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OTEC RESEARCH IN JAPAN

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Abstract—Research on ocean thermal energy conversion (OTEC) has been going on in Japan since 1974. The R&D program is sponsored by the Ministry of International Trade and Industry in cooperation with a number of universities and industrial organizations. To date, the focus has been on the engineering of the power system and on the end use of OTEC-produced electric power. Although not all of Japan can benefit from electricity cabled directly to shore, Japan, because of its heavy dependence on foreign sources of energy, considers OTEC to offer other opportunities. In particular, OTEC-produced electricity may be used to extract uranium to fuel nuclear power plants located on land. Mariculture is another potential benefit of OTEC. In the paper, a summary of the technical, economic, environmental and resource factors of OTEC is presented.

1. INTRODUCTION

Energy consumption in Japan has been steadily increasing with the increased development of industry. The amount of energy consumed in 1976 was equivalent to about 386×10^6 tons of oil. This is the second highest consumption level in the free world, following the U.S.A. The energy imported by Japan amounts to 88% of the total consumption. Thus Japan is very dependent on imported fuels.

Japan is a relatively small island country. She ranks 51st in size with a total land area of 370,000 km^2. But Japan is also surrounded by a vast expanse of preferential seas, which are estimated to be twelve times larger than the land area. When the new law of the sea is concluded, Japan's total area including the land and the sea will raise her area ranking to the eleventh position worldwide. Accordingly, energy production from the sea should be an important goal for Japan.

The study of ocean thermal energy conversion (OTEC) in Japan was started in 1970 by the Committee on Investigation of New Power Generation Methods.[1] A system concept was presented by Japan to the sixth General Meeting of the Pacific Basin Economic Council in New Zealand by the author, entitled "Equatorial Marine Industrial Complex", which includes an OTEC power plant and subsystems. The complex would not only produce power but would also utilize the nutrient-rich cold water discharged from the plant for the production of mariculture.[2]

To guide the OTEC effort in Japan, the Agency of Industrial Science and Technology (AIST) of the Ministry of International Trade and Industry (MITI) established in April 1974 a committee for investigating the feasibility of OTEC at the Japan Heat Management Association (JHMA).[3] The program name "Sunshine Project" was adopted. The project aim was the development of new energy technologies. In the same year, experimental research on OTEC was started at the Electrotechnical Laboratory of AIST in Tokyo and at the Science and Engineering Faculty of Saga University in Saga.

2. CONCEPTUAL DESIGN AND ECONOMIC EVALUATION OF OTEC

The objectives of the OTEC feasibility study by the committee in JHMA were the evolution of a conceptual design of OTEC power plants and the evaluation of technical and economic factors related to the concept as a whole.[4] As a first step, design work was conducted in 1974 on a 1.5 MW land-based experimental OTEC power plant. This was followed by a system analysis of a larger, ocean-based OTEC power plant. In the second year (1975), a conceptual design was prepared for an ocean-based demonstration OTEC power plant rated at 100 MW and sited at a benign tropical location. The design was based upon the current state of technology with minor technical improvements, particularly in the heat exchangers. In the third year (1976), an improved conceptual design of a 100 MW OTEC power plant, to be located at sea near Japan, was made. This later design was based upon advanced technology. In the fourth year (1977), additional work on the previous year's design was carried out. Emphases were placed especially on the platform structure, station keeping, riser cable to the station, and improvements in the heat exchangers.

2.1 *Working fluid selection*

Prior to the design work of the 100 MW plant, which consisted of four 25 MW power modules, the problem of working fluid selection was addressed. Twelve substances were considered including "Flon" compounds [halocarbons or Freons], hydrocarbons, and ammonia. The result was that R-22 [Freon-22], propane, and ammonia were found to be suitable for turbines rated at 25 MW and 1800 rpm. Further evaluation took into account the reduction of heat exchangers size and piping cost. As a result, ammonia was judged to be the best working fluid for this design.

2.2 *Heat exchangers*

Heat exchangers are the most important components of an OTEC power plant. They account for a substantial part of the capital cost of the plant. For the base-line design which was executed in 1975, the shell-and-tube type heat exchangers were selected. A review of experimental data of heat transfer performance applicable to an OTEC power cycle led to the conclusion that a corresponding overall heat transfer coefficient of 3300 kcal/m^2-hr-°C [$\sim$750 Btu/hr-ft^2-°F] could certainly be achieved for both the evaporator and the condenser at a water velocity of 2 msec.

For this base-line design, a 100 MW OTEC plant is divided into four power modules, and each module is provided with four units of evaporators and condensers. Each evaporator consists of 32,800 titanium tubes of 9.82 m in length, with 20 mm outer dia. and 2 mm wall thickness. The tubes provide a total heating area of 20,150 m^2. The total pressure head loss of water flow through the evaporator is estimated to be 3.33 m at a water velocity of 2 msec. On the other hand, each condenser has 20,500 titanium tubes of 12.9 m in length, with 25 mm outer dia. and 2 mm wall thickness; total area for condensing is 20,800 m^2. The total pressure head loss of the cold water flow through the condenser amounts to 3.37 m at the water velocity of 2 msec.

It was found by the cost estimation of the 1975 design that the total heat exchanger cost amounted to 45.7% of the plant construction cost. Improvement of the heat exchanger should be the most important item in OTEC plant development. For the 1976 design, use of new plate-type heat exchangers, based upon advanced technology, were proposed by T. Uehara of Saga University. These heat exchangers were developed by his group as described in a later section. The overall heat transfer coefficient of the titanium plate evaporator of his type could reach 5000 kcal/m^2-hr-°C at 2 msec warm water velocity, and the overall heat transfer coefficient of the titanium plate condenser could reach 4500 kcal/m^2-hr-°C at 2 msec cold water velocity.

Through the optimization process described in the next section, final designs for these heat exchangers were made. For the evaporator, an overall heat transfer coefficient of 3476 kcal/m^2-hr-°C at a water flow velocity of 0.79 msec is predicted. The overall length and diameter of each evaporator are 32.2 and 9 m respectively. For the condenser, an overall heat transfer coefficient of 3015 kcal/m^2-hr-°C is predicted at a water flow velocity of 0.87 msec. The dimensions of the condenser unit are 28.7 m in length and 6 m in diameter.

2.3 *System optimization*

For a low efficiency system such as OTEC, optimization of the power generating cycle is very important. The cumulative sum of each component loss influences considerably

Table 1. Major specifications and costs of 100 MW OTEC power plants.

items	1975 design	1976 design
gross power output (kW)	100,000	100,000
net power output (kW)	73,940	77,210
working fluid	ammonia	ammonia
w f flow rate (kg/h)	$1\ 18 \times 10^7$	$1\ 114 \times 10^7$
warm water temp (°C)	28	28
intake warm water (kg/h)	$9\ 88 \times 10^8$	$9\ 74 \times 10^8$
cold water temp (°C)	7	7
intake cold water (kg/h)	$1\ 01 \times 10^9$	$8\ 09 \times 10^8$
evap heat transfer area & units (m^2)	$3\ 2 \times 10^5$, 16	$3\ 106 \times 10^5$, 8
cond heat transfer area & units (m^2)	$3\ 3 \times 10^5$, 16	3508×10^5; 8
T/G output & units (kW)	25,000 4	25,000 4
type of platform	rectangular barge	submerged cylinder
unit construction cost (¥/kwh)	780,000	644,600
unit power cost at the busbar (¥/kwh)	11 75	9 56

the net output of the plant. No matter how small a particular loss item may appear, it should not be overlooked. Optimization calculations including the computer program development were conducted by T. Kajikawa of Electrotechnical Laboratory. Numerous industrial firms have cooperated by providing cost data of major components. Calculations were made for both base-line and advanced designs. The optimization criterion used is the minimum ratio of the sum of the costs of six major components to the net output, gross power outlet (fixed at 100 MW) minus total pumping power. Intake warm and cold water temperatures were fixed at 28 and 7°C respectively. There are tradeoff relationships in the system, among the temperature distribution, flow velocity, heat transfer value, pumping power, and cost of major components, mainly of the heat exchanger. Calculations were repeated until convergence to the minimum-cost performance ratio was obtained. Finally, the costs of the platform structure and of the cold water pipe were added to the cost of the generating cycle components obtained through optimization.

Optimized net power outputs at the busbar of the OTEC plants are 73,940 kW for the base-line design and 77,210 kW for the advanced design. Optimized unit construction costs (at a conversion rate of $1 = 250 yen) are 780,000 yen ($3120) and 644,600 yen ($2580) per 1 kW of net power output, for respective design cases. In the advanced design, contribution of the heat exchangers to the construction cost was reduced to 40.1% from 45.7% in the base-line design. Unit power costs for both the base-line and the advanced designs were calculated to be 11.78 yen/kWh (47 Mills/kWh) and 9.65 yen/kWh (38.2 mills/kWh) respectively. Table 1 indicates the optimized specifications of the base-line and advanced designs respectively.

2.4 *Platform structure*

The size and structure of the OTEC power plant platform is mainly determined by the weight and volume of the components loaded on it. Platform design is also influenced by the expected worst sea states at the plant site. In the 1975 design, the 100 MW OTEC power plant was assumed to be located at a benign tropical site. The platform was a large rectangular barge type with space to accommodate a hydrogen plant for energy conversion. Since 1976, the power plant has been assumed to be located at sea around Japan. The size of the platform became smaller than that of the 1975 design because plate-type heat exchangers were utilized instead of the shell-and-tube type and because the power generated was assumed to be electrically transmitted directly to Japan itself.

In the 1976 design, two types of platforms, a surface ship and a submerged cylinder, were selected to meet the rough sea conditions around Japan. Dynamic forces acting on

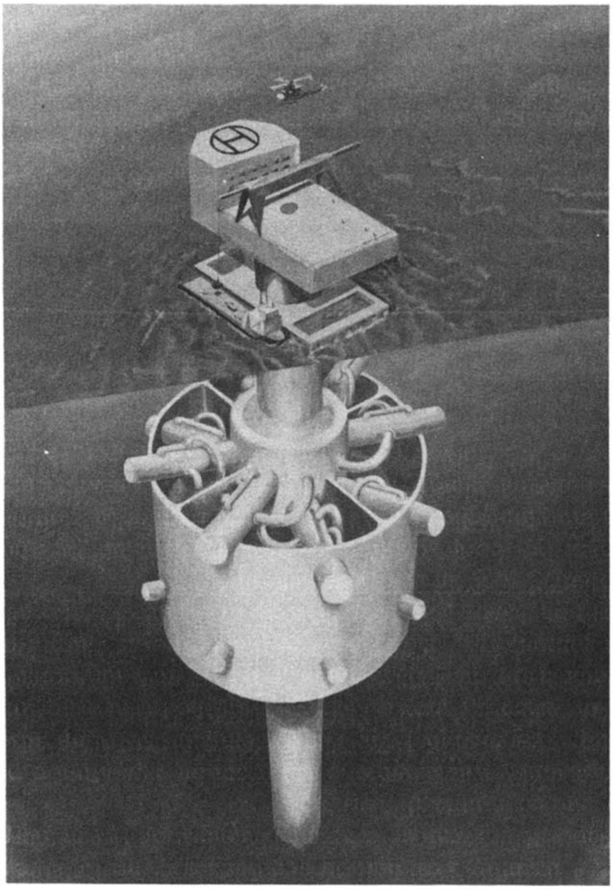

Fig. 1. An artist model of the submerged cylinder type 100 MW OTEC.

these platforms were calculated and the designs of the two platforms were made for the sea states of a maximum wind velocity of 60 msec, a maximum wave height of 18.5 m (in a period of 16 sec) and a surface current of 2 knots. Figure 1 shows an artist's model of the submerged cylinder type.

Suitable sites for OTEC in the sea around Japan were classified according to potential thermal resources, which are described later, accessibility to the power users, and other natural and social conditions. In 1977, more precise designs were made of three types of platforms: surface ship, surface disc, and submerged disc. The environmental and sea state conditions at two representative sites were considered: offshore of the Osumi Islands, and in the Toyama Bay of the Sea of Japan. The characteristics of the sea states at the respective sites are shown in Table 2. External forces on the platforms, cold water pipes, and the sea-keeping performance were estimated by calculation and by preliminary tests in a wave flume. It was identified that the wave drifting force is most important, and that some of the conventional formulas to calculate it should be reexamined. The overall dimensions of the platforms designed in three years and the sea-keeping performance of the 1977 design are tabulated in Table 3.

Table 2. Characteristics of sea states.

	max. significant wave height	max. significant wave period	current speed		max. wind velocity
			at surface	at the depth of 500m	
Offshore of Osumi Island	13.0m	13 sec	1.74m/sec	0.25m/sec	60m/sec
Toyama Bay	8.4m	13 sec	1.00m/sec	0m/sec	60m/sec

Table 3. Comparison of overall dimension and calculated motion for typical platforms for Osumi sea states.

study year		1975	1976		1977		
type		rectangular barge	surface ship	submerged cylindrical	surface ship	surface disc	submerged disc
length	m	204	350	70φ	230	110φ	110φ
width	m	110	80		60		
depth	m	35	25	65	27	37	40
draft	m	21	11	100	13	27	55
displacement long ton		400,000	250,000	169,700	145,000	276,000	409,300
structure material		steel	steel	concrete	steel	steel	steel
max horizontal load for Osumi	t	—	—	—	1 262	1 606	1 596
sea keeping response for Osumi sea states: surge	m				2 5	3 0	2 3
sway	m				3 4	3 0	2 3
heave	m				3 9	5 9	3 1
roll	°				11 3	0 7	0 1
pitch	°				4 9	0 7	0 1
yaw	°				2 6	0	0

3. PARAMETRIC STUDIES OF POWER SYSTEMS PERFORMANCE

Experimental and theoretical studies on OTEC power systems and research to improve heat exchanger performance have been undertaken by two groups. At the Electrotechnical Laboratory in Tokyo affiliated with MITI, T. Kajikawa's group is conducting experimental work using an ETL-OTEC-II loop as shown in Fig. 2.[5] At the Science and Engineering Faculty of Saga University, the work is being conducted by H. Uehara's group using the power loops of Siranui series as shown in Fig. 3.[6] ETL-OTEC-II is a small power loop. The warm fresh water source is kept within a temperature range of 26–42°C and a flow rate of 0.7–2.7 msec using a 75 kW electrical heater. The cold fresh water source is kept within a temperature range of 5–24°C by a 70 kW chiller unit. The working fluid used so far is Flon-114, [R-114]. The boiling surface of the horizontal evaporator is a doubly-fluted aluminum tube coated with copper powder to enhance nucleate boiling. Doubly-fluted aluminum tubes were used for the vertical condenser. The power output of the d.c. generator in the system is about 500 W, while the mechanical work at the turbine is 1.3 kW under the temperature conditions of warm water at 30°C and cold water at 5°C respectively. Figure 4 shows the gross power output of the generator as a function of the warm and cold water velocities V_H and V_L respectively. It also shows a series of experiments of power generation, obtained by changing the physical parameters. Temperatures (at 140 points), pressure distribution in the working fluid (at 12 points), velocity of cold and warm water, head loss in the heat exchangers, and

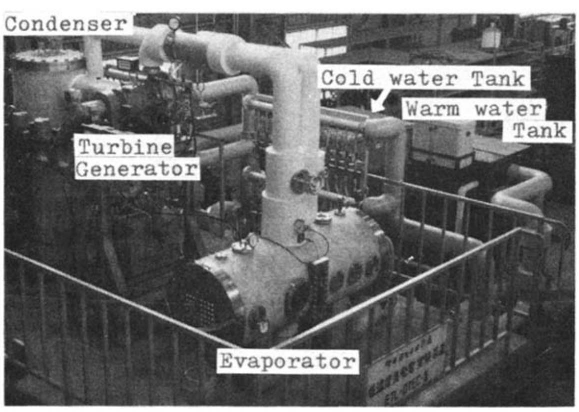

Fig. 2. ETL-OTEC-II experimental power loop.

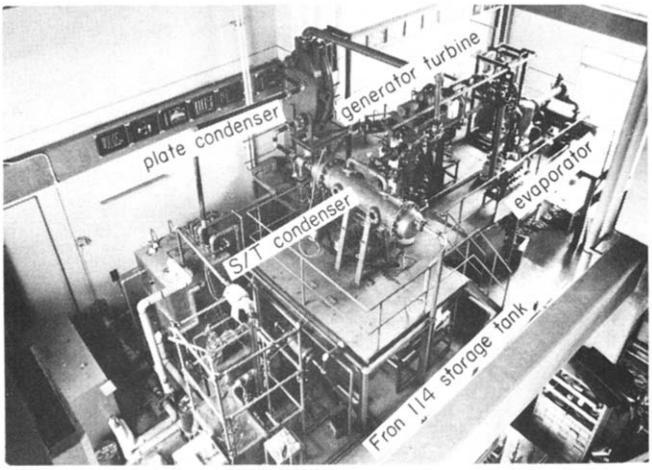

Fig. 3. Siranui 3 OTEC experimental power loop.

speed and output power of the turbine-generator were measured. An analytical model of ETL-OTEC-II was developed. The model takes into account the relationship among the system components. From a comparison between the theoretical results and the experimental data, it was identified that there is close interaction among the characteristics of the system components. For example, the behaviors of both the evaporator and the condenser are determined not only by the external conditions but also by the up-stream behavior of the system.

Figure 5 shows the layout of Siraniu 3, a power loop used by H. Uehara. Flon-114 was chosen as the working fluid, for two reasons: (1) Flon-114 turbine of such a small output is easier to build than a corresponding ammonia turbine. (2) It is easier to meet the Japanese industrial safety regulations with Flon-114 than with ammonia. The warm water was secured from a boiler rated at 85000 kcal/hr and the cold water from a refrigerator rated at 85000 kcal/hr. The temperatures of the warm water can be changed from 25 to 50°C and that of the cold water from 5 to 12°C. The rated output of the Flon turbine is 1 kW at 3600 rpm. A major result identified by the Siranui 3 experiments is that the optimum condition of each component can only be determined by a total system experiment. There are close couplings among the system components.

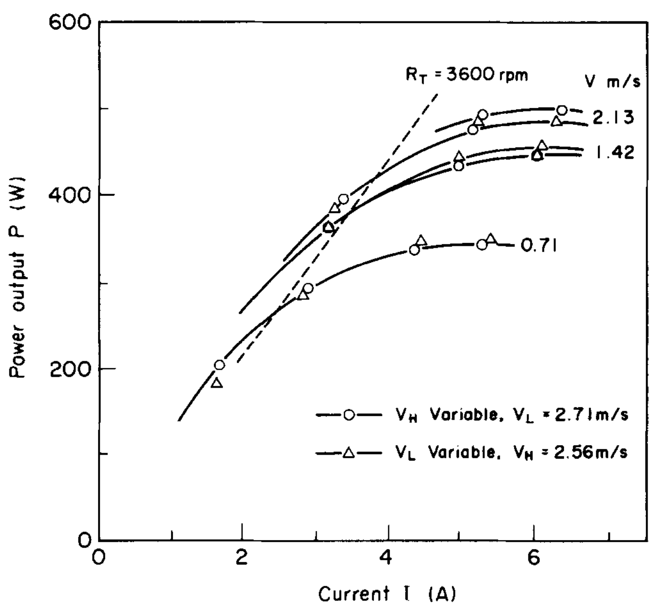

Fig. 4. Power characteristics of the T/G of ETL-OTEC-II.

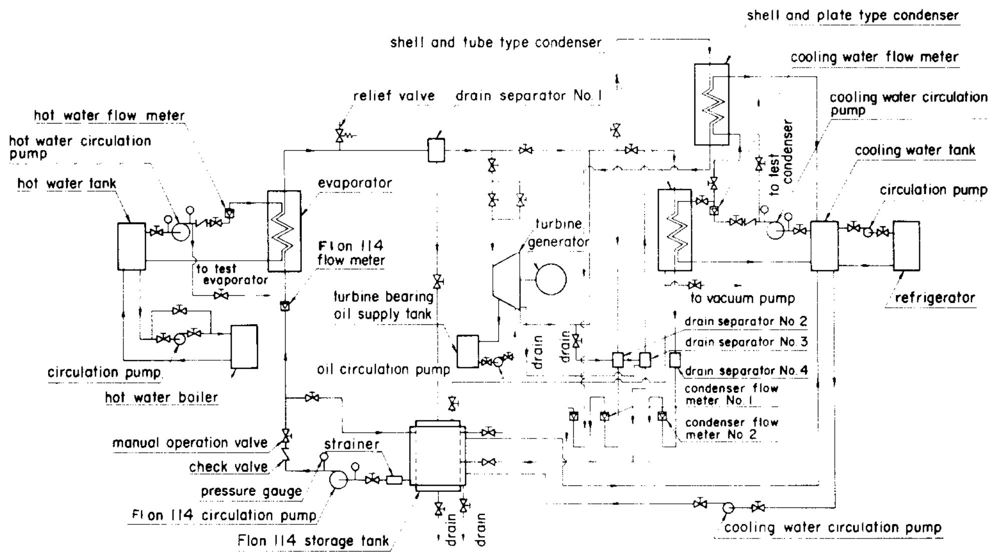

Fig. 5. Siranui 3 OTEC experimental power loop at Saga University.

Uehara has studied the heat transfer of condensation and evaporation since 1961. New types of evaporators and condensers suitable for OTEC are being developed using Siranui 3 and other simpler loops. The experimental data analyzed by the theory of heat transfer, using the Flon-114 experimental data, could be generalized to apply to other fluids; for example, ammonia.[7] New plate-type evaporators and condensers were developed and intended to achieve high performance in heat exchangers in which working fluid phase change occurs. Figure 6 shows an element of the plate condenser.

The overall heat-transfer coefficient of the plate evaporators was estimated at about 5000 kcal/m^2-hr-°C in the case of ammonia-sea water as shown in Fig. 7. The overall

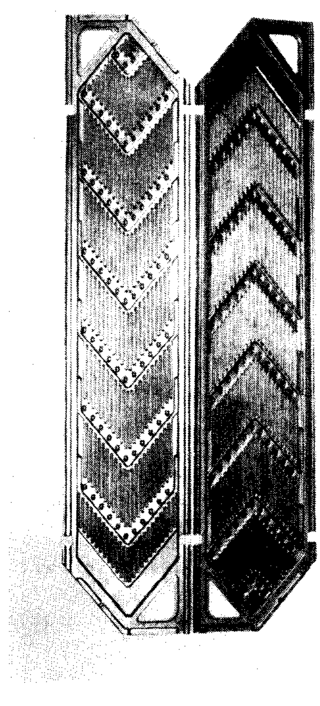

Fig. 6. An element of the plate type condenser (Uehara).

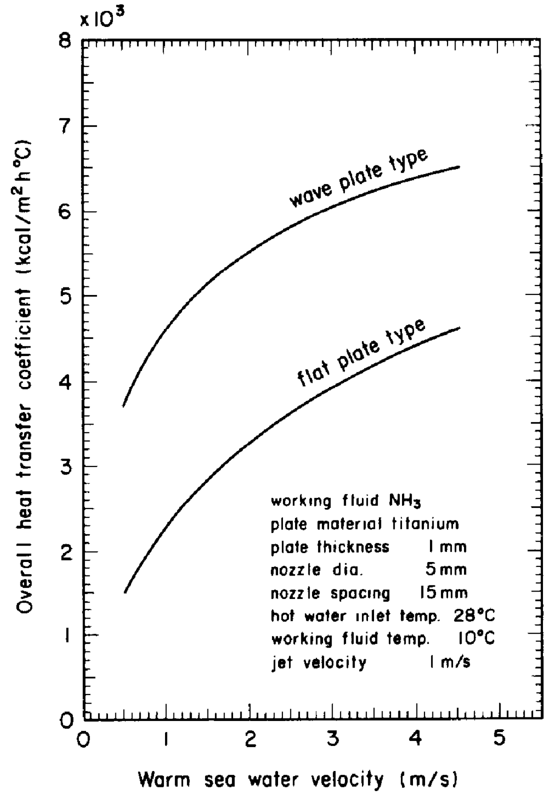

Fig. 7. Overall heat transfer coefficients of plate type evaporator (Uehara).

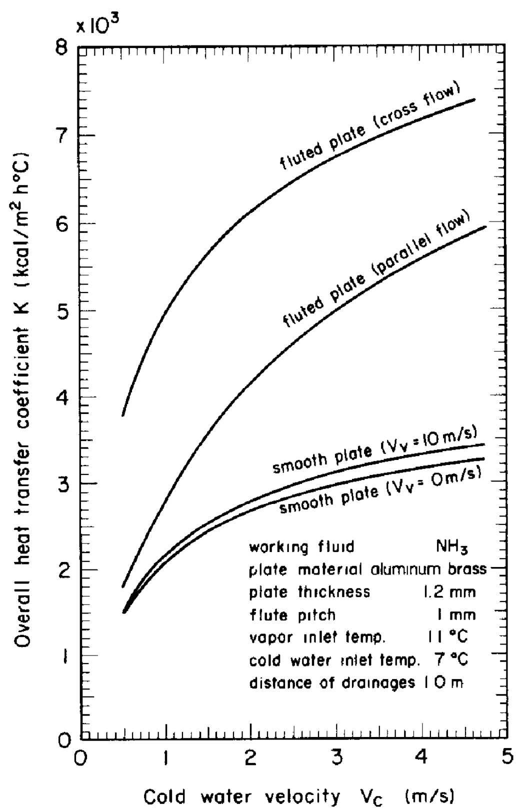

Fig. 8. Overall heat transfer coefficients for plate type condenser (Uehara).

heat transfer coefficient of the plate evaporator is estimated at about 5000 kcal/m^2-hr-°C as shown in Fig. 8.

4. INDUSTRIAL PARTICIPATION

Since the Japanese OTEC research is at an early stage, industrial firms having OTEC-related technologies have contributed mainly as members of the JHMA OTEC study committee, or as suppliers of the OTEC experimental facilities. Among them, both Toshiba Corporation and Mitsubishi Heavy Industries Co. have a potential interest in OTEC power systems, based upon these firms' capabilities in the binary cycle power technology. Both companies have independently developed 1000 kW hot water type geothermal plants under the "Sunshine Project". Ishikawajima Heavy Industries Co., Mitsubishi Heavy Industries Co., Shimizu Construction Co., and others have contributed to the OTEC platform structure designs, based upon their shipbuilding or civil engineering capabilities. Tokyo Electric Power Service Co. (TEPSCO) is developing land-based OTEC power plants, based upon their expertise in civil engineering and power plant engineering.

5. OTEC THERMAL RESOURCES

The potential thermal resources of the equatorial Pacific Ocean and the sea surrounding Japan have been estimated by the author and by T. Kajikawa. The sea condition, especially near the surface, fluctuates seasonally. Enormous amounts of monthly sea data of each mesh of one degree latitude and one degree longitude have been compiled at the Oceanic Data Center of the Maritime Safety Board of Japan since 1906. Seasonal temperature difference maps between the surface and 600 m depth were prepared for the northern half of the western Pacific Ocean. Monthly temperature difference maps were prepared of the sea around Japan. The thermal resources were estimated utilizing these maps and the method reported in reference 8.

The thermal resource in the equatorial sea is estimated at about 5×10^5 GWh/yr/mesh. A resource map around Japan, compiled by Kajikawa is shown in Fig. 9. The figures in GWh/yr/mesh unit attached to the contour lines in the map indicate the yearly total amount of OTEC power available from the sea surface per one degree mesh. For example, 3.75×105 GWh/yr/mesh could be available from the sea southeast of Kyushu. This figure is comparable to the yearly total electric power generated in Japan.

6. URANIUM EXPLOITATION BY OTEC

For OTEC power plants located on the equatorial zone, numerous industrial applications for on-board energy utilization of hydrogen production are one possibility. Another is to extract valuable minerals from the large volumes of warm and cold water processed by an OTEC plant. A uranium exploitation plant at sea seems to be important for Japan, because uranium deposits are scarce in Japan. The question is whether such an approach is both technically and economically feasible.

A preliminary case study was made of a sea uranium exploitation plant on board the 100 MW OTEC barge designed in 1976. The system consists of an adsorption subsystem and a desorption subsystem as shown in Fig. 10. In the former, not only the discharged warm and cold water from the OTEC plant, but also the additional water, which was pumped up utilizing about 85% of 77.2 MW of the net power output of the plant, passes through the adsorption layer. The head loss of the water by the adsorption layers is estimated to be about 15% of the net power output.

Uranium adsorbed on the adsorption layers is leached out by the desorption cycle using a solution of inorganic chemicals. Fresh water used for the solution can be supplied by the OTEC desalination plant. Assuming the adsorption efficiency is 50% and the desorption efficiency is 90%, it was estimated that 110 tons per year of uranium can be

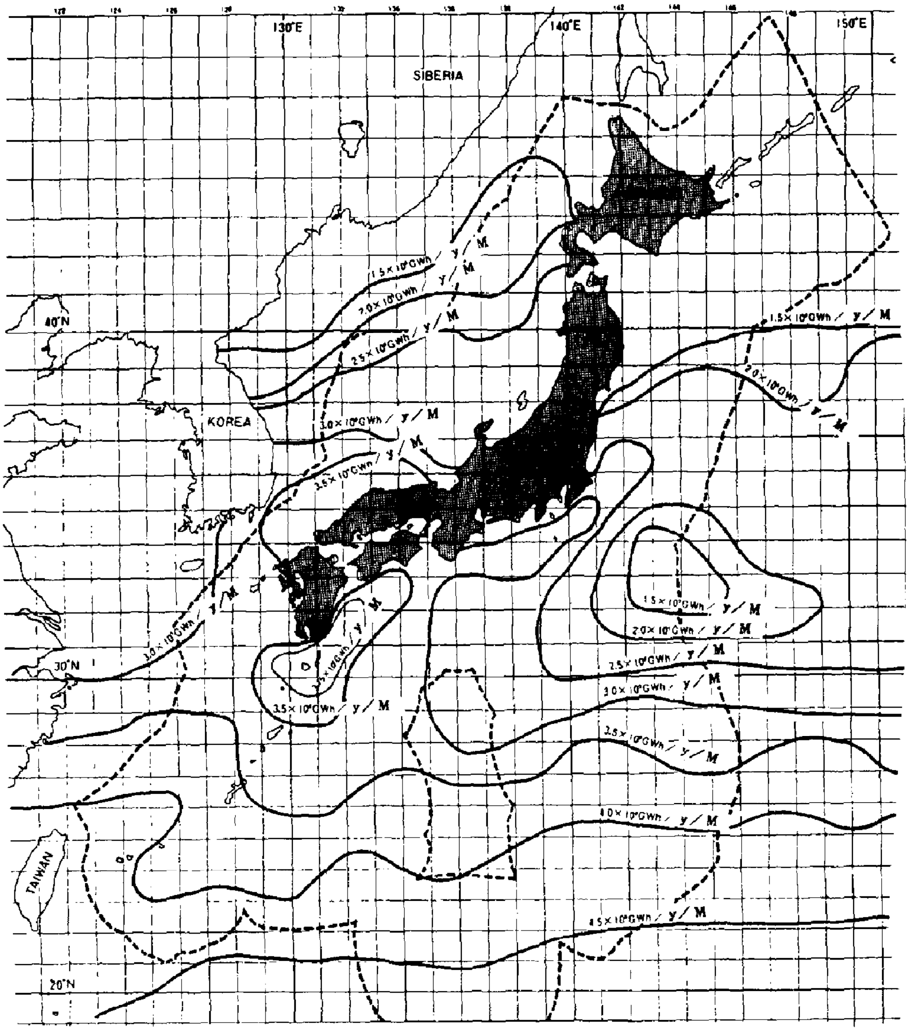

Fig. 9. The OTEC thermal resource map of Japan. Electric power can be available in one year per mesh: one mesh indicates sea area of 1° longitude and 1° latitude: cold water depth 600 m. Total power available in 1 yr in the area covered by dotted lines is 1.06×10^8 GWh/yr/mesh. [Based on JODC data (1923–71)].

exploited by this 100 MW OTEC plant, at the plant operation factor of 80%. From 110 tons of natural uranium, 22.5 tons of the enriched uranium (enrichment 2.7% and the tail 0.2%) is calculated to be available, which is sufficient to operate a 700 MW BWR type nuclear power station for 1 yr.

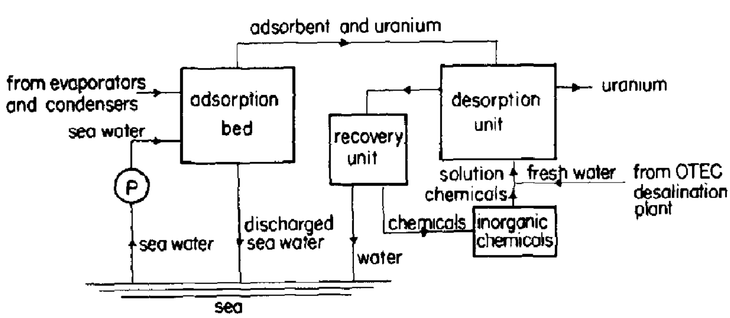

Fig. 10. The OTEC uranium exploitation system.

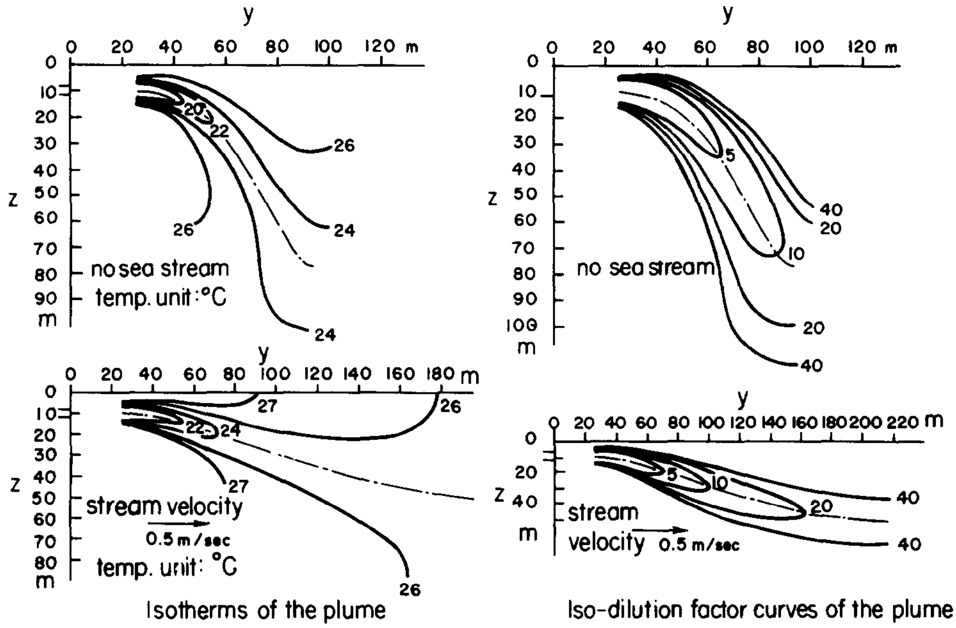

Fig. 11. Isotherms and iso-dilution factor curves in the plume of the 100 MeV OTEC plant, when the initial plume direction at the outlet (at -10 m) and the sea stream direction are along y-axis. The ambient sea temperature is 28°C and the outlet temperature is 11.1°C.

7. EFFECTS ON MARINE BIOLOGICAL PRODUCTIVITY

A feasibility study of the utilization of OTEC power plants for the enhancement of marine biological productivity is particularly important for Japan. Japan is a small island country surrounded by a vast expanse of preferential sea area. The marine products taken from the sea serve as the main source of protein for Japan. The Japanese coastal waters and the Oyashio current have had fairly high marine biological productivity, but in the Kuroshio current area and beyond, the sea is warm and clear and has poor marine biological productivity. OTEC power plants seem to be well suited for the Kuroshio sea area, because they provide the possibility of generating power and marine products simultaneously. As a result of the studies at the two model sites for OTEC, i.e. the offshore of Osumi Islands and Toyama Bay which are rich in pelagic fish eggs and fish larvae, the significance of two conflicting factors has been recognized. The discharged cold water is rich in nutrients and thus a growth in the phyto-plankton population caused by the presence of the plant is to be expected. On the other hand, an increase of mortality rate due to the entrainment by the intake water to the plant should be expected also. The question is, which feature is dominant? Further research appears necessary.

8. ASSESSMENT OF ENVIRONMENTAL EFFECTS

Assessment of OTEC has been conducted by an oceanophysics group in collaboration with the marine biology group mentioned above under the leadership of T. Teramoto of Ocean Research Institute of Tokyo University. The study covered the behavior of the discharged water from the plants and included the behavior of the plume from the outlet and the dependence on the current direction and velocity. The 100 MW OTEC plant was used in the study. Some results are shown in Fig. 11. Life-time of the plume in the euphonic zone may be closely connected to the marine biological productivity. The study also was made on the behavior of the diluted water mass far outside of the OTEC, taking into account the Coriolis' force and comparing it with the behavior of the natural cold water mass. Interaction between sea surface and atmosphere on the Sea of Japan and East China Sea has been fairly well studied in Japan, because it closely relates to the Japanese climate. The study of heat balance between sea and air was made at the offshore of Osumi Islands and Toyama Bay along the Sea of Japan, utilizing previous results.

9. CONCLUSION

OTEC research in Japan has been carried out since 1970. In the past 4 yr the research activity has expanded further. Design and cost estimation of the model 100 MW OTEC plants, two OTEC power loop experiments and development of new heat exchangers for OTEC, and applications of OTEC have been worked out. Evaluation of OTEC thermal resources and the assessment of the OTEC concept as a power system have also been made.

However, the activity is still in the early stage, and enormous amounts of research and development work is needed before OTEC power plants can contribute to Japan's energy demand. It is the author's opinion that the development of OTEC through international collaboration should be pursued for the benefit of mankind.

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