OCEAN THERMAL ENERGY CONVERSION (OTEC)

By

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INTRODUCTION

The surface temperature of the oceans between the Tropic of Cancer and the Tropic of Capricorn stays remarkably constant at about 77°F (20°C). At depths as shallow as 1,000 meters in these latitudes, the water temperature is 41°F (5°C). This temperature gradient may be used to generate mechanical power using a conventional heat engine. The maximum theoretical efficiency (carnot engine) of a power plant operating between these two temperature limits is only 6.7%. The efficiency of actual systems is in the order of 2 to 3%. Even at this very low conversion efficiency, experts estimate that a conservative 5 x 10^{12} watts of electrical power can be realized from the thermal energy of the ocean. The global electrical installed capacity is of an order of magnitude of 10^{12} watts, thus, OTEC can provide all the global electrical energy needs from a renewable source.

OTEC is one of the possible indirect utilization of solar energy where the ocean is a huge solar collector-storage system.

The economic feasibility of converting thermal energy stored in the oceans depends on the ability to optimize the performance of key components, such as heat exchangers used for evaporating and condensing a working fluid by means of sea water. Because of the low thermal gradient available, the heat exchangers needed for practical power generation are unusually large, and constitute one of the major expenditure items in an ocean thermal power plant. It is therefore important to evaluate the performance and attempt improvements of proposed heat exchanger concepts.

OTEC SYSTEMS DEVELOPMENT IN THE U.S.A.

Figure 1 shows a very aggressive program development schedules for Power Plants, Cold Water Pipe, Electric Cable, OTEC-1 Engineering Test Facilities and two modular experiments planned to be about 10 MWe and is scheduled to be completed and operational by 1982.

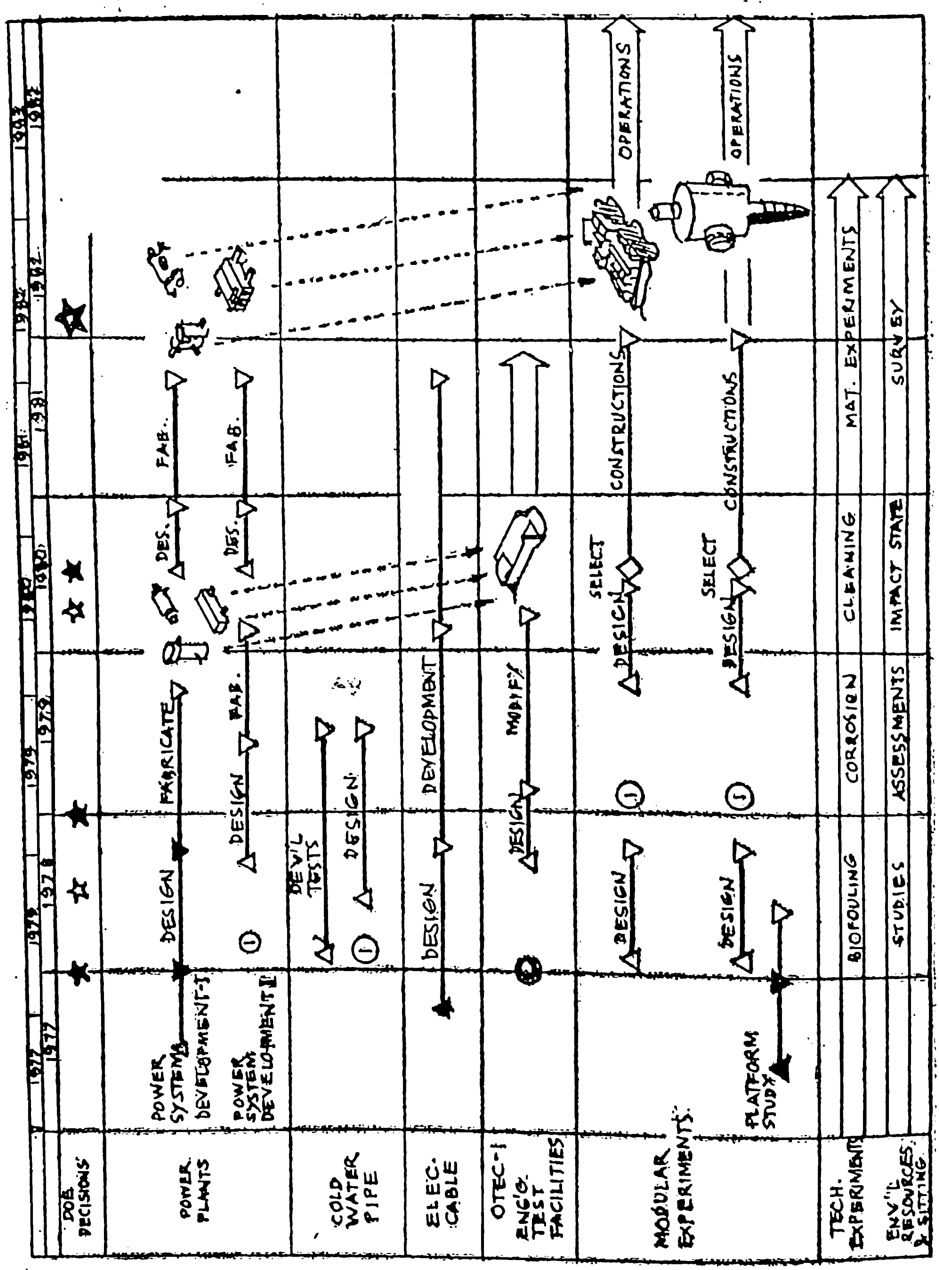

DOE DECISIONS
POWER PLANTS
COLD WATER PIPE
ELEC. CABLE
OTEC-I ENG'G TEST FACILITIES
MODULAR EXPERIMENTS
TECH. EXPERIMENTS
ENV'L RESOURCES & SITTING
1977
1978
1979
1980
1981
1982
1983
POWER SYSTEMS DEVELOPMENT-I
POWER SYSTEM DEVELOPMENT II
DESIGN
FABRICATE
FAB.
DES.
DEVIL TESTS
DEVELOPMENT
MODIFY
PLATFORM STUDY
SELECT
CONSTRUCTIONS
OPERATIONS
BIOFOULING
CORROSION
CLEANING
MAT. EXPERIMENTS
STUDIES
ASSESSMENTS
IMPACT STATE
SURVEY

FIG. 1

During the 5th OTEC conference held February, 1978, the Division of Solar Technology of the U.S. Department of Energy reported that they have equaled or exceeded their technical goals (Figure 2) established for 1978. The exception is the area of corrosion where the problems warrant further examination. They have determined that ocean thermal resources accessible to the U.S. do exist at 38°F to 40°F, and that the heat exchanger performance of core units has reached an overall heat transfer rate of 750 Btu/hr ft^2°F. Manufacturer's computer programs show that this result translates to an overall co-efficient in the range of 600-700 for larger size units.

The slope with time of variations in biofouling coefficient indicates a reasonable rate of accumulation, amenable to readily cleaning the heat transfer surfaces.

Although the heat exchanger represents the key single economic issue, the cold water pipe and the interaction with the platform represents a major technical issue. Four pipe materials are being considered concrete, compliant structures (rubber and fiberglass), and steel.

RESOURCE

One of the significant advantages of OTEC, unlike many other forms of solar energy utilization, is that it can operate day and night without the use of an auxiliary storage medium. In order to harness this energy stored in the ocean on a continuous basis, a consistent temperature difference resource must be available.

The warm water intake will be in the surface mixed layer 0-30 meters in depth, the turbulence associated with the intake pumping will produce a mixed intake with a mean temperature representative of this depth range. This temperature varies during the year.

Cold water intake is nominally at 1000 meters. Variability of temperature at this depth is not seasonal and is less than 1°C in many areas observed. Temperatures at 1000 meters are widely different in various ocean basins due to a variety of physical and oceanographic causes (Table 1).

In addition to warm and cold water availability there are additional requirements for continuous year-round operation. An adequate temperature differential $\Delta T > 30°F$ (16.7°C) for the coldest month is required. The annual average ΔT for a site should equal or exceed 36°F (20°C). The bottom depth should be less than 1,500 meters for mooring. Desirable sites should have weak currents and light winds. A mixed layer depth is favorable-deep enough to assure

FIGURE 2

PROGRAM GOALS

	1977		1978	
	Goal	*Achieve*	*Goal*	*Achieve*
1. Thermal Resource ΔT – (°F)	36	38 to 40	38	
2. Heat Exchange Performance				
° Single Tube-U (BTU/Hr Ft^2 °F)	600	750 - 1200	800	
° Core Unit-U (BTU/Hr Ft^2 °F)	400	750	600	
Biofouling – $1/U_{BF}$ $\frac{(\text{Hr Ft}^2\ °\text{F})}{\text{BTU}}$	—	.0001/2Kks	3000	
Cleaning – U_{BF} $\frac{\text{BTU}}{(\text{Hr Ft}^2\ °\text{F})}$	2000	3000	Quant.	
Corrosion	Signif. Effects	Calcareous Deposits 6Mo-1Yr Data Excellent Incipent Pitting	Design # S	

TABLE 1

COLD WATER TEMPERATURE

	1000 Meter Temp.	*Mean Monthly Temp. Giving – 30°F ΔT (16.7°C)*
1. Hawaii	4.3°C	21.0°C
2. Puerto Rico	5.1	21.8
3. Gulf of Mexico	5.1	21.8
4. N. Red Sea	21.5	38.2
5. E. Mediterranean	13.6	30.3
6. Indian Ocean off Oman	8.0	24.7
7. Indian Ocean off India	7.5	21.8
8. Equator Mid. Pac.	4.4	21.1
9. Equator Mid. Atl.	4.5	21.1
10. Equator Indian Ocean	6.5	23.2

an intake of uniformly warm water, but not too deep so that the exhaust water can be discharged below the mixed layer depth.

Figure 3 shows a typical temperature profile as a function of depth and extreme weather conditions. It illustrates the effects of storm activity on the temperature stratification of a typical site. Since most of the absorbed solar energy is captured in the first few meters of the surface waters, a highly stratified temperature profile develops during calm summer months. Vertical mixing occurs as a result of wave action.

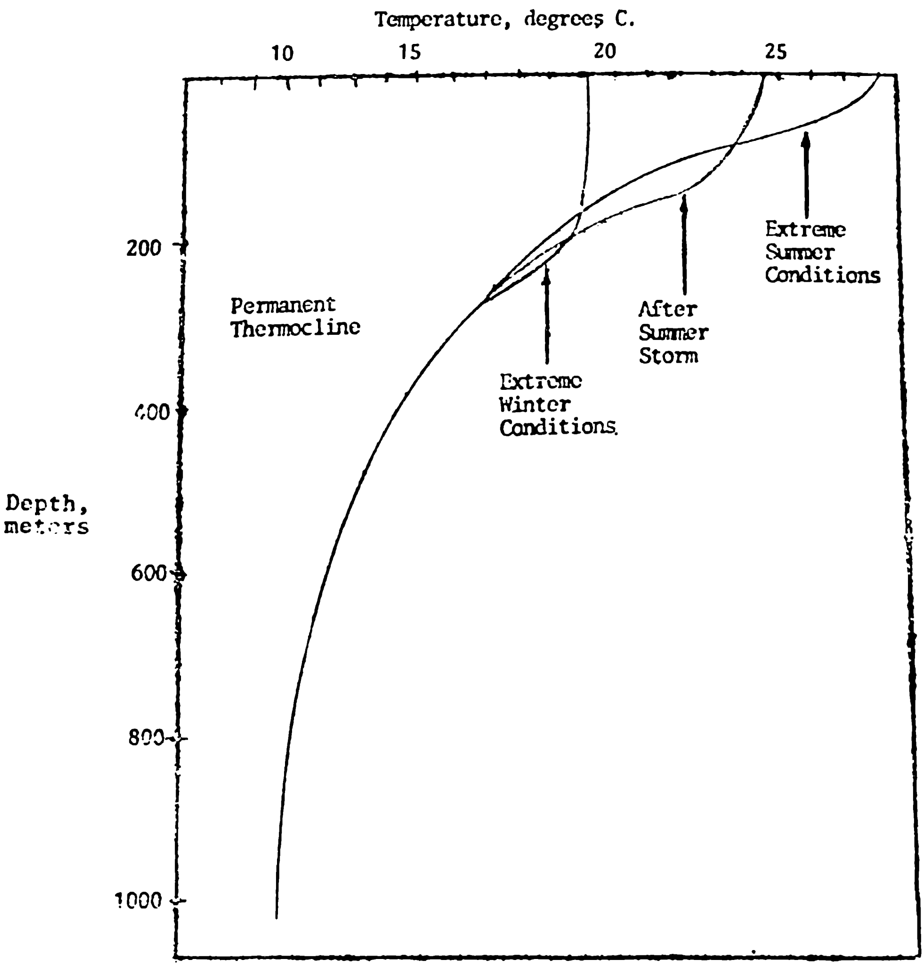
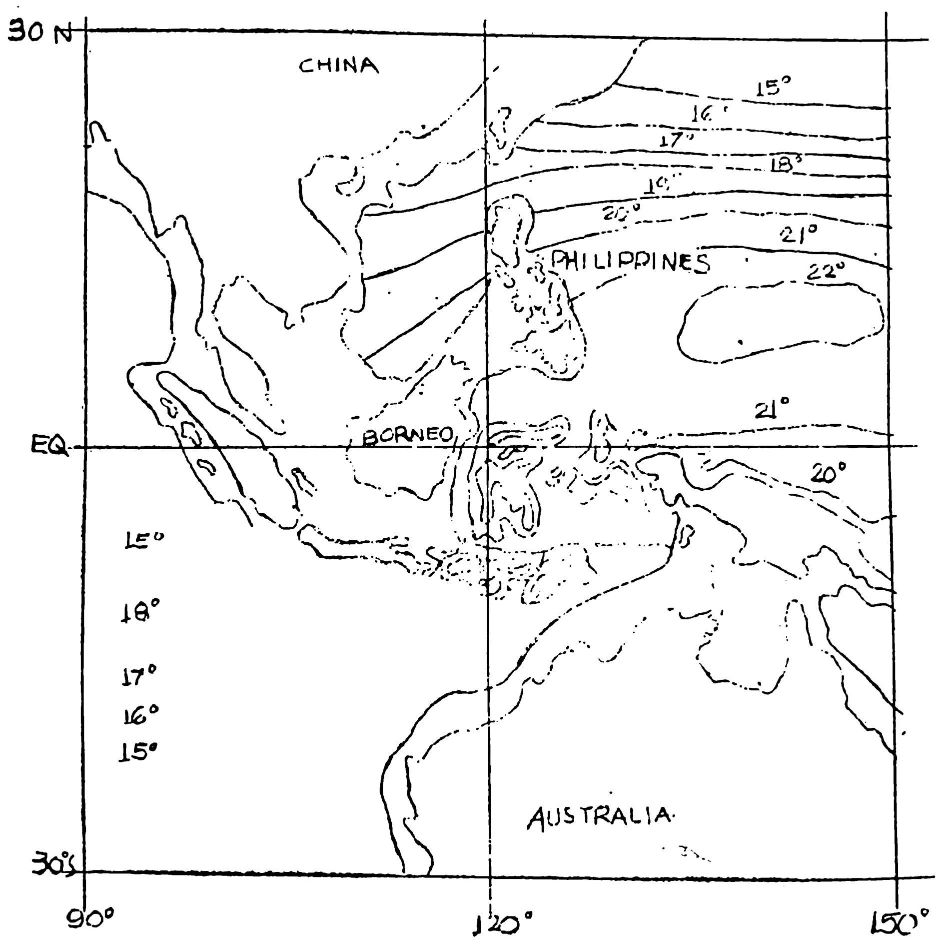


Fig. 3. *Typical temperature profiles above the thermocline.*

Table 2 identifies some potential locations for on-shore OTEC plants in the Philippines where deep water is no more than 3 km. from the shore. Figure 4 shows OTEC average ΔT between surface and 500 meter depth near and around the Philippines.

FIG. 4. *OTEC average ΔT (°C) between surface and 500 meter depth.*



POWER CYCLES

The U.S. Department of Energy is investigating four candidate power cycles. Within each cycle there are numerous design approaches. While not all cycles and approaches will eventually reach the hardware testing stage, the R & D program must provide opportunities for new ideas and concepts.

TABLE 2. *Some Points Along the Coast of the Philippines where Deep Water is no more than 3 Km from the Shore.*

400 FMS Depth – No more than 2 miles from shore (Approximately)

PHILIPPINES – NORTHERN PART

Luzon Strait – Batan Islands	
1. Y'ami Island East Coast	121° 58' East
2. North Island East Coast	121° 57' East
3. Mabudis Island East Coast	121° 58' East
4. Silayan Island West Coast	121° 52' East
5. Itbayat Island West Coast	121° 40' to 121° 45' East
6. Batan Island North Coast	122° 00' East
7. Baintang Island West Coast	122° 10' East
8. Babuyan Island: Camiguin Island – East Coast	121° 58' EEast
Luzon Island	
9. West Coast – Cape Bolinao	119° 44' East and 16° 15' North
10. East Coast – Cape San Ildefonso	122° to 122° 15' East and 16° 02' to 16° 16' North
11. West Coast – Palauig Pt.	199° 53' East and 15° 30' North
12. South Coast – Bondoc Peninsula—	Bondoc Pt. 122° 32' East and 13° 10' North
13. East Coast – Caramoan Peninsula	on Lagonoy Gulf 123° 50' East and 13° 42' North
14. East Coast – East of Mayon Volcano Point	124° 13' East and 13° 11' North
Mindoro Island	
15. North Coast – Cape Calauite	120° 17' East to 120° 36' East
16. West Coast – Dongon Pt.	120° 48' East and 12° 43' North
Tablas Island	
17. East Coast	122° 07' East and 12° 27' North
Romblon Island	
18. West Coast	122° 15' East

Burias Island	
19. Aguja Pt.	123° 21' East
Ticao Island	
20. West Coast	123° 35' East to 123° 47' East
Masbate Island	
21. North Coast – on Masbate Pass	123° 26' East to 123° 41' East
Samar Island	
22. East Coast – Cape Espiritu Santo to Bunga Pt.	12° 12' North to 12° 30' North; 3 miles from shore
23. Tugnug Pt.	125° 37' East and 11° 22' North; 3 miles from shore
Leyte Island	
24. South Coast – on Sogud Bay	125° 05' East and 10° 12' North
25. South Coast –	125° East and 10° 05' North
Panaon Island	
26. East Coast	125° 15' East
Bohol Island	
27. Nauco Pt.	124° 24' East and 09° 40' North

PHILIPPINES - SOUTHERN PART

Mindanao Island

28. North Coast —	125° 23' East and 9° 10' North to 9° 40' North
29.	Point on Gingoog Bay 125° 10' East and 9° North
30.	Point on Macajalar Bay 124° 37' East and 8° 48' North
31.	Point on Iligan Bay 124° 15' East and 8° 30 North
32. West Coast —	West Coast of Zamboanga Peninsula Batotindog Pt. 122° 02' East and 7° 22' North
33.	Coast on Illana Bay 123° 32' East to 123° 50' East
34.	Tapian Pt. 124° East and 7° North
35. South Coast —	Maguling Pt. 124° 20' East and 6° 06' North
36.	Point at 125° 17' East and 5° 36' North

37.	East Coast —	Tambunan Pt. 125° 30' East and 5° 42' North to Banos Pt. 125° 39' East and 5° 56' North
38.		Cape San Augustin 126° 05' East and 6° 35' North to 126° 11' East and 6° 16' North
39.		Tugubun Pt. Mayo Bayat 126° 28' East and 7° North

THE CLOSED CYCLE

Warm water (Figure 5) from the ocean surface is passed through an evaporator (boiler) containing a working fluid such as

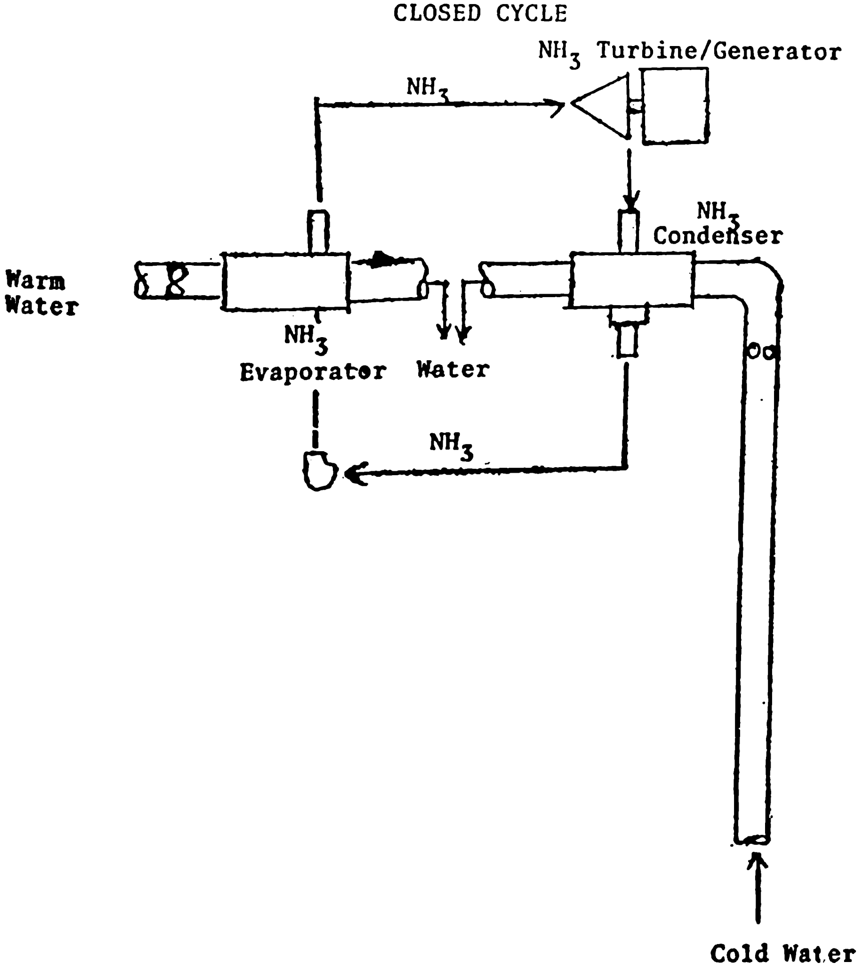


FIG. 5. *A schematic of the Rankine closed cycle for OTEC.*

ammonia. The heat transfer evaporates or boils the working fluid into vapor which then expands on drives a low-pressure gas turbine, then exhausts into a condenser cooled by water pumped from the ocean depths of about 1000 meters. The condensed working fluid is pumped back to the evaporator and the cycle is repeated. Power extracted by the turbine is used to generate electricity.

The major cost item of the closed cycle is the heat exchangers. Because of the low thermodynamic efficiency of low ΔT cycles, the heat exchangers must transfer very large amounts of heat thus necessitating the use of large heat exchangers. To keep the efficiency from deteriorating altogether, the thermal potential drop across the heat transfer surfaces must be kept at a minimum. For a given heat transfer rate, this can be realized by increasing either the overall heat transfer coefficient U or the heat transfer area A or both since

$$Q = UA(\Delta t)m$$

Figure 6 shows some OTEC heat exchanger (evaporator) configurations.

All other closed cycle components appear to be within the state of the art and there appears to be neither the need for R & D nor the new ideas which merit development. Some problems however are highlighted in the following other closed cycle components.

a) *Turbines* — anticipated problem areas are the seals. Compared to steam, ammonia is a corrosive fluid and requires special seals but this problem is not expected to require more than minimal development effort. Turbine size may be another problem area. Depending on the OTEC modular size selected and the optimum size of an OTEC turbine in terms output rating, efficiency and cost, various turbine-heat exchanger groupings are possible: a single turbine fed by one evaporator; a double flow turbine fed by one or two evaporators or a single turbine fed by two evaporators. Practical considerations such as existing fabrication capability and economy of scale will dictate the optimum size. Lubrication is another problem area. Oil at the ammonia side heat transfer surface would greatly reduce heat transfer performance.

b) *Demister* — liquid-vapor separators for ammonia service have been built for several years and they are known to perform at high efficiency. A hook-vane design, a wire mesh design or a combination of the two could be used. Centrifugal separators are not recommended because of their high inherent pressure drop.

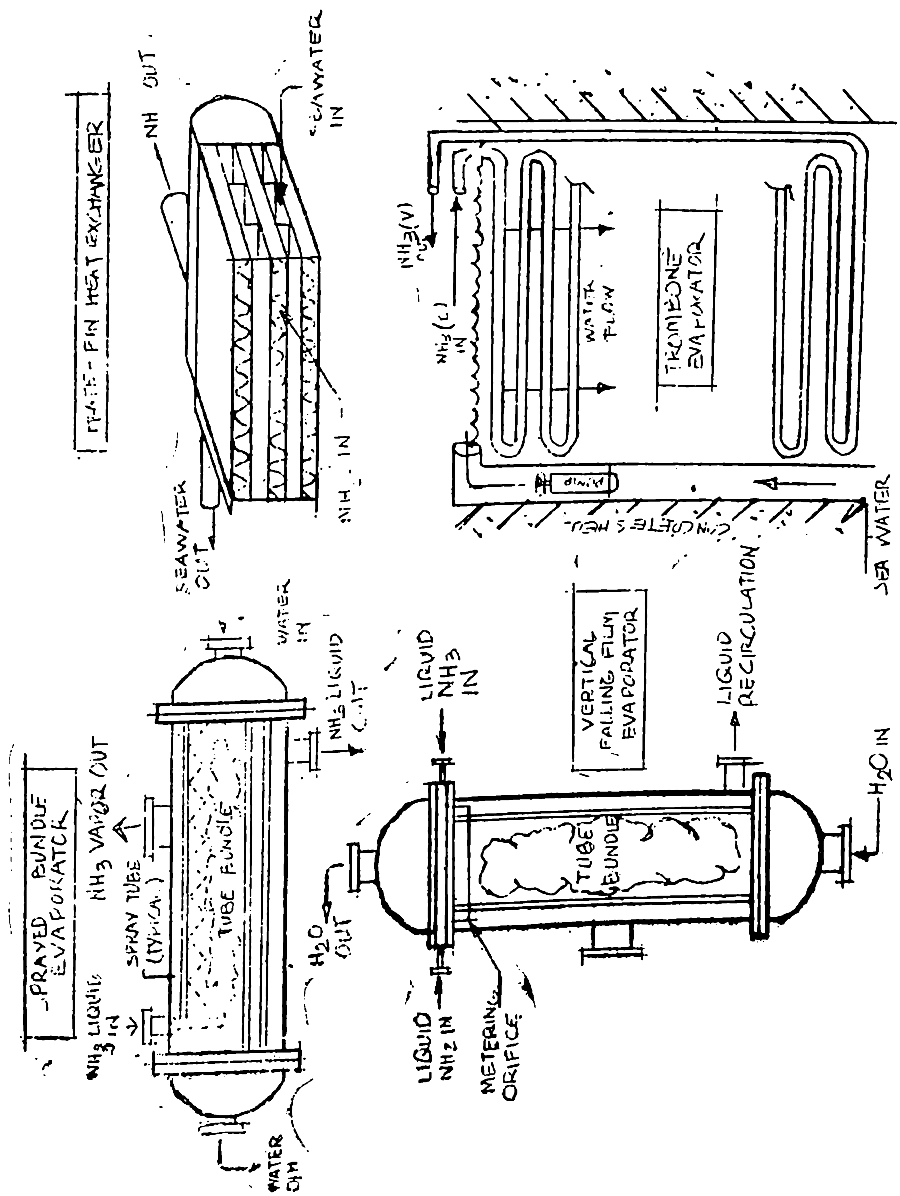


FIG. 6. *OTEC heat exchanger concepts.*

Demister problems are possible in the areas of size and cost. If OTEC evaporators produce low quality vapors, large and relatively expensive demisters are required. Large demisters can affect power system layout since the turbine inlet must be above the demister outlet. The bigger the demister, the higher the turbine elevation which can pose structural problems.

c) *Sea Water Pumps* — No problems are anticipated here. Existing pumps that can satisfy OTEC requirements and perform at good efficiency have already been identified.

THE OPEN CYCLE

Warm sea water is de-aerated and then passed into a flash evaporation chamber where a fraction of the sea water is converted into low pressure steam (Figure 7). The steam expands through a turbine then exhausts into a condenser. The condensate need not be returned to the evaporator. Rather, if a surface condenser is used, the output is desalinated water. Or, if a spray, direct contact condenser is used, the condensate is mixed with the cooling water and the mixture is discharged back into the ocean.

A complete open cycle power system requires additional hardware such as compressors to remove the undissolved air and demisters. The open cycle remains an attractive alternative to the closed cycle approach. There has been less emphasis on this concept vis-a-vis the closed cycle because of what many researchers have conceived to be difficult and costly problems such as huge low pressure turbines, the need to maintain near vacuum in extremely huge volumes, and the increase parasitic losses. However, with good design, the open cycle may become competitive to the closed cycle.

All of the open cycle component concepts are essentially within the state of the art. However, for the production of power on a meaningful scale, the size of the hardware becomes particularly huge. Thus, the turbine cost is thought to dominate the open power cycle cost, just as the heat exchangers dominate the closed power cycle cost.

The problem of biofouling of heat transfer surfaces is expected to be less severe than in the closed cycle if flash evaporator preceded by a multi-stage de-aerator is used. The direct contact condenser will similarly avoid condenser fouling. The trade-off for the biofouling problem is the necessity using compressors to purge the non-condensibles from the system on a continuous basis and the size of the hardware involved due to operation near vacuum.

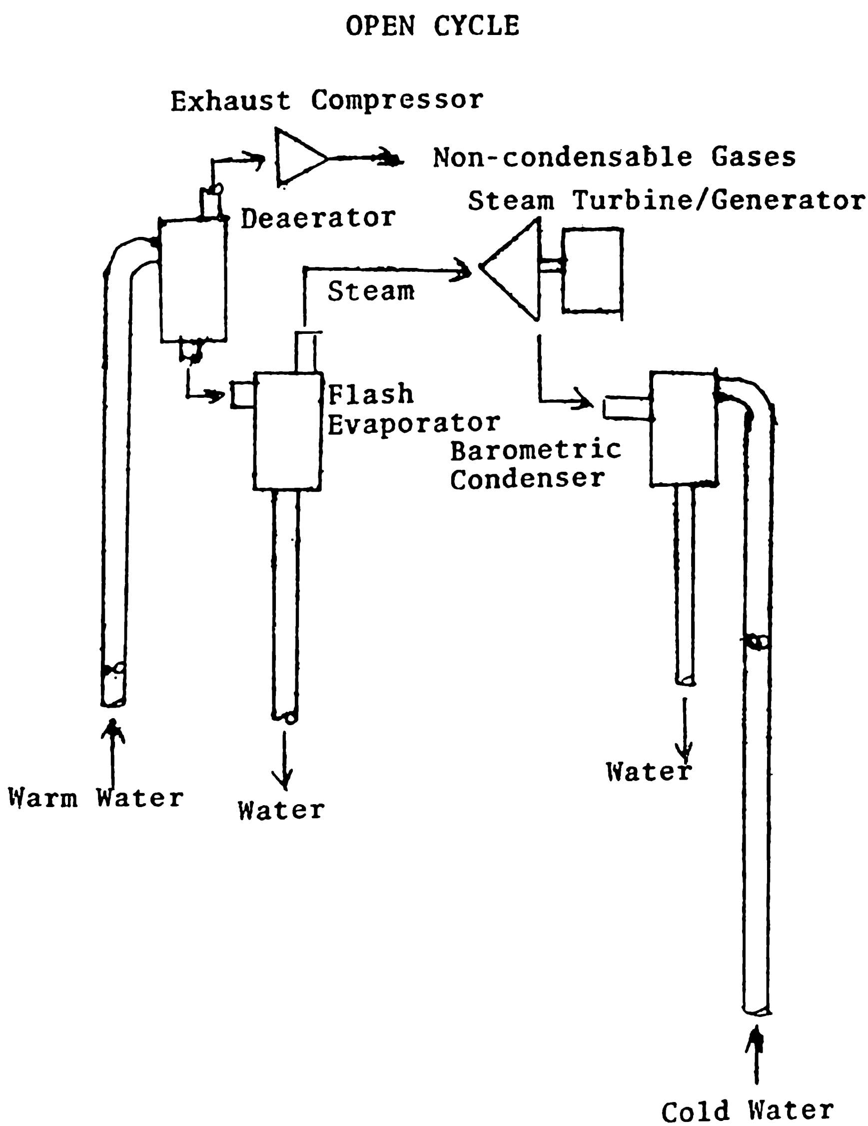


FIG. 7. *A schematic of the Rankine open cycle.*

The HYBRID CYCLE

Steam is generated by flash evaporation as in the open cycle (Figure 8). This steam then acts as the heat source for a closed cycle using ammonia as the working fluid. It is claimed that this system combines the heat features of both the open and closed cycles.

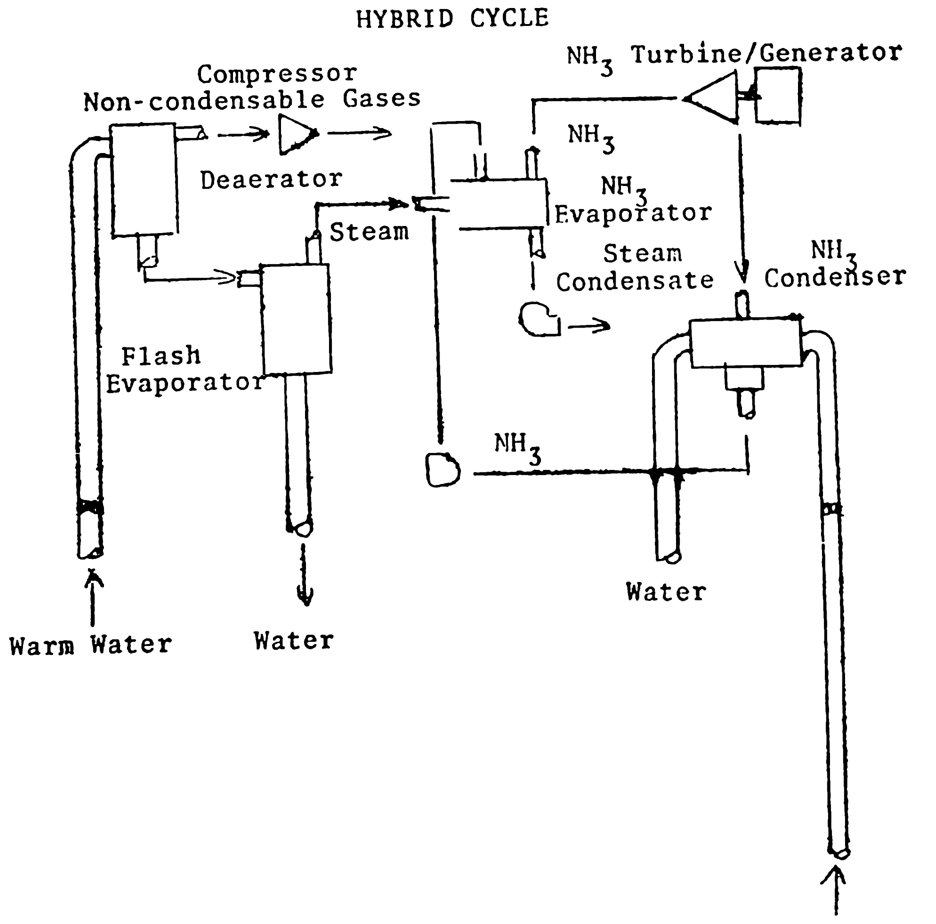


FIG. 8

The VAPOR LIFT CYCLE

Another open cycle concept is the vapor lift cycle. In this case, the power cycle requires a *hydraulic turbine* instead of a vapor turbine (Figure 9). The warm surface water is allowed to evaporate in such a way that it entraps substantial mass of liquid water with it. The condenser is located above the evaporator and it receives its cooling water from the cold water pipe. Thus, the pressure gradient created by the temperature difference raises the vapor-liquid mixture from the evaporator to the condenser.

LIFT/FOAM CYCLE SCHEMATIC

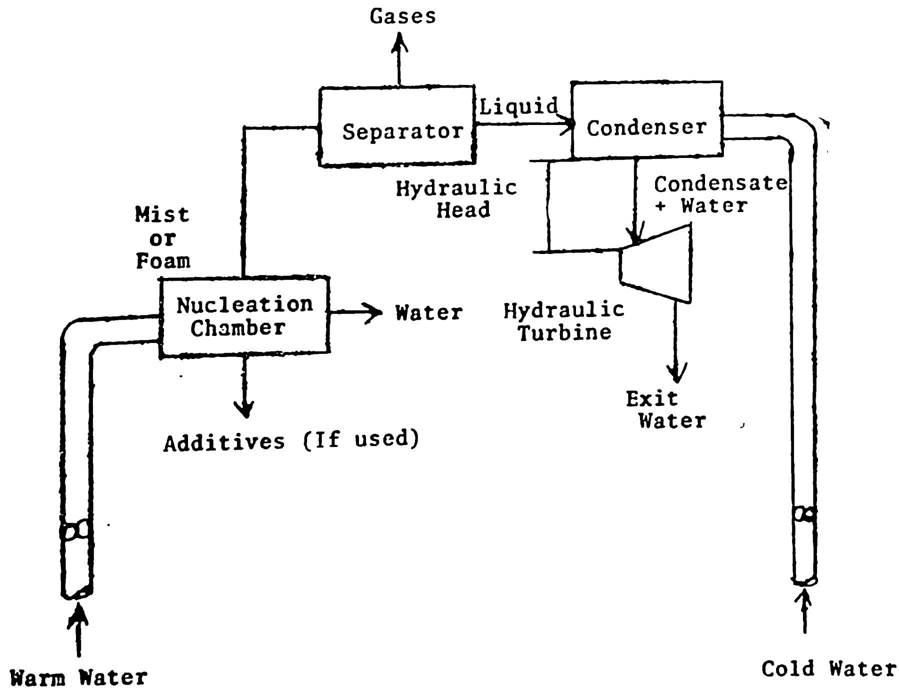
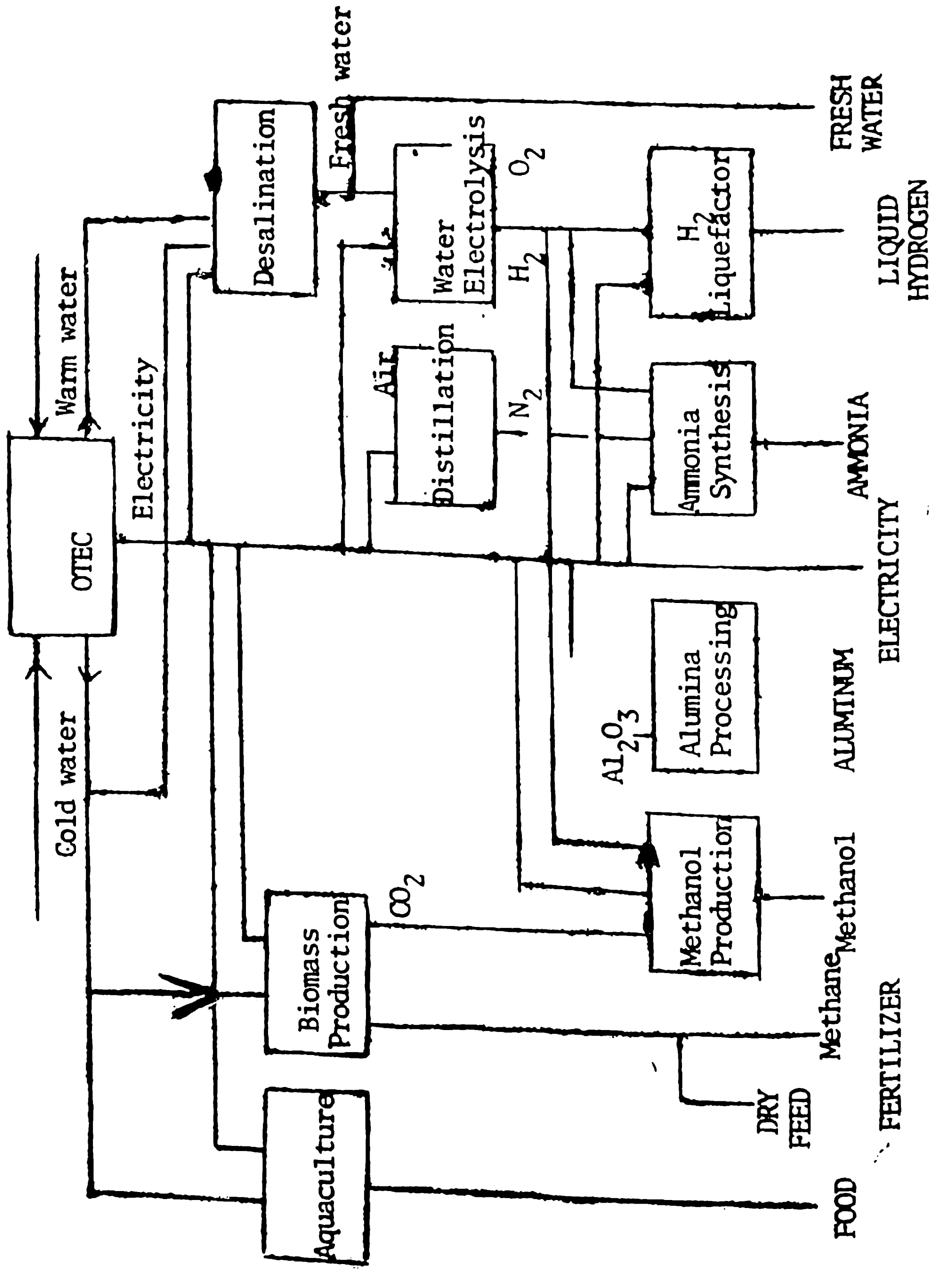


FIG. 9. *A schematic of the lift/foam cycle schematic.*

The potential energy of the warm water to the condenser level can then be converted into shaft power through the use of a hydraulic turbine located at the "same" elevation as the warm water intake. This concept is at an early R & D stage.

The real issue is the efficient generation of a vapor-liquid mixture and the transport of the mixture without separating the vapor from its liquid or initiating instabilities in the flow process. Two approaches for lifting the warm water have been proposed: The foam concept relies on the addition of small quantities of surfactant (detergent) to create the foam, and the second is the mist concept where a mist generator is used and installed at the warm water entrance.

A ΔT of 40°F could theoretically raise the foam or mist to a height exceeding 600 ft. However, not all of this head can be realized. To raise the foam to such an elevation, which is considered high for an ocean structure, the foam must be stable. This means a substan-



OTEC
Warm water
Cold water
Electricity
Desalination
Fresh water
Water Electrolysis
O_2
H_2
Air
Distillation
N_2
H_2 Liquefactor
Ammonia Synthesis
Alumina Processing
Al_2O_3
Methanol Production
CO_2
Biomass Production
Aquaculture
Methane
Methanol
DRY FEED
FRESH WATER
LIQUID HYDROGEN
AMMONIA
ELECTRICITY
ALUMINUM
FERTILIZER
FOOD

FIG. 10

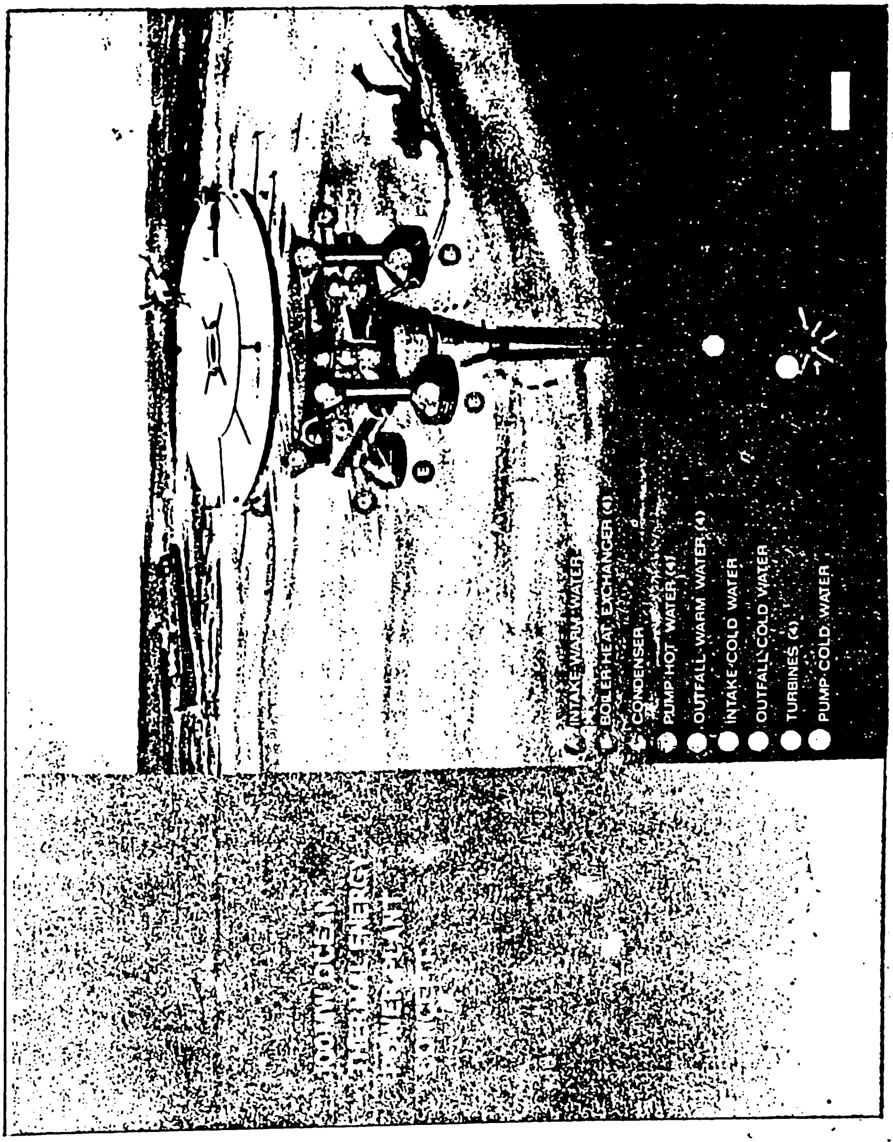


FIG. 11

tial addition of detergent which adds to cost on one hand and could present environmental problems. Having established a stable foam, it would be difficult to break it and to separate the vapor from the liquid. In the mist approach, there is an added energy loss in the mist generator and the added problems of mist generator erosion, fouling and mist instability. The problems of deaeration on the purging of the non-condensables, maintenance of near vacuum and huge hardware are also present us in the open cycle.

Proponents of both foam and mist are optimistic about the cost. The system is very simple, containing less components than the closed or open cycles. However, there are a number of unknowns and research is needed.

COMPARISON OF OTEC POWER SYSTEMS

Table 8 summarizes the comparisons among the Open, Closed and Hybrid systems with respect to problem areas.

Tables 9 thru 12 show potential advantages/disadvantages of Open and Hybrid systems compared to a closed system, Preliminary study Baseline Reference Conditions, Power Summary, Major Power System Component Descriptions, and Estimated Cost of Major Power System Components (not including cold water pipes, platforms, etc.)

ECONOMICS

In a paper by Lockheed Missiles and Space Company read at the 5th Ocean Thermal Energy Conversion Conference in 1978, they reported the following conclusion. On the question of the competitiveness of projected OTEC plants operating in the Gulf of Mexico with currently available conventional modes of baseload electricity generation, taking into account the effect of variations in the cost of fuels and capital resources, it was concluded that the fuel escalation rates at which OTEC plants become competitive with nuclear plants by the year 2000 range from 0.9% to 3.9% and those for coal-fired units from 0 to 2.5%. In the face of current uncertainty concerning construction cost of OTEC plants and future fuel price escalation rates, it is not possible to determine with any certainty whether current OTEC plant designs will become commercially attractive towards the end of the century. However, the results of this study suggest that current OTEC plant concepts are close enough to being competitive with conventional power plants to provide grounds for cautions optimism regarding the ultimate commercialization of OTEC technology.

In the same OTEC conference the Mitre Corporation reported the results of their estimates (1977 US$) as $1666/KWe and $1711/KWe average for plants using aluminum heat exchangers (HX) and Titanium HX respectively for a 3,000 MWe complex, grid connected, and rated at $\Delta T = 40°F$ (22.2°C). (See Table 3).

Tables 4, 5, 6 show mainly the effects of changing some design or operating parameters such as terminal temperature difference, cold water pipe length and surface water temperature on the cost of electricity produced. This study was done by Colorado School of Mines and reported its results at the 5th OTEC conference. The resulting cost of generating electricity ranged from 3.22 to 4.10¢/Kwh (₱.24 to ₱0.31/Kwh). A frequent expense which was not included in their costing is construction interest costs and A & E fees.

A possible way of improving the economics of OTEC plants is to combine OTEC with other activities. The OTEC electricity generating plant may be combined with industrial activities in three different ways:

a) Using the cold nutrient sea water to grow biomass or feed aquaculture.

b) Using the electricity to process free and abundant raw materials like air and water to obtain high value and easily transportable products like ammonia and liquid hydrogen.

c) Using the electricity to transform raw materials which are brought to the OTEC plant, into an energy intensive process.

There are of course certain restraints on such combinations, such as space and weight available on the floating structure, the motion of the sea, and environmental aspects. Figure 10 show some selected combinations for further studies on possible integration.

TABLE 3

ULTIMATE CAPITAL COST ESTIMATES FOR OTEC SYSTEMS*
(3000 MWe COMPLEX, GRID CONNECTED, RATED AT $\Delta T = 40°F$)

Module	*Aluminum Hx* (1977$/kW)		*Titanium Hx* (1977$/kW)
Heat Exchangers	400-700		470-820
Demisters	7- 40		7- 40
Turbogenerators	70-112		70-112
Seawater Pumps	85-200		95-200
Other Power Systems	115-195		108-195
Platform	50-300		50-300
Cold Water Pipe	71- 80		71- 80
Mooring/Deployment	50-197		50-197
Elec. Cable	100-450		100-450
TOTAL	948-2274		1021-2394
Average (1977 Dollars)	1611		1711
(1975 Dollars)	1343		1426
Modal Value (1975) Dollars)	100		1100
Range	—20%, +90%		—20%, +80%
Capital Cost (1975 Dollars)	800-1900$/kW	or	880-1980$/kW

*NOTE: On a module basis, these represent the highest and lowest estimates by four doe contractors and doe personnel as reported during February 1978. The contractors names corresponding to the estimates made are proprietary information, and are not presented for that reason. These estimates are for sites 3 miles to 200 miles from shore.

TABLE 4

OC-OTEC PERFORMANCE AND COSTS
EFFECTS OF CHANGING TERMINAL TEMPERATURE DIFFERENCE
(T_{Td})

Item	*Condition*	*Condition*
Cold water pipe length (m)	1100	1100
Temperature, °C		
Evaporator in	25	25
Evaporator out	21	25
Evaporator, T_{Td} (variable)	1	.5
Steam	20	20.5
Condensing	10	9.5
Condenser, T_{Td} (variable)	1	.5
Condenser out	9	9
Condenser in	4.34	4.34
Water head loss, meters		
Warm	4.3	4.3
Cold	5.5	5.5
Efficiencies		
Pumps and Turbines	0.75	0.75
Turbine/generator	0.70	0.70
Degasifiers (.3— .8)	0.60	0.60
Mass flow rates, 10^3 kg/s		
Warm water	246	224
Steam	1.68	1.53
Cold water	192	172
Power MW		
Turbine/generator output	100	100
Warm water pump	14.46	13.18
Cold water pump	19.36	17.51
Degasifiers	5.97	5.40
Start up	5.97	5.51
Auxiliary	5.00	5.00
System Output	55.2	58.9
Costs (millions of dollars)		
Warm water pipe	2.7	2.5
Warm water pump	7.2	6.6
Evaporator	13.6	16.8
Turbine/generator	52.3	49.0
Cold water pump	6.3	5.6
Cold water pipe	24.2	22.6
Condenser	12.5	15.4
Degasifier	2.4	2.2
Start up equipment	.6	.5
Auxiliary and controls	2.0	2.0
Operating costs per year (millions of dollars)	2.5	2.5
Cost rate $/kW	2242	2084
Cost of electricity ¢/kWh*	4.0	3.7

* Based on a 12% cost of money and assumed 8000 hours of operation per year. Includes operating costs but excludes platform costs.

TABLE 5

OC-OTEC PERFORMANCE AND COST
EFFECTS OF VARYING COLD WATER PIPE LENGTH

Item	*Condition*	*Condition*	*Condition*
Cold water pipe length (m) (variable)	800	1100	12.00
Temperatures, °C			
Evaporator in	25	25	25
Evaporator out	21	21	21
Evaporator TTd	.5	.5	.5
Steam	20.5	20.5	20.5
Condensing	9.5	9.5	9.5
Condenser, TTd	.5	.5	.5
Condenser out	9	9	9
Condenser in	5.29	4.43	4.30
Water head loss, meters			
Warm	4.3	4.3	4.3
Cold	5.5	5.5	5.5
Efficiencies			
Pumps and turbines	.75	.75	.75
Turbine/generator	.70	.70	.70
Degasifier (.3— .8)	.60	.60	.60
Mass flow rates, 10^3 kg/s			
Warm water	209	209	209
Steam	1.43	1.43	1.43
Cold water	207	159	159
Power MW			
Turbine/generator output	100	100	100
Warm water pump	12.31	12.31	12.31
Cold water pump	19.19	16.25	12.31
Degasifiers	5.77	5.01	5.01
Start up	5.66	5.20	5.20
Auxiliary	5.00	5.00	5.00
System Output	57.7	61.43	61.00
Costs (millions of dollars)			
Warm water pipe	2.4	2.4	2.4
Warm water pump	6.2	6.2	6.2
Evaporator	15.7	15.7	15.7
Turbine/generator	58.00	58.00	58.00
Cold water pipe	18.7	20.7	22.8
Cold water pump	6.6	5.2	5.24
Condenser	16.46	14.33	14.33
Degasifier	2.3	2.0	2.0
Start up equipment	.56	.52	.52
Auxiliary and controls	2.0	2.0	2.0
	128.9	127.1	129.2
Operating Costs per year (millions of dollars)	2.57	2.54	2.58
Costing rate $/kW	2233	2068	2118
Cost of electricity ¢/wWh*	3.97	3.67	3.76

* Based on a 12% cost of money and assumed 8000 hours of operation per year. Includes operating costs but excludes platform costs.

TABLE 6

OC-OTEC PERFORMANCE AND COSTS
EFFECTS OF CHANGING SURFACE WATER TEMPERATURE

Item	*Condition*	*Condition*	*Condition*
Cold water pipe length (m)	1100	1100	1100
Temperatures, °C			
Evaporator in (variable)	24	26	27
Evaporator out	21	21	21
Evaporator T_{Td}	.5	.5	.5
Steam	20.5	20.5	20.5
Condensing	9.5	9.5	9.5
Condenser, T_{Td}	.5	.5	.5
Condenser out	9	9	9
Condenser in	4.34	4.34	4.34
Water Head Loss, meters			
Warm	4.3	4.3	4.3
Cold	5.5	5.5	5.5
Efficiencies			
Pumps and turbines	.75	.75	.75
Turbine/generator	.70	.70	.70
Degasifiers (.3— .8)	.60	.60	.60
Mass flow rate, 10^3kg/s			
Warm water	279	167	139
Steam	1.43	1.43	1.43
Cold water	159	159	159
Power MW			
Turbine/generator output	100	100	100
Warm water pumping	16.37	9.87	8.24
Cold water pump	16.25	16.25	16.25
Degasifier	5.84	4.52	4.18
Start up	5.81	4.83	4.58
Auxiliary	5.0	5.0	5.0
System Output	56.5	64.4	66.3
Costs (millions of dollars)			
Warm water pipe	2.99	1.96	1.68
Warm water pump	8.21	4.92	4.11
Evaporator	18.56	13.73	12.24
Turbine/generator	58.00	58.00	58.00
Cold water pipe	20.75	20.75	20.75
Cold water pump	5.20	5.20	5.20
Condenser	14.33	14.33	14.33
Degasifier	2.33	1.81	1.67
Start up equipment	.58	.48	.46
Auxiliary and controls	2.0	2.0	2.0
	132.9	123.2	120.5
Operating costs per year (millions of dollars)	2.65	2.46	2.41
Costing rate $/kW	2351	1913	1860
Cost of electricity ¢/kWh*	4.18	3.40	3.22

* Based on a 12% of money and assumed 8000 hours of operation per year. Includes operating costs but excludes platform costs.

An additional run was carried out at 27°C surface temperature with a steam temperature of 21.5° and a terminal temperature difference of .5°C. The resulting cost of electricity is 3.00 ¢/kWh.

TABLE 7

OVERALL ECONOMICS OF A COMBINED OTEC POWER PLANT & SEAWEED FARM

OTEC POWER PLANT—100 Megawatt					*(Millions $)*
Construction costs of power plant facility					85
Construction costs of chemical plant sea & land					35
Installation and start-up in Philippines					15
Average annual operating expenses (20 years)					15
Average annual by-product credits:					50
	electrical power	15	methanol	20	
	purified oxygen	5	ammonia	10	
Time for design, construction, installation 3-5 years					
SEAWEED FARM—10,000 Acres					*(Millions $)*
Plant investment in the ocean area:					50
	cultivation	25	supports	5	
	harvesting	15	mariculture	5	
Chemical Processing factory on land					25
Farm installation and start-up costs					15
Average annual operating expenses (20 years)					15
Average annual by-product credits:					29
	food supplements, etc.	3	methane +	10	
	fertilizer, etc.	4	mariculture	12	
Methane productivity approx. 2×10^9 cu ft/yr					
Time for construction, installation, demonstration 3-5 years					

TABLE 8

COMPARISON OF OTEC POWER SYSTEM PROBLEMS

Problem	*Open*	*Closed*	*Hybrid*
1. Large Vapor Turbine	Yes	No	No
2. Low Energy Level Turbine Working Fluid	Yes	No	
3. Large Volumes for Working Fuid Containment	Yes	No	No
4. High Pumping and Parisitic Losses	Yes	No	No
5. Large Platforms	Yes	No	Yes
6. Deaeration of Warm Water	Yes	No	Yes
7. Potential Cold Water Tube Fouling	No	Yes	Yes
8. Potential Cold Water Tube Fouling	No*	Yes	Yes
9. Large High Pressure Heat Exchangers	No	Yes	Yes
10. Ammonia Handling Systems	No	Yes	Yes
11. Ammonia Induced Corrosion	No	Yes	Yes
12. Environmental Pollution	No	Yes	Yes

* Except when a fresh water saver option is included.

POTENTIAL COST SAVINGS RESULTING FROM CONCRETE PLATFORM CONSIDERATIONS FOR A 100 MWe OPEN-CYCLE POWER SYSTEM

$ 40	For Evaporator and Generator Shells
4	For Barometric Condenser Shell
15	For Diffusers
7	For Turbine Casing and Cover
5	Estimated Other components
$ 71	Total Potential Saving

(Numbers are Dollars in Millions)

TABLE 9

POTENTIAL ADVANTAGES AND DISADVANTAGES OF OPEN AND HYBRID SYSTEMS COMPARED TO A SYSTEM

OPEN STEAM SYSTEM		HYBRID STEAM/NH_3 SYSTEM	
ADVANTAGES	*DISADVANTAGES*	*ADVANTAGES*	*DISADVANTAGES*
Reduced Sensitivity to Biofouling	High Turbine Exhaust Specific Volume	Reduced Sensitivity to Biofouling	Steam Evaporator Required
Higher Heat Transfer Coefficients	Lower Pressure Change to Temperature Change Ratio	Higher Heat Transfer Coefficient in NH_3 Evaporator	Warm Water Deaeration Required
Elimination of High Pressure Working Fluid System	Warm Water Deaeration Required	Desalinated Water Produced	
Elimination of Potentially Hazardous Working Fluid			

TABLE 10

PRELIMINARY STUDY BASELINE REFERENCE CONDITIONS

	Closed NH_3 System	*Open Steam System*	*Hybrid Steam/NH_3 System*
Warm Water			
Inlet Temperature (F)	80	80	80
Δt Across Evaporator (F)	5	5	5
Cold Water			
Inlet Temperature (F)	40	40	40
Δt Across Condenser (F)	5	5	5
Working Fluid			
Evaporation Temperature (F)	70		75
Evaporation Pressure (psia)	128.8	0.43	Steam 0.43
			NH_3 70
			128.8
Condensation Temperature (F)	50	45	75
Condensation Pressure (psia)	89.18	0.143	Steam 0.43
			50
			NH_3 89.18
Power			
System Net Power Output (MWe)	25	25	25

TABLE 11

POWER SUMMARY

COMPONENT	*Closed NH_3 System*	*Open Steam System*	*Hybrid Steam/NH_3 System*
Net Output	25 MWe	25 MWe	25 MWe
Warm Water Pump/Motor	4.49 MWe	6.70 MWe	12.67 MWe
Cold Water Pump/Motor	6.67 MWe	7.96 MWe	9.33 MWe
NH_3 Feed Pump/Motor	0.69 MWe	—	0.97 MWe
Steam Condensate Pump/Motor	—	—	0.08 MWe
Generator Compressor(s)/Motor(s)	—	1.85 MWe	3.53 MWe
Gross Output (Turbine)	37.60 MWe	42.36 MWe	52.63 MWe
Gross Output (Generator)	36.85 MWe	41.51 MWe	51.58 MWe
Systems Efficiency	2.11 %	2.76 %	1.51 %

TABLE 12

MAJOR POWER SYSTEM COMPONENT DESCRIPTIONS

COMPONENTS	NUMBER OF UNITS	DESCRIPTION
CLOSED NH_3 SYSTEM		
Warm Water Pump/Motor	2	Vertical, axial flow propeller type pump units, low speed ($\sim$100 rpm), 815,000 gpm capacity per unit. Electric motor turning at pump speed.
Cold Water Pump/Motor	2	Vertical, axial flow, propeller type pump units, low speed ($\sim$150 rpm), 785,000 gpm capacity per unit. Electric motor turning at pump speed.
NH_3 Evaporator	2	Plain tube and shell, 7/8 inch O.D., 22 BWG titanium tubes, 84,000 tubes (635,000 ft. heat transfer surface area) per unit, each unit approximately 30 feet in liameter, NH_3 evaporation on shell side.
NH_3 Condenser	2	Plain tube and shell, 7/8 inch O.D., 22 BWG titanium tubes, 82,000 tubes (1.035 x 10^6 ft^2 heat transfer surface area) per unit, each unit approximately 30 feet in diameter, NH_3 condensation on shell side.
NH_3 Turbine/Generator	1	Double flow expansion turbine, 36000 rpm, itp to tip rotor diameter approximately 5 feet. Air cooled generator turning at 3600 rpm.
NH_3 Condensate Pump/Motor	2	Centrifugal pump with electric motor driver. Capacity of 12,150 gpm per pump.

TABLE 12 (Cont'd.)

COMPONENTS	NUMBER OF UNITS	DESCRIPTION
OPEN STEAM SYSTEM		
Warm Water Pump/Motor	2	Vertical, axial flow, propeller type pump units, low speed ($\sim$200 rpm), 595,000 gpm capacity per unit. Electric motor turning at pump speed.
Cold Water Pump/Motor	2	Vertical, axial flow, propeller type pump units, low speed ($\sim$235 rpm), 595,000 gpm capacity per unit. Electric motor turning at pump speed.
Deaerator	3	Multi-stage vacuum deaerator (s), pressure ratio of $\sim$3.0 per stage, total water capacity of 1.19 x 10^6 gpm, unit height of 10 feet.
Deaerator Compressors/Motors	3	One 7-stage centrifugal compressor with inlet volumetric flow rate of 38,360 ACFM, adiabatic head of 78,450 feet, and pressure ratio of 3.0. One 6-stage of 69,600 ACFM, adiabatic head of 70,650 feet, and pressure ratio of 3.0. One 5-stage centrifugal compressor with inlet volumetric flow-rate of 134,200 ACFM, adiabatic head of 54,400 feet, and pressure ratio of 3.0. All compressors driven by electric motors.
Steam Flash Evaporator	3	Vacuum flash evaporator(s), internal pressure of 0.43 psia, total water capacity of 1.19 x 10^6 gpm, unit height of 10 feet.

[a] Indeterminate at this time

TABLE 12 (Cont'd.)

COMPONENTS	NUMBER OF UNITS	DESCRIPTION
Steam Condenser	*	Multi-Jet "Barometric" condenser(s), internal pressure of 0.148 psia, total water capacity of 1.19 x 10^6 gpm, unit height of 10 feet.
Steam Turbine/Generator	6 Flowpaths	Steam expansion turbine(s), six flowpaths (rotor/stator assemblies), 600 rpm, tip to tip rotor diameter of ∾35 feet. 600 rpm air cooled generator(s).
HYBRID STEAM/NH_3 SYSTEM		
Warm Water Pump/Motor	4	Vertical, axial flow, propeller type pump units, low speed (∾220 rpm), 562,500 gpm capacity per unit. Electric motor turning at pump speed.
Cold Water Pump/Motor	4	Vertical, axial flow, propeller type pump units, low speed (∾180 rpm), 550,000 gpm capacity per unit. Electric motor turning at pump speed.
Deaerator	*	Multi-stage vacuum deaerator(s), pressure ratio of ∾3.0 per stage, total water capacity 2.25 x 10^6 gpm, unit height of 10 feet.
Deaerator Compressors/Motors	3	One 7-stage centrifugal compressor, inlet volumetric flowrate of 73,250 ACFM, adiabatic head of 77,600 feet, pressure ratio of 3.0. One 6-stage centrifugal compressor, inlet volumetric flowrate of 131,600 ACFM, adiabatic head of 70,120 feet, pressure ratio of 3.0. One 9-stage axial flow compressor, inlet volumetric flowrate of 256,000 ACFM, adiabatic head of 56,600 feet, pressure ratio of 3.0. All compressors driven by electric motor.

* Note: Indeterminate at this time.

TABLE 12 (Cont'd.)

COMPONENTS	*NUMBER OF UNITS*	*DESCRIPTION*
Steam Flash Evaporator	*	Vacuum flash evaporator(s), internal pressure of 0.43 psia, total water capacity of 2.25 x 10^6 gpm, unit height of 10 feet.
NH_3 Evaporator	4	Plain tube and shell, 7/8 inch O.D., 18 BWG aluminum tubes, 62,000 tubes (285,000 ft^2 heat transfer surface area) per unit, each unit approximately 25 feet in diameter, NH_3 evaporation on shell side.
NH_3 Condenser	4	Plain tube and shell, 7/8 inch O.D. 22 BWG titanium tubes, 58,000 tubes (730,000 ft^2 heat transfer surface area) per unit, each unit approximately 25 feet in diameter, NH_3 condensation on shell side.
NH_3 Turbine/Generator	1	Double flow expansion turbine, 1800 rpm, tip to tip roto diameter of approximately 6 feet. Air cooled generator turning at 1800 rpm.
Steam Condensate Pump/Motor	4	Centrifugal pump with electric motor driver. Capacity of 8500 gpm per group.
NH_3 Condensate Pump/Motor	4	Centrifugal pump with electric motor driver. Capacity of 2750 gpm per pump.

* NOTE: Indeterminate at this time.

TABLE 13

ESTIMATED COST OF MAJOR POWER SYSTEM COMPONENTS

	CLOSED NH_3 SYSTEM		*OPEN STEAM SYSTEM*		*HYBRID STEAM/NH_3 SYSTEM*	
	Million $	*$/kWe (NET)*	*Million $*	*$kWe (NET)*	*Million $*	*$kWe (NET)*
Warm Water Subsystem	2.5	100.0	24.0	960.0	45.7	1828.0
Warm Water Pumps/Motor	2.5	100.0	2.4	96.0	4.7	188.0
Generators/Compressors	0.0	0.0	21.6	864.0	41.0	1640.0
Cold Water Subsystem	2.6	104.0	2.4	96.0	4.40	176.0
Cold Water Pumps/Motors	2.6	104.0	2.4	96.0	4.40	176.0
Power Generation Subsystem	36.4	1456	62.4	2496	78.7	3148
Evaporators	12.2	488.0	20.2	808.0	7.7 (NH_3)	308.0
Condensers	21.0	840.0	2.8	112.0	38.0 (Fleash)	1520.0
Condensate Pumps	.065	2.6	0.0	0.0	.143	5.7
Turbines/Generators	3.1	124.0	39.4	1576.0	4.0	160.0
Total Estimated Cost	41.5	1660	88.8	3552	128.8	5152