FEASIBILITY ANALYSIS OF AN OTEC PLANT AS THE BOTTOM CYCLE OF THE THIRD NUCLEAR POWER PLANT

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Key Words: ocean energy, solar energy, renewable energy.

ABSTRACT

A conceptual design, performance analysis, system optimization and simulation of an OTEC (Ocean Thermal Energy Conversion) power plant was carried out in the present study. The OTEC plant acts as the bottom cycle of the Third Nuclear Power Plant, utilizing the warm water discharged from the nuclear plant as the heat source and the cold deep seawater pumped from the nearby sea bottom as the heat sink. The nominal net power output from the OTEC plant is estimated to be 8.74 MWe. A plant simulation was further carried out to study the OTEC plant performance due to seasonal variation of the warm water temperature, which shows that the OTEC plant is able to deliver an electricity of 5.18×10^7 kWH per year. The net power output in the winter season will be reduced to about one eighth of that in the summer season. The final discharged warm water temperature was shown to be below 29°C all year around, so that the current thermal pollution problem of the nuclear power plant can be eliminated. Additionally there is the side benefit of 8.74 MWe net power generation from ocean energy resource. This OTEC plant will become economically feasible if the installation cost is considered as a thermal pollution control investment.

以温差電廠作核三廠底循環之可行性分析

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摘 要

本研究主要探討以溫差電廠作核三廠底循環之可行性，包括構想設計、運轉性能分析、系統模擬、與系統最佳化設計。此溫差電廠係利用核三廠冷凝器

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所排出的廢熱水當作熱源，並由附近海底抽取冷海水當作熱匯。估計此温差電廠之額定淨發電量爲8.74MWe。本研究並探討温差電廠運轉性能受核三廠温排水季節性變化的影響，發現每年之總發電量爲5.18×10^7度；冬季的淨發電量約爲夏季時的八分之一。此一温差電廠可使核三廠的廢熱水排放水温終年都維持在29°C以下，所以目前核三廠所產生的嚴重廢熱水污染問題可以獲得解決，同時還可產生8.74MWe的額外電力。此一温差電廠的投資若當成環保投資的話，則其經濟可行性是無庸置疑的。

INTRODUCTION

Ocean thermal energy conversion (OTEC) has been proposed to convert the ocean thermal energy, one of the largest renewable energy resource in the world, into electricity. Extensive R&D was carried out in the 1970's, and a number of OTEC plants scaled from 10 to 25 MWe were planned to be built in the United States and Japan. An attempt has also been made in Taiwan to develop an OTEC system, since Taiwan is geologically suitable for OTEC application.

In addition to the OTEC development, the waste warm water (at 36 to 38°C) discharged from the Third Nuclear Power Plant, which is located at Ma-An Shan, in southern Taiwan, reaches approximately 40 ton/s for each turbine unit (with two units in total). The environmental impact on the Nan Wan Bay area, the current discharging site, due to the waste warm water is very serious. A shore-based OTEC power plant at Hung-Tzei near the nuclear plant was therefore proposed in order to utilize the discharged water of the nuclear plant as the heat source and the cold deep seawater separately drawn from Taiwan Strait at about 300 meters depth and 3 kilometers offshore as the heat sink. The OTEC plant will act as the bottom cycle of the Third Nuclear Power Plant. The OTEC plant, as shown in Fig. 1, thus has a dual effect of reducing the thermal pollution of the nuclear power plant and acting as a pioneer OTEC plant. A conceptual design and engineering analysis including system design, optimization and plant simulation was carried out several years ago by a research team at National Taiwan University. The present paper will present some of the results concerning the design, simulation and overall feasibility of this OTEC plant.

SYSTEM DESIGN

1. Thermal cycle

The shore-based OTEC plant is essentially composed of a closed Rankine cycle for power generation and a cold water intake system for pumping cold deep seawater. Ammonia was selected as the working fluid of the Rankine cycle, according to Ganic and Wu [8]. The evaporator of the Rankine cycle is directly heated by the waste warm water discharged from the nuclear plant and the condenser is cooled by the cold deep seawater.

The performance of the OTEC power plant can be illustrated by a thermodynamic cycle as shown in Fig. 2. The evaporator is heated by the waste warm water and ammonia is vaporized and expanded in a turbine-generator to generate electricity. The expanded ammonia vapor is then cooled and condensed by the cold

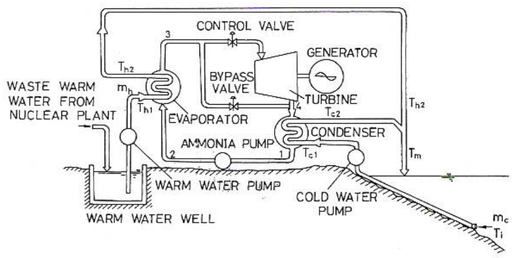


Fig. 1. Schematic diagram of the OTEC plant.

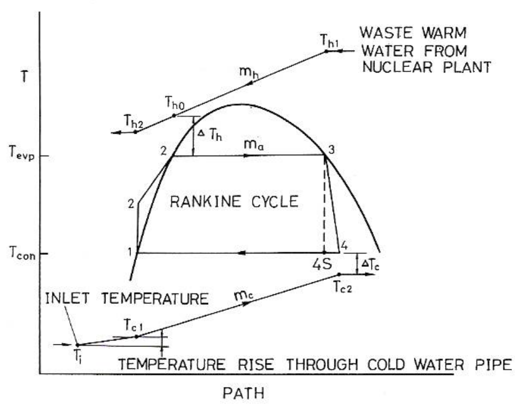


Fig. 2. Thermodynamic diagram of the OTEC plant.

deep seawater in the condenser. The ammonia condensate is then pumped back to the evaporator by a liquid pump to complete a cycle.

Part of the electric energy generated in the turbine-generator unit will be consumed by the three pumps individually to pump the cold deep seawater through the underwater pipeline, the waste warm water from the nuclear plant, and the liquid ammonia in the Rankine cycle. The net power generation of the OTEC plant is

$$W_{net} = W_T - W_a - W_h - W_c. \tag{1}$$

2. System design variables

It was assumed in the analysis that the temperature (T_{h1}) and flowrate (m_h) of the waste warm water and the cold deep seawater inlet temperature (T_i) are all fixed. From the system analysis procedure for the OTEC plant, we obtain 5 independent design variables, namely: evaporating temperature (T_{evp}), condensing temperature (T_{con}), depth of the cold water pipe intake head (H), and the neck temperatures of the evaporator and condenser (ΔT_h, ΔT_c). Here, the neck temperature is an important specification in the evaporator or condenser design, due to two-phase heat exchanging characteristics. With these 5 given variables, the system performance analysis can then be carried out by using the governing equations of each component of the Rankine cycle and the cold water pipeline.

3. Estimation of heat leakage in cold seawater pipeline

The temperature of the cold seawater is T_i at the intake of the cold seawater pipeline in deep sea and is heated up to T_{c1} at the entrance of the evaporator due to heat leakage of the pipeline. The consideration of temperature rise in cold seawater pipeline due to the heat leakage is very important, since the OTEC power plant operates at a very small temperature difference. An analytical model was derived here to account for this effect. Assume that the cold seawater pipeline is to be straightly installed on an inclined sea bed nearby Hung-Tzei, as shown in Fig. 3. An energy balance taken to a differential fluid volume inside the cold seawater pipeline yields

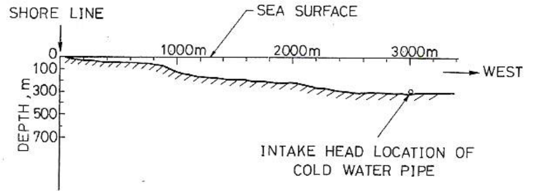


Fig. 3. Sea-bed near Hung-Tzei.

$$\frac{dT(Y)}{dY} = -\frac{4U}{K_f P_r R_e}\frac{L_c}{H}[T_s(Y) - T(Y)] \tag{2}$$

where $T_s(Y)$ is the temperature distribution of seawater and $T(Y)$ is the water temperature inside the cold water pipeline, both expressed in terms of the sea depth Y, and U is the overall heat transfer coefficient from the outside to the inside of the cold water pipeline. The heat transfer coefficient inside the pipeline is evaluated by the empirical correlation of forced convection derived by Dittus and Boelter [7]. The heat transfer coefficient at the outside wall surface of the pipeline is assumed to be of free convection and is evaluated by the empirical correlation of Churchill and Chu [5] since the cold water pipeline will be touching the sea bottom.

The seawater temperature distribution $T_s(Y)$ can be fitted to an exponential function [10]:

$$T_s(Y) = T_R + (T_o - T_R)e^{-\beta Y} \tag{3}$$

where β is a constant to be determined by fitting the oceanographic survey data to the equation, T_R is an arbitrary reference temperature, and T_o is the seawater temperature at sea surface. The fitting of the yearly-mean data collected by Taiwan Power Co. results in $T_R = 1°C$, $T_o = 2.72°C$, $\beta = 0.00249\ m^{-1}$.

Substituting Eq. (3) into Eq. (2) and assuming constant coefficients, we obtain the following solution:

$$\frac{T(Y) - T_o}{T_i - T_o} = E - \frac{Ce^{-nY}}{n+C} + [1 - E + \frac{CEe^{-n}}{n+C}]\, e^{C(y-1)} \tag{4}$$

where $E = (T_o - T_R)/(T_o - T_i)$; $n = bH$; $y = Y/H$; $C = 4L_cU/(K_f P_r R_e)$. The temperature of cold seawater reaching the shore-based OTEC plant T_{c1} can then be determined by

$$\frac{T_{c1} - T_o}{T_i - T_o} = E + (1-E)e^{-C} - \frac{CE}{n+C}[1 - e^{C-n}]. \tag{5}$$

4. Consideration in OTEC plant component designs

The capabilities of the evaporator and the condenser in an OTEC plant require a special manufacturing technique and should be considered in the OTEC plant design. The existing technique can manufacture an evaporator or condenser for the OTEC plant with neck temperature $\leq 3°C$ and pressure drops ≤ 3 psi [2,6,9,15,18]. The present OTEC power plant is designed with neck temperature of 1.94°C in the condenser and 2.5°C in the evaporator in order to achieve a better performance. The maximum allowable pressure drops for the seawater flow sides are designated as 2.8 psi.

The turbine expansion efficiency was taken as

0.89 in the analysis, since it is attainable in current turbine technology [14]. The efficiency of the electric generator is taken as 0.90, and the efficiency of the liquid ammonia pump is taken as 0.75. The pump efficiencies of the cold and warm seawater pumps are taken as 0.67, according to the capabilities of the present pump industry.

The diameter selection of cold seawater pipeline affects the system performance dramatically, since the pipe size affects the frictional and the pumping power required. A compromise thus has to be made between the technical difficulties, the pipeline installation cost and the plant efficiency. A carbon steel cold water pipeline with inside diameter of 3.0 meter and thickness of 15 mm was chosen in the design. 3 mm-thick insulation material made from polymer is to be coated onto both sides of the pipe wall using a special tar epoxy.

5. System analysis and optimum design

The cold seawater intake head is assumed to be installed at 300 m depth and about 3 km distance from the shore-based OTEC plant. The waste warm water discharged from a turbine unit of the nuclear plant is assumed to be fixed at 36°C and 40 ton/s.

The system design analysis was then carried out for various condensing and evaporating temperatures. It can be seen from Fig. 4 that for a fixed T_{evp}, W_{net} first increases with increasing T_{con} then starts to decrease. This is due to the fact that, at a fixed T_{evp}, the increase in turbine output due to lowering T_{con} is partly compensated by the increase in the pumping power W_c since the cold seawater flowrate must also be increased in order to maintain sufficient condensing effect in the condenser. An optimum design point then exists for each T_{evp}, as shown in Fig. 4.

An optimum OTEC system design thus can be concluded according to Fig. 4 and is summarized in Table 1. This is the base-design of the OTEC plant. The OTEC plant is seen to be able to deliver a net electric power of 8.76 MWe at 1.61% net thermal efficiency. The required cold seawater flowrate m_c is 22.2 ton/s.

The detailed design of the evaporator and condenser for the OTEC plant requires sophisticated calculations due to the required small neck temperatures. A plate-fin heat exchanger with cross flow is adopted in the design of the evaporator and condenser. The design procedure follows the design model of Chapman and Heydt [2]. Empirical correlations derived by Chen [4] and Chawla [3] were used in the calculations of boiling heat transfer coefficient. Empirical correlations presented in [1] were used to calculate the condensation heat transfer coefficients. The overall dimensions are shown in Fig. 5.

A four-stage, double-flow axial turbine with 14 MW output power designed by Koster and Vincent [14] was used in the analysis. The turbine base diameter is

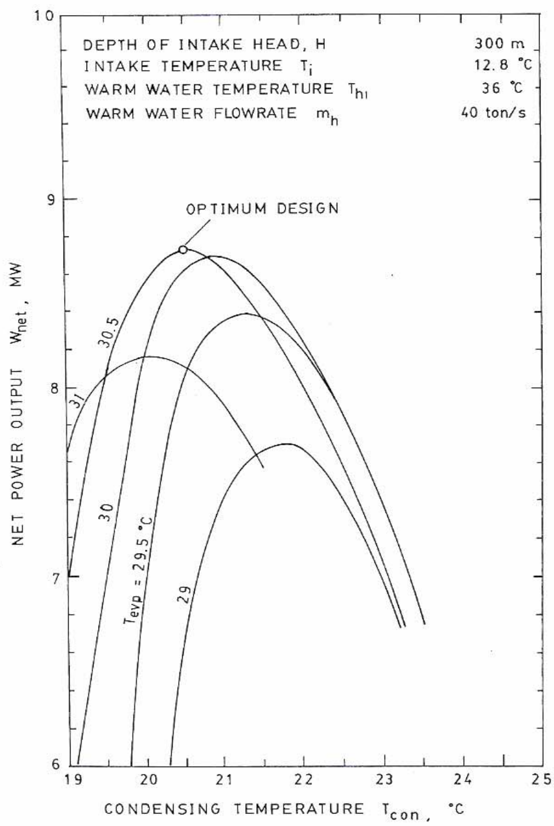
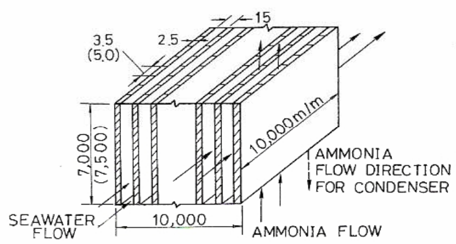


Fig. 4. Net power output W_{net}.



(NUMBERS IN PARENTHESES ARE FOR CONDENSER DESIGN)

Fig. 5. Overall dimensions of evaporator and condenser.

78.7 cm. This ammonia turbine could achieve 0.896 expansion efficiency at 1800 rpm.

OTEC PLANT SIMULATION

1. OTEC plant design

The system design of the OTEC plant as summarized in Table 1 is based on the base-design point.

Table 1. Optimum system design specification

Evaporating temperature, T_{evp}	30.5°C
Condensing temperature, T_{con}	20.5°C
Evaporator neck temperature, ΔT_h	2.5°C
Condenser neck temperature, ΔT_c	1.94°C
Depth of cold water intake head, H	300 m
Cold seawater flowrate, m_c	22.2 ton/s
Cold seawater temperature at intake, T_i	12.8°C
Cold seawater temperature at condenser entrance, T_{c1}	12.86°C
Warm seawater temperature at evaporator inlet, T_{h1}	36.0°C
Warm seawater temperature at evaporator exit, T_{h2}	32.9°C
Discharging temperature of mixed seawater, T_m	27.8°C
Ammonia flowrate, m_a	456 kg/s
Evaporator heat rate, Q_e	541 MW
Condenser heat rate, Q_c	527 MW
Pumping power of ammonia pump, W_a	0.31 MW
Pumping power of cold seawater pump, W_c	3.14 MW
Pumping power of warm seawater pump, W_h	2.06 MW
Turbine power generation, W_T	14.25 MW
Net power output, W_{net}	8.74 MW
Net thermal efficiency	1.61%
Final discharge warm water temperature, T_m	27.8°C

The operating conditions are assumed to be fixed at the nominal values (i.e. optimum point in Fig. 5). All the component designs of the OTEC plant will be made according to these design specifications. However, when the OTEC plant has been built, the operating conditions may vary due to seasonal effects or disturbances. Any slight change in the temperatures of warm and cold seawatear in field operation would significantly affect the OTEC plant performance, since the OTEC plant usually operates at a very small temperature difference between the cold and warm seawater. The OTEC designed previously was based on the yearly mean seawater temperature data obtained from an oceanographic survey in Hung-Tzei area. It is therefore necessary to carry out a plant simulation to predict the performance of the OTEC plant at off-design operating conditions.

To maintain a stable performance and raise power generating efficiency, the Rankine cycle in practical design will be augmented by an internal recirculating loop to the evaporator so that a constant ammonia circulating flowrate m_r can be sustained and automatically controlled [16] (see Fig. 6). The recirculating loop includes a pump, a liquid-vapor separator and an ammonia condensate receiver. The power consumption of the recirculating pump is small as compared to that of the primary ammonia circulation pump and thus is negligible in the calculation of the net power output. A turbine speed control system as used in conventional power plant is also required in order to deliver steady electric power.

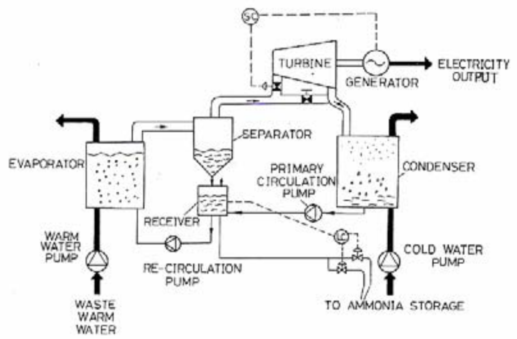


Fig. 6. System flowchart of the OTEC plant.

2. Simulation flowchart and results

The monthly-mean temperature of the waste warm water discharged from the nuclear plant is shown in Fig. 7. The discharged water temperature will exceed the base-design temperature (i.e. $T_{h1} > 36°C$) in the summer season from June to September and will be below this during winter and spring seasons.

The cold seawater is to be drawn from Taiwan Strait at about 300 meter depth. An oceanographic

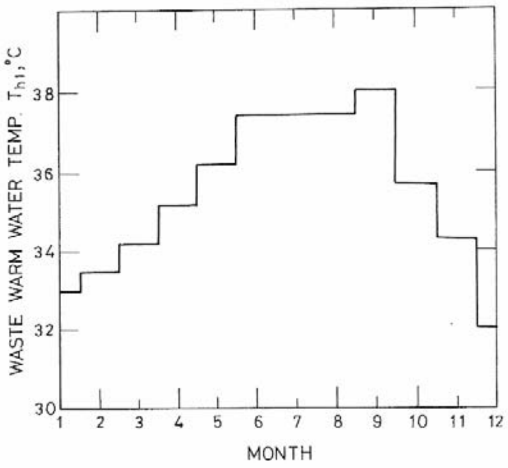


Fig. 7. Seasonal variantion of warm water temperature T_{h1}.

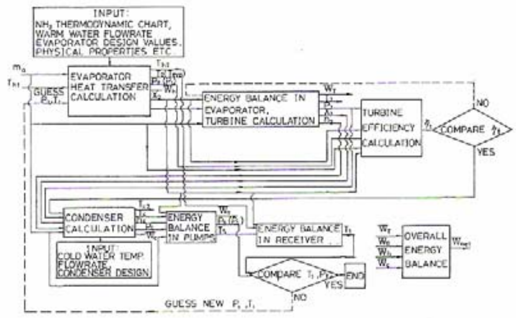


Fig. 8. Simulation flowchart of the OTEC plant.

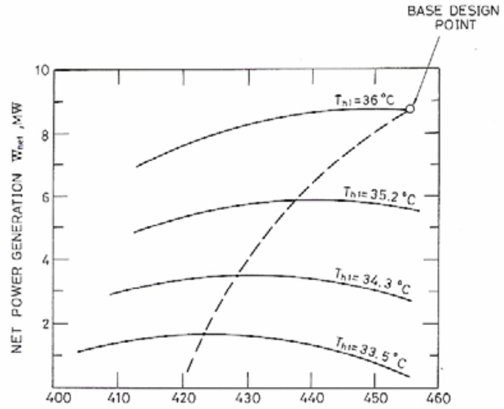


Fig. 9. Variation of net power output W_{net} with warm water temperature T_{h1} and ammonia recirculation flowrate m_r.

survey shows that the seawater temperature at this depth in this area is approximately constant all year around. Therefore, only the effect of T_{h1} variation was considered in the simulation.

The most complex computation in the OTEC plant simulation is the thermal performance calculations of evaporator and condenser. The heat transfers of the evaporator and condenser at off-design conditions were computed by following the heat transfer model derived by Chapman and Heydt [2]. Empirical correlations derived by Chen [4] and Chawla [3] were used to calculate the boiling heat transfer coefficients, and empirical correlations of [1] were used in the calculation of condensation heat transfer. Finite difference equations were then derived and a computer program was developed for the simulation.

It should be noted that the evaporator performance (including evaporating rate, temperature and pressure) will vary with the waste warm water temperature. The effect of ammonia flowrate variation on the turbine blade stage efficiency and reheat factor thus has to be considered for the ammonia turbine performance at off-design operating conditions [14,16].

A bypass valve and automatic speed control system are included in the OTEC plant in order to avoid turbine overload. The extra heating energy is thus bypassed by the bypass valves whenever the waste warm seawater temperature exceeds the base-design value (36°C) and hence the turbine will not be overloaded.

The simulation involves some iteration procedures, as shown in the simulation block diagram in Fig. 8. A computer program was developed for the simulation. The performance simulation of the OTEC plant designed according to the base-design specifications presented in Table 1 was then carried out. Fig. 9 shows the variations of W_{net} with the waste warm water temperature T_{h1} and ammonia recirculation rate m_r. The best operation is seen to be located at the base-design point for which unity of ammonia vapor quality at the exit of evaporator (i.e. $x_2=1.0$) occurs and m_a and m_r are the same and equal to the base-design value.

The evaporating rate m_a and temperature T_{evp} was found to decrease if T_{h1} decreases (Fig. 10) and the ammonia vapor at the exit of evaporator isn't saturated, i.e. $x_2 < 1$. The vapor quality x_2 depends on the recirculation flowrate. It is, however, of no use to adjust the recirculation flowrate m_r to exceed the base-design value, since the evaporator is operated at underload conditions.

For the OTEC plant operating at warm water temperature below the base-design value (i.e. $T_{h1} < 36°C$), T_{evp} increases if m_r decreases, as shown in Fig. 11. The net power output W_{net} then increases. However, a further decrease of m_r will in turn cause the boiling heat transfer rate to decrease due to the high rate of increase

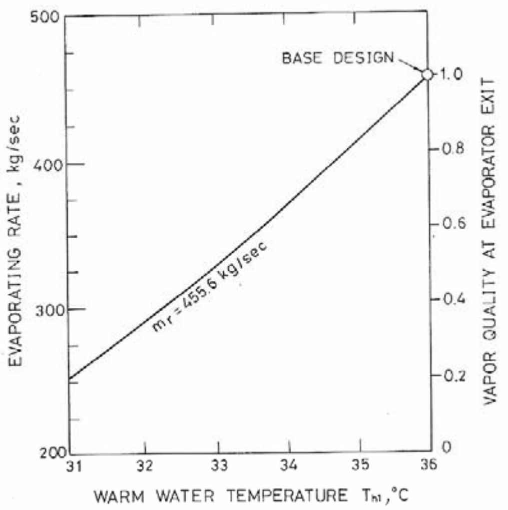


Fig. 10. Variation of evaporating rate and vapor quality with warm water temperature T_{h1}.

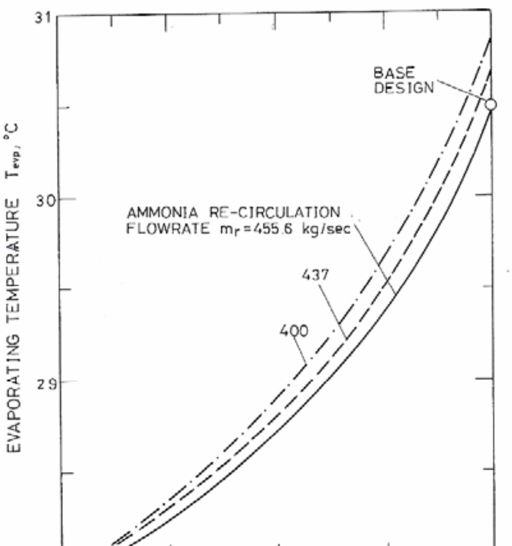


Fig. 11. Variation of evaporating temperature T_{evp} with warm water temperature T_{h1} and recirculation flowrate m_r.

of vapor quality along the ammonia flow inside the evaporator. This phenomenon results in an optimum recirculation flowrate for each T_{h1}, as shown in Fig. 9. Fig. 12 presents the optimum recirculation flowrate curve which was plotted from the locus of the optimum recirculation flowrates of Fig. 9. Fig. 12 provides the information for the optimum recirculation flowrate control

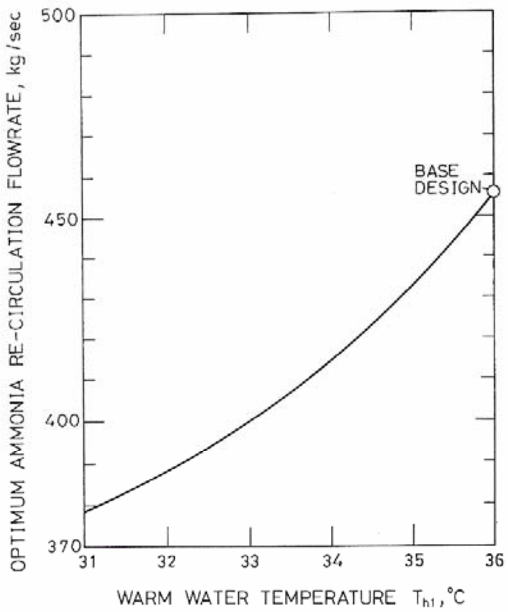


Fig. 12. Optimum ammonia recirculation flowrate.

in the field operation.

Similarly, the condensing temperature T_{con} is also affected by T_{h1} and m_r. T_{con} is seen from Fig. 13 to decrease with increasing T_{h1} and to decrease with decreasing m_r.

By using the monthly-mean data of waste warm water temperature T_{h1} as shown in Fig. 7 and the simulation results in Fig. 9, the monthly variation of W_{net} can be evaluated and presented as the solid line in Fig. 14 if m_r is controlled according to the optimum locus shown in Fig. 12. The maximum yearly total net electric energy gain reaches 5.18×10^7 kWH, assuming no line loss and 8640 hours operation per year. Provided that the ammonia recirculation rate m_r is fixed at the base-design value (456 kg/s), the monthly net power output is shown as the dotted line in Fig. 14, which is smaller than the optimum value.

The final discharged warm water temperature T_m from the OTEC plant is seen to range from 24.5°C in winter season to approximately 29°C in summer season, as shown in Fig. 16. The solid line in Fig. 15 is the original warm water temperature discharged by the nuclear plant. In addition to the yearly gain of 5.18×10^7 kWH electricity, the thermal pollution caused by the waste warm water of the Third Nuclear Power Plant can also be greatly reduced by this OTEC plant.

POWER GENERATION COST ESTIMATION

The capital investment of the OTEC plant will

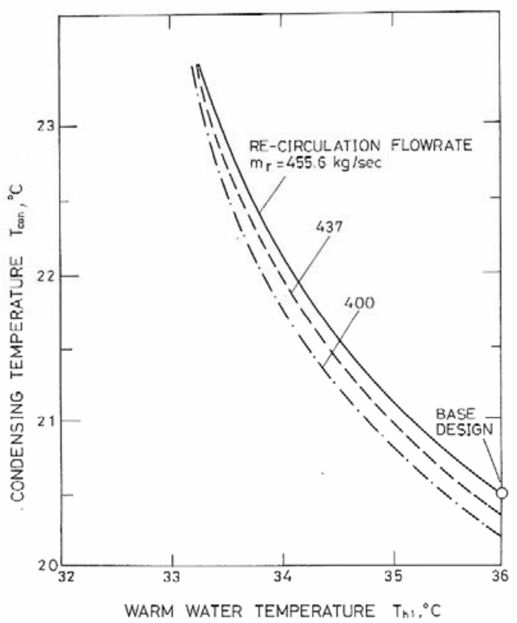


Fig. 13. Variation of condensing temperature T_{con} with warm water temperature T_{h1} and recirculation flowrate m_r.

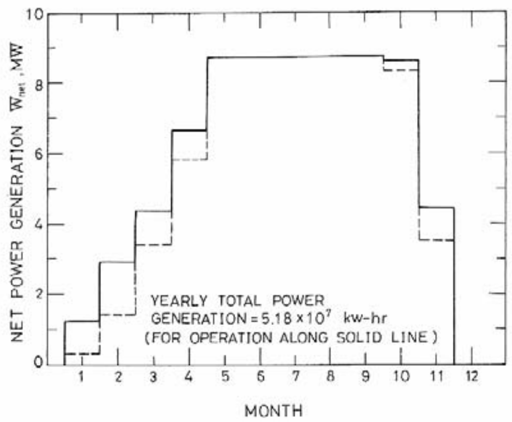


Fig. 14. Monthly variation of net power output.

be spent in the installation of the cold water pipeline, the pumping facilities, the Rankine cycle, and civil engineering.

Laying a pipeline of 3.0 meters in diameter and 3000 meters in length down to the sea bottom requires a highly technical process. The installation of a PE pipeline with 700 mm in diameter and 940 meter in length on the sea bottom at the depth of 550 meters had been successfully done by Japan in the 100kW shore-based OTEC plant in Nauru, the Central Pacific [12].

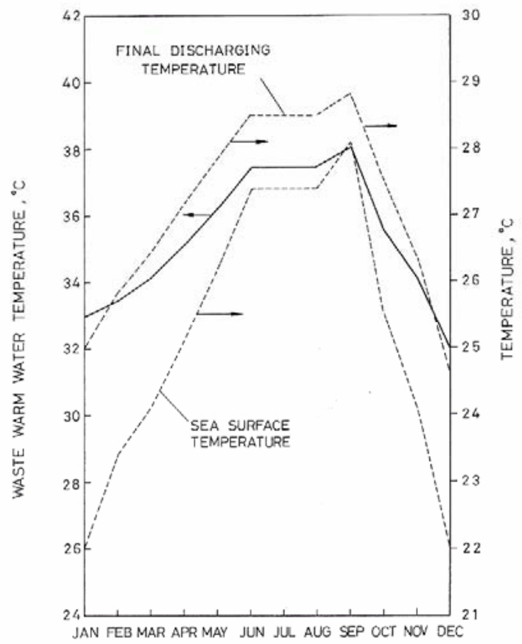


Fig. 15. Monthly variation of final discharged warm water temperature T_m.

The installation engineering used surface pulling technique [11]. A PE water pipeline with 500 mm in diameter and 2400 meter in total length was successfully installed on the sea bottom in a 50 kW shore-based OTEC plant located in Tokunoshima, Kyusui, Japan by bottom pulling technique [11,17]. Besides, a lot of engineering experiences in laying pipelines using surface pulling technique have been learned by SWECO Co. in Sweden [13]. An engineering study has shown that the bottom pulling technique will experience minimum risk in laying the large cold water pipeline on the sea bottom for the OTEC plant [11]. The cost of this engineering work was estimated to be 36.5 million US dollars (at the 1983 US dollar value) and the total installation cost was estimated to be US$ 8,660 per kW net power output [15,17,18]. The power generation cost of the OTEC plant was estimated to be around 12.6 US cents/Kw-hr, about 2 to 3 times that of nuclear or fossil plants [11].

DISCUSSION AND CONCLUSIONS

An engineering design, analysis, optimization and simulation of an OTEC power plant was carried out in the present study. The OTEC plant utilizes warm water discharged from the third nuclear power plant as the heat source and the cold deep seawater pumped from the nearby sea bottom as the heat sink. The nominal net power output of the OTEC plant is estimated to be 8.74 MWe. A plant simulation was further carried out to study the seasonal variation of the warm water temperature on the performance of the OTEC plant. The OTEC plant is estimated to deliver 5.18×10^7 kWH of electricity per year. The net power output in the winter season will be dropped to about one eighth of that in the summer season. The final discharged warm water was shown to be reduced to below 29°C, so that the current thermal pollution problem of the nuclear power plant can be solved.

The idea of an OTEC plant coupled with a nuclear power plant is thus shown to be technically feasible from the present study. The installation cost of this OTEC plant was estimated to be 36.5 million US dollars (at the 1983 US dollar value) or US$ 8,660 per kW net power output. The power generation cost of the OTEC plant was estimated to be around 12.6 US cents/kWH, about 2 to 3 times that of nuclear or fossil plants. This is still too expensive, if electricity generation is the major purpose of this OTEC plant. However, if the elimination of thermal pollution produced by the third nuclear power plant is the major concern, then this OTEC plant can be a solution with a side benefit of 8.74 MWe power generation. The installation cost of the OTEC plant can be considered as the thermal pollution control investment, and this OTEC plant will then become economically feasible.

ACKNOWLEDGEMENT

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NOMENCLATURE

D_c inside diameter of pipeline, m
H depth of cold water pipeline intake head, m
K_f thermal conductivity of seawater, W/m°C
L_c total length of cold water pipeline, m
m_a ammonia evaporating rate in the Rankine cycle, kg/s
m_c cold seawater flowrate, ton/s
m_h warm seawater flowrate, ton/s
m_r ammonia recirculation flowrate, kg/s
P_r Prandtl number of seawater
Q_c condenser heat rate, MW
Qe evaporator heat rate, MW
R_e Reynolds number of seawater
T temperature, °C
T_{con} condensing temperature, °C
T_{c1} cold seawater temperature at the inlet of condenser, °C
T_{c2} cold seawataer temperature at the exit of condenser, °C
T_{evp} evaporating temperature, °C
T_{h1} warm seawater temperature at the inlet of evaporator, °C
T_{h2} warm seawater temperature at the exit of evaporator, °C
T_{h0} warm seawater temperature at the neck point of evaporator, °C
T_i cold seawater temperature at intake, °C
T_m final discharge seawater temperature of the OTEC plant, °C
T_o sea surface temperature, °C
T_s seawater temperature, °C
ΔT_c neck temperature of condenser, °C
ΔT_h neck temperature of evaporator, °C
U overall heat transfer coefficient, W/m^2°C
x vapor quality
W_a power consumption by ammonia pump, MWe
W_c power consumption by cold water pump, MWe
W_h power consumption by warm water pump, MWe
W_{net} net power output, MWe
W_T shaft power consumption of turbine, MWe
Y depth, m

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