capability		9	10	10	9	9	9	9	9	10	7	7	7	8	8	9
Favorable Habitability and Work Conditions		5	5	5	6	6	6	6	6	6	10	10	10	10	10	7
Easy Transfer of Crew, Mat. and Consumables		8	8	8	8	8	8	8	8	8	10	10	10	10	10	8
Maintainability of Vessel Structure (Dry Docking)	*	1	1	1	3	3	3	3	3	3	5	5	7	7	10	5
Accessability of Heat Engine Components		5	3	1	3	3	3	3	5	5	10	10	10	10	10	10
Maintainability of Heat Engine Components	*	5	3	1	3	3	3	3	5	5	10	10	10	10	10	10
Level Req'ts of HE-Components Relative to Sea Surface		1	1	1	10	10	10	10	10	10	10	10	10	10	10	10
Level Req'ts of HE-Components Relative to Each Other		10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Compliance with Existing Regulations		5	5	5	9	9	9	9	9	5	10	10	10	10	10	8
Low Insurance Rates		1	1	1	5	5	5	5	5	1	9	9	10	10	10	7
Capability of De-Taching and Re-Attaching of CW-Pipe in Emergency Cases		1	1	1	2	2	2	2	2	1	3	3	3	3	10	2
Capability of Repair in Case of Collision		6	6	6	7	7	7	7	7	7	8	8	8	8	10	8
Favorable Mooring Capability		10	10	10	5	5	5	5	5	1	8	8	7	7	7	8
Favorable Dynamic Positioning Capability		10	10	10	5	5	5	5	5	1	8	8	8	8	8	8
Capability of Plant Capacity Increase by Improvement Modifications		3	3	1	3	3	3	3	5	1	6	6	6	6	10	6
Total Evaluation Rating:		87	84	80	113	113	112	111	118	97	164	163	169	171	193	149



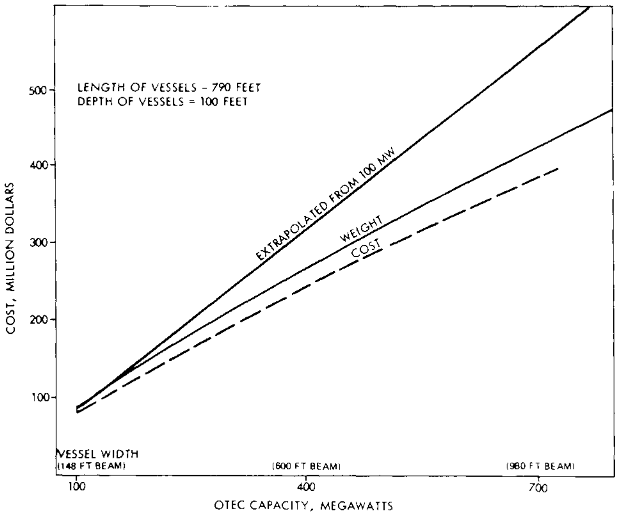


Fig. 5 Cost versus plant size for barge concept.

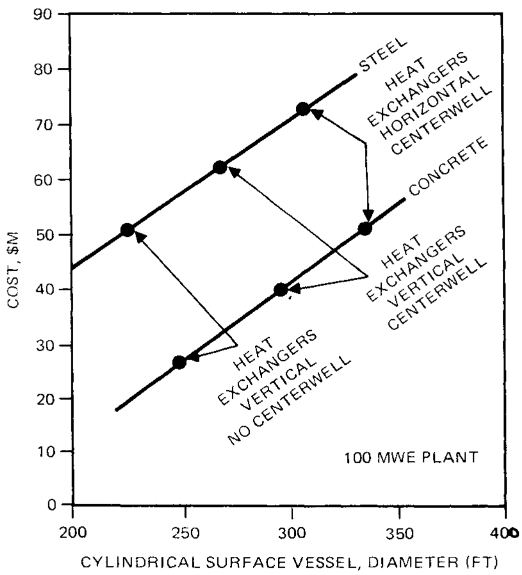


Fig. 6 Hull cost tradeoffs.

components, over-riding considerations in a prototype design. When the reliability of the heat exchangers is proven by testing, a location outside the hull can be considered. Compact (plate and fin) heat-exchanger designs have the potential for additional reduction of the required hull size.

Cold Water Pipe

The cold water pipe is the third major cost item (approximately \$20 million) in the TRW baseline design. This cost estimate is for a fiber-reinforced plastic pipe design, which is our baseline design. Novel designs that could reduce this cost significantly include a membrane design with ring stiffeners and tension rods. Firm estimates of cost for such a design are not yet available. The optimum length of the cold water pipe depends on site characteristics, in particular bathythermal profile. Systems optimization led to 4000 ft length as the best compromise between cold water pipe cost and overall ΔT provided to the heat engine.

Figure 7 indicates the dependence of direct capital cost on overall ΔT for a TRW baseline design with cold water pipe length fixed at 4000 ft. These results were obtained with our design optimization model using a fixed cold water temperature of 39°F.

If we assume a power dependence

$$C \sim (1/\Delta T)^P$$

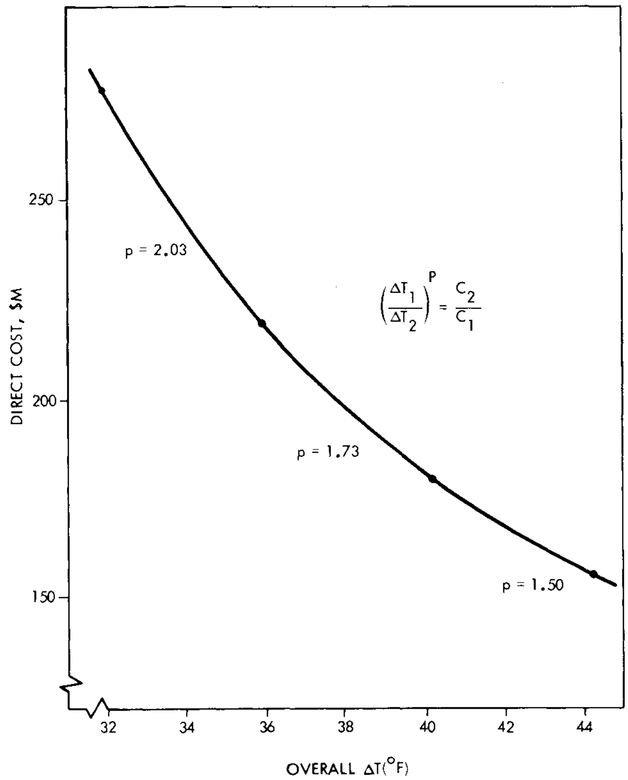


Fig. 7 Direct cost versus overall temperature difference.

the power P can be computed from the data. The value of P depends on the temperature and is approximately equal to 1.8 for $\Delta T = 38°F$ as shown in the figure. In other words, the power function is only a good approximation for a small range of ΔT. A better fit may be obtained by a function of the form

$$C \sim 1(\Delta T - a)$$

as suggested by J.H. Anderson in a private communication ($a \approx 24°F$).

System Design and Optimization

Developing an optimized baseline concept is a two-level iterative tradeoff process. The top level tradeoffs involve selecting major design characteristics such as working fluid, heat exchanger materials, single versus multiple pumps, single versus multiple cold water pipes, level of modular design, fixed mooring versus dynamic positioning, and hull design.

Based on these tradeoffs, a baseline concept evolved. The next level of tradeoff involved selecting design parameters for the baseline concept that minimize cost of delivered power within the given constraints of operating environment and design feasibility. To facilitate this baseline optimization task, a computer model, OTEC, was developed. This model has been used to determine an optimum set of design parameters such as flow rates of warm and cold water, diameter and length of cold water pipe(s), heat exchanger sizes and performance, working fluid flow and condenser/evaporator temperatures and pressures, parasitic pumping power (warm and cold water and working fluid).

A simplified schematic of the OTEC model is shown in Fig. 8. Due to the low ΔT available and consequently low cycle efficiency, system optimization is essential. Presently detailed cost data are scarce, the present TRW design is optimum only with respect to the crude cost assumptions made. As better data become available, improved systems designs will evolve.

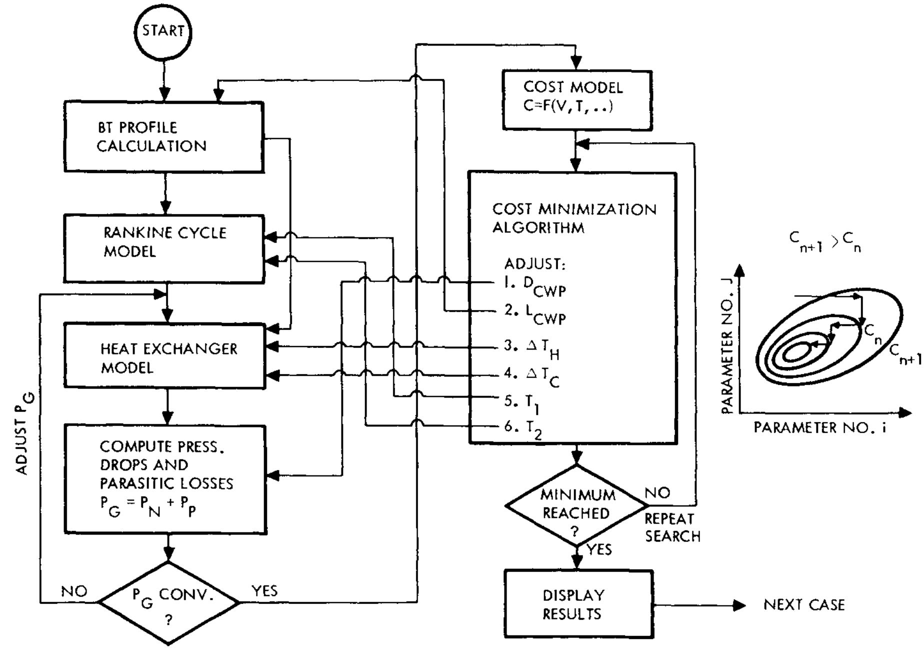


Fig. 8 OTEC optimization model schematic.

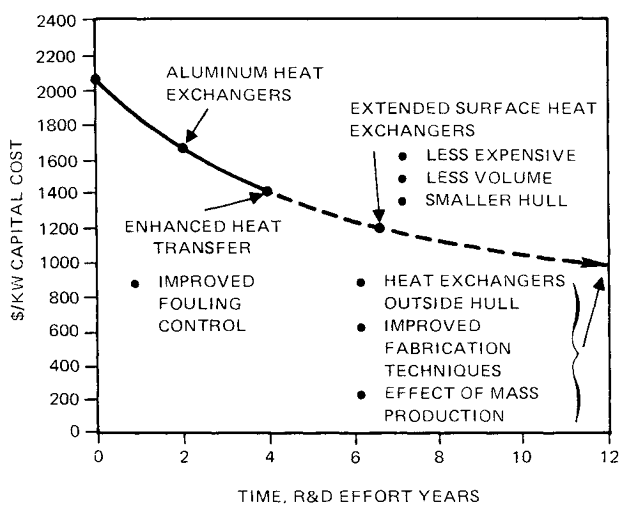


Fig. 9 Effect of research and development on captital cost of OTEC plant.

Conclusions

Our design objective was to postulate a low-risk system approach drawing on existing technology, or modest extrapolations thereof. Although this has been achieved, the design is not regarded as economically optimal. Technological innovations have been suggested that promise major reductions in system cost.

We have projected the effect on system cost of incorporation of some of the innovations discussed previously as indicated in Fig. 9. A reduction from 2100/KW to $1100/KW would involve a saving in capital investment of $100 million for a single 100 MWe plant, and a saving of 20,000 MWe. A potential payoff of this magnitude warrants a rigorous, well-financed program to achieve key technological advances.. ERDA is now well underway to establish such a program aimed at commercializing OTEC within the next two decades.

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