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LOW LEVEL TEMPERATURE ENERGY TECHNOLOGIES

BY

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ENGINEERS INDIA LIMITED

INDIA

AT

THE SESSION 9 (MAY 1984)

TRAINING IN ALTERNATIVE ENERGY TECHNOLOGIES

UNIVERSITY OF FLORIDA

GAINESVILLE

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1.0 INTRODUCTION

The dismal world energy scenario with a complete depletion of conventional and non-renewable energy sources leads one to pessimistically believe that man has not learnt to live harmoniously with nature. Such gloomy projections indicate a highly energy dependent society grinding to a halt or exploding in a shimmering nuclear holocaust. One country's attempt at cornering whatever remains of the "Black Gold" may incite such harsh measures from a competing yet energy starved nation that the dictum "man never learns" may yet come true.

But is that the only scenario one can envisage? Or is it that man shall rise above the morass of defeatism and yet once again prove that "necessity is the mother of invention" and plunge on exploring newer and yet untried technologies on a scale not even evisioned as yet. The sanity that knowledge demands is certain to prove stronger than the cravings of self destruction. Man shall be able to substitute at a reasonable cost new energy types for his insatiable demands. Untapped and as yet unexplored sources of energy shall replace oil and gas to drive the economies the world over.

Considering the urgency and the acute necessity for energy substitutes, it seems enough research and exploration is not being undertaken and all countries- rich and poor, big and small- are dragging their feet on the matter. In fact, one can trace the development of alternative sources of energy to the oil price increases. Acceleration and deceleration in this effort can be linked directly to the prevailing oil prices. One could cynically wish for an ongoing increase in oil prices to drive the fact home that the present prices have no bearing to the development and commercialisation of alternative energy technologies. It is rather the constant and unstoppable depletion of oil and gas that dictate other energy sources in the very near future.

An attempt is made to comprehend two of the technologies that could partly help address the future energy demands. Both the energies are bound to the thermodynamic principles and the main reason of potential success may be that there really is nothing new so far as the harnessing of the resources goes. The technologies for use of oceanic thermal energy and geothermal energy are quite developed and well understood. In the case of geothermal energy, there are existing operational plants which could help one better understand the commercialisation and harnessing of this resource. Ocean thermal energy conversion (OTEC) is a new technology so far as the resource goes-the technology is quite conventional; though now more efficient OTEC technologies are also being explored.

As both these technologies are governed by the Carnot efficiency limitations, the lower the source temperature (with a given sink temperature), the poorer the efficiency; but considering the vastness of the resources (especially in the case of OTEC), even poor efficiencies cannot translate into outright rejection of the technologies. Subsequent sections discuss the geothermal energy and OTEC from the view point of various methodologies that are being envisaged to utilise the resources on a most efficent and yet practicable manner.

2.0 GEOTHERMAL ENERGY

Geothermal energy as the name indicates, is energy resource from the earth - in the form of steam, hot water or hot rock. The resource is quite extensive in availability in some parts of the world and may play a fair role in alleviating the energy crunch in the future.

2.1 Resource Availability

It is estimated that the earth's geothermal heat may represent a total energy resource equal to 27 million tons of oil per square kilometre of the earth's surface. While most of this energy is too diffused to use economically (at the present prevailing energy costs), there are concentrated pockets of heat within the earth's crust that are economically accessible.

Geothermal energy resources can be classified into:

- normal gradient (temperature gradient 2.5°C/100m)
- radiogenic (radio active decay - very diffused)
- high heat flow areas (by conduction - very diffused)
- geopressured (fluids under pressure - ver attractive)
- point heat sources (magma intrusion - steam & hot water processes)

The first three are of relatively low practical value, the fourth holds considerable promise and the last is already being exploited for electric power in quite a few countries.

2.2 Resource Spread

Present day knowledge of resource identification indicates that The United States, Japan, U.S.S.R., New Zealand, China, Ethiopia, the Philippines, Iceland, Italy, Mexico, El Salvador, Turkey are countries which have substantial resources which can be exploited on a commercial scale. To cite some examples: U.S. geothermal reserves are sufficient to generate 60,000 MW of electrical power, which is about 15 percent of U.S. electric power generation; resevers in Ethiopia are sufficient to meet the electrical demands of the entire continent of Africa; two thirds of Turkey is believed to have geothermal potential; in the U.S.S.R. known reserves of thermal waters with temperatures from 40 to 250°C reach 22 x 10^6 M3/day which is equivalent to 40 to 50 million tons of oil per year.

Geothermal exploration of the Puga and Chumsthang hot spring regions in India conducted over a 4 month period each in two seasons of work has established that these regions hold promise of utilization of geothermal energy for power generation, space heating, hot house cultivation and mineral refining. In the Cambay area north of Bombay, gradients ranging from 30 to 60°C/km have been recorded. But the fluid pressures are very high - 100 to 320 atm. This pressure energy could be utilized for running a hydraulic turbine and the thermal energy for power generation using a binary cycle.

2.3 Energy Conversion Systems

2.3.0 Various energy conversion systems are in use for geothermal power generation throughout the world, and several new systems are in the research and development stage. Present geothermal power plants may be classified as under:

- dry (or superheated) steam plants
- separated-steam (single flash) plants
- separated-steam/hot-water-flash (double flash) plants
- separated-steam/multiple flash (multi flash)plants

- single-flash steam plants with pumped wells
- double-flash steam plants with pumped wells
- binary cycle plants with a secondary working fluid
- combined flash/binary plants
- hybrid fossil/geothermal plants
- total flow systems

Plants of the first seven types are already in commercial operation / under construction. The remaining three are in the design stage and being considered seriously for application.

Major and attractive conversion systems are discussed as regards technology status, equipment needed, and possible applications.

2.3.1 Dry Steam Plants

The most desirable geothermal resource to develop is one which supplies saturated and slightly superheated steam directly to a normal steam power plant. Superheated steam from the production well gathering system expands thru a condensing steam turbine which drives an electric generator. Turbine exhaust steam is condensed by direct contact with cooling water circulated to a mechanical - draft cooling tower or spray ponds. As the raw steam from the well contains large quantities of non-condensibles, corrsive substances, particulates etc., degassing plants, scrubbing equipment, and other steam processing devices are often found at the inlet to the turbine. Moreover if the turbine exhaust contains non-condensibles which should not be mixed with the cooling tower effluent, shell and tube heat exchangers are then used for condensing. It is possible to have non-condensing turbines with atmospheric exhaust.

Power plants utilizing this basic cycle are in operation in Italy, Japan and the United States.

Resource utilization efficiency ($\eta_u = \frac{\text{net plant output}}{\text{Energy}}$) can be between 50-60% with specific fluid consumption, ($SFC = \frac{\text{mass flow rate of geofluid}}{\text{net plant output}}$) of about 8 kg/kW-h. Figure shows a schematic of the cycle.

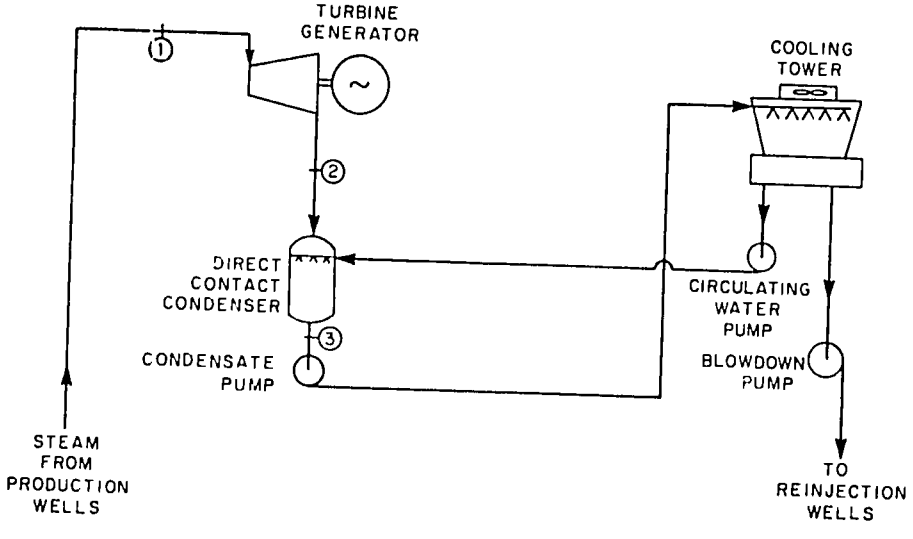

FIG. DRY STEAM GEOTHERMAL PLANT

2.3.2 Separated-Steam (Single Flash) Plants

Though it is preferred to have dry steam coming out of the geothermal well, one often time encounters a liquid dominated hyddrothermal reservoir. The quality of the well head product, consisting of a two-phase mixture of liquid and vapour, depends on reservoir properties and well head pressures. It is possible to separate the phases either at individual well head, or at centrally located stations or at the power house. The basic feature is that a single stage of steam separation or flashing is used.

As the fluid condition at reservoir is that of a compressed liquid at elevated temperature, it flashes into steam as it comes to surface under a falling pressure. It can attain a well head quality ranging from about 10 to 50% for each well. The difference from the earlier cycle is the addition of separators and a float-ball check valve to prevent liquid entering the turbine in event of separator back pressure build up. Utilization efficiency is inferior to that of dry steam plant because of discarding of hot water separated from the steam. Plants using this cycle are installed in Mexico (Cerro Prieto), Japan, U.S.S.R. and El Salvador.

2.3.3 Double flash Plants

The cycle is similar to the single flash cycle except that a flash vessel is included to generate additional steam from the hot water separated from the well head mixture. This additional steam is admitted to the turbine via a plenum, where it mixes with the primary steam before expanding through the low-pressure stages. The second flash is thus occuring in the flash tank. This increases the utilization of energy at the cost of increase in capital cost. Plants operating on double flash are based in Japan and Iceland.

2.3.4 Multi-flash Plants

This is an extension of the earlier cycle in that multiple flashing is resorted to, to increase the efficiency of energy utilization. This multiflash process translated into economic terms can get prohibitively expensive and careful analysis needs to be done before opting for such a complicated operation/system. The only known commercial plant of this type is in Wairakei (New Zealand).

2.3.5 Single/Double Flash Plants with Pumped Wells

It is sometimes desirable to install pumps down inside the production wells in order to increase the flow rate of the fluid and to prevent flashing as it may lead to precipitation and clogging of wells. The essential difference between this system and the single flashing unpumped system is that flashing of steam is restricted till all the non-condensibles, particulates and other materials are removed - in other words with the help of pressure, the geothermal fluid is flashed in a surface equipment.

2.3.6 Binary Cycle Plants

Binary systems essentially have a secondary working fluid, typically a fluorocarbon or hydrocarbon, in a Rankine cycle with the geothermal fluid serving as the source for the heat energy needed to superheat the secondary working fluid. Some advantages of using a binary circuit are:

- more suited to low-temperature hydrothermal resources
- smaller turbine size for given output
- less expensive turbine for given output
- high pressure operation; thus eliminating vacuum operation and hence no air-leakage
- non-corosive working fluid in turbine
- higher isentropic turbine efficiencies
- dry expansion, eliminating erosion problems
- lower condensing temperatures for better cycle efficiency

Disadvantages of this cycle are:

- expensive secondary working fluid
- leakage cannot be permitted in the system
- expensive heat exchangers are additional equipment
- huge brine flow rates for reasonable-size plant, leading to disposal problem
- fire hazard due to inflammable working fluid

The plant at East Mesa, Imperial Valley, California utilizes a dual binary cycle - the working fluids being isobutane in the primary loop and propane in the secondary circuit. The rated capacity of this plant is 11.2 MWe with 2.2 MWe being contributed by the secondary propane circuit. Here the flashing of the hydrothermal fluid is done after the pumping and cleaning of the fluid.

In some cases binary cycle as referred in context of geothermal energy also means that an organic fluid is being used as the working medium and that there are two fluids. It is an erroneous definition but a lot of work done on organic Rankine cycle based geothermal plants is categorized under the heading of binary cycle.

Figure indicates the organic working fluid concept.

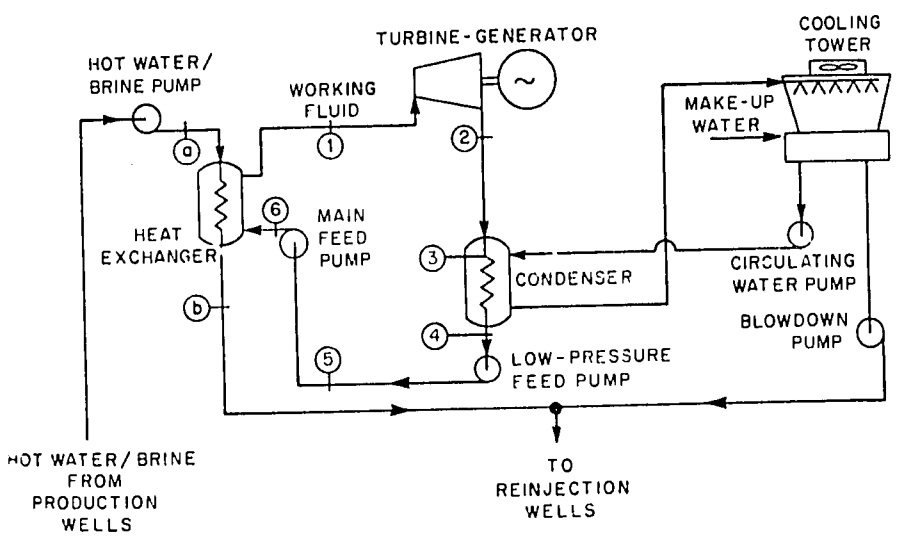

FIG. BINARY GEOTHERMAL POWER PLANT

2.3.7 Combined Flash/Binary Plants

One of many possible combined flash and binary cycle configurations is where the hydrothermal fluid is flashed on the surface in a flasher, the hot reject water is used to vaporize a secondary binary fluid. Thus power is obtained both from the steam via a steam turbine and from the organic fluid via an organic Rankine Cycle turbine. This is more suitable where resources have excessive salinity like the hypersaline brines of the Salton Sea or geofluids burdened with excessive non-condensibles.

2.3.8 Hybrid Fossil/Geothermal Plants

This plant combines a fossil-energy fuel with a geothermal resource in a single plant in such a way as to take advantage of the synergistic possibilities of this configuration. Generally such plants fall into either - geothermal-preheat systems or fossil-superheat systems. A plant coming up in Southern California (100 MWe) shall be using fossil fuel in conjuction with hydrothermal resource to produce electric power.

2.3.9 Total flow systems

Said to be the simplest energy conversion concept, total flow involves a two-phase flow from the well to the expander. Theoretically, the advantages stem from the fact flashing/separation losses shall be eliminated. The greatest difficulty has been in the development of such an expander. Axial flow and positive displacement type expanders have been tested in the laboratories while field tests are continuing in the latter case.

2.4 TECHNOLOGY LIMITATIONS AND ENVIRONMENTAL CONTROL

Enough technology is available at the present time to exploit the world's geothermal resources. The biggest stumbling block is not the design of the plants but the front end cost of such ventures. Although the geothermal resources in most cases shall last a rather large finite time, it still is assumed to be an untried technology except in the very

few areas where the cost of harnesing the resource initially was not too expensive and big utilities/governments went into geothermal resource exploitation. It was however a limited effort to tap the known and proven resource. Not enough has been done to exploit the resource which is deep down inside - say beyond ten or fifteen thousand feet.

Initially the geothermal spent fluid was not reinjected back and this led to severe depletion of the reservoir. The Larderello site in Italy faced such a problem of drop in power generation due to severe reservoir depletion. It is not universally accepted that the fluid/make up water has to be pumped back at a depth so that it can permeate down to the geothermal reservoir and regenerate itself.

Major troubles have also been encountered with the heat exchangers and in quite a few cases with turbine blades in case of direct expansion of steam source. True counter current heat exchangers (with very little pressure drops) need to be designed.

Environmental precautions need to be emphasized as both liquid effluents and gaseous emmissions occur in geothermal plant. Liquid effluents can be controlled by reinjecting into the reservoir. Gaseous emissions contain hydrogen sulphide which is quite unacceptable to local population. The U.S. EPA has instituted a 200 g/Mw-h limit on H_2S emissions. This requires some form of H_2S abatement equipment. The Geysers at Sonoma & lake Counties, California have about 20 units generating power. Although the initial units do not have any H_2 S control, the new ones are using surface condensers instead of jet condensers and the earlier ones are being provided with oxidizers etc. to remove sulphur from the emissions. Another potentially harmful emission can be radon, a radio active decay product of uranium. Work needs to be done to understand the control of this substance in the emission- especially in the ejector gas.

2.5 Economic Evaluation

The bottom line for any alternate energy technology to be accepted by society is not just the technical viablity of the scheme but the cost it incurs to society. In other words, if geothrmal energy has to bid for a fraction of the overall eneryg demand, the technology to harness it has to be cost effective. The very perception of cost effectiveness lays open a very intriguing phenomenon - does the cost of generating 1 MW of electricity using geothermal resouces have to be competitive with electricity generated thru fossil fuels - a technology being used by man for well over two centuries and developed to the extent of receiving no gains from further improvement?

And what is the scenario with increase in oil prices once the reserves start vanishing? Geothermal energy conversion technology can still be said to be in that phase of development where breakthroughs in turbine technology, heat exchanger and waste heat disposal system design can bring down the cost of electrical energy generated substantially.

But surprisingly enough, electrical energy generated using geothermal resources can still compete quite favorably at the prevailing oil prices. Three basic expenses contribute to the total cost of electricity:

- capital investment, which includes the outlay for power plant, interest incurred during construction, working capital, organization and cost of transmission lines.
- operating and maintenance expense, and
- fuel cost, which in the case of geothermal power plants means the price the generating company must pay to the field developor/government for the geofluid.

Table 1 is a comparison of fossil fuel, nuclear and geothermal based electricity generation on standard 1976 dollars. It made for evaluating the economic competitivness of various energy sources. It is apparant

that if the plant is comparatively large (greater than 50MWe), electricity produced by geothermal source can be quite cheap and competes favourably with that produced from nuclear, coal or oil.

Another analysis conducted by Pacific Gas and Electric (PG&E) indicates that their geothermal power plants (primarily the Geysers in North California) produced electricity at the lowest cost of any other type of steam plant in its system. The figures (in 1977 dollars) are as follows:

geothermal - 18 mill/kWh

nuclear - 24 mill/kWh

coal-fired - 26 mill/kWh

oil fired - 36 mill/kWh

In addition, PG&E stated that geothermal plants were the least expensive to construct:
- 26% cheaper than oil-fired plants,
- half as expensive as coal - fired plants,
- cost only 38% of a typical nuclear plant.

To get a better understanding of the economics of scale, figure indicates bottoming out of the electricity cost once the plant size exceeds 50 MWe. Various conversion technologies are also plotted.

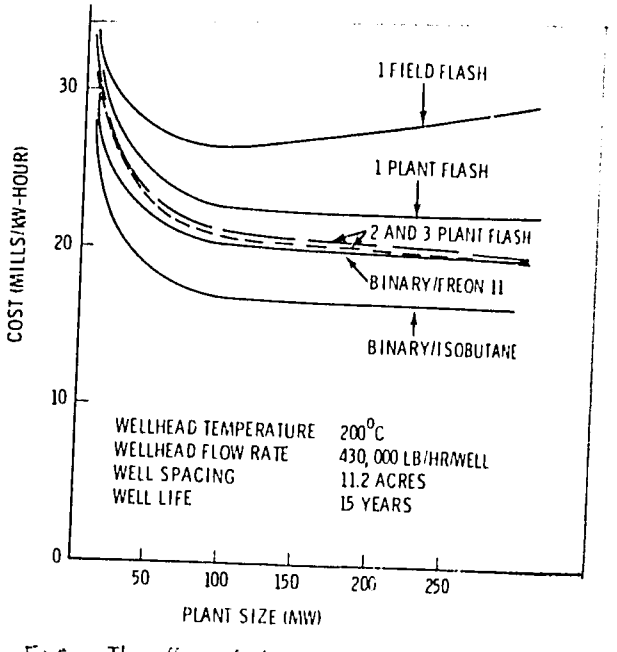

FIG The effect of plant size and power cycle on operating costs for electricity.

In addition to the economics, reliability of operation is a key factor for electricity generation. Studies conducted by PG & E and D.O.E., of Government of U.S.A. indicate that the availability factor for the geothermal resource based power plants varied from 0.70 to 0.96 with an average over a 15 year period of 0.87. This is less than 0.91 reported for fossil plants. But the studies also indicated an increase in availability as the experience gained at the Geysers is put to use at the design conception stage. The Cerro Prieto Geothermal power plant in Mexico also has a capacity factor of 0.87.

Resource Type	Installed Equipment Costs ($/kW)	Equipment Costs as (¢/kWh)	Operating and[1] Maintenance as (¢/kWh)	well or fuel cost (¢/kWh)	Total Generating Cost (¢/kWh)
Direct Flashing[2]	300-600	0.68-1.37	0.13	0.80-2.80	1.61-4.30
Binary Fluid cycles[2]	400-700	0.91-1.60	0.13	0.53-2.45	1.57-4.18
Nuclear	800	1.83	0.13	0.30	2.26
Fossil fuel-oil	400-600	0.91-137	0.13	2.0	3.06-3.50
Fossil fuel-coal	400-600	0.91-137	0.13	1.0	2.06-250

1. 17% annual fixed charge rate
   85% (7446 hr/yr) load factor

2. 150-200°C resources with geofluid flow about 100-300 lb/sec.

TABLE 1 Comparison of Fossil-fuel, Nuclear and Geothermal Generating Costs (1976 Dollars)

3.0 OCEAN THERMAL ENERGY CONVERSION

3.1 Resource Availability

By far the largest available natural source of power is solar energy. One of the possible sources of solar energy is the energy entering the oceans, which cover 70% of the earth's surface. In the tropical ocean, the water is heated by the sun. This heated water on expansion raises the level of the ocean slightly. This causes the ocean to overflow towards the poles where the water density is higher and the level is slightly lower. As a result, currents are set up, e.g. the Gulf Stream in the Atlantic flows north from the tropics. In the polar regions the surface water is cooled. This denser water sinks and flows along the bottom of the ocean back to the tropics. As a result surface water is much warmer than that at the bottom. The idea of extracting useful work from a heat engine powered by this temperature difference has received attention sporadically right from the nineteenth century. Typically between 5 to 25°C difference in temperature between the surface and deep seawater has been the cornerstone for developing of the technology for driving this resource based heat engine.

As this resource is available all the 24 hours of the day, all the year round, development of this technology shall provide continuous power. Not only is ocean thermal energy an enormous source of power, it is self generating, and can supply energy as long as the sun continues to shine.

3.2 Resource Spread

Since a seawater temperature difference of at least 15°C should be available to operate an OTEC system there are limited sites where thermal plants can operate without excessively long pipelines.

Both coasts of Africa, the west and southeastern coasts of the Americas, and many Caribbean islands are situated where the seawater decreases from a surface temperature of 25 to 30°C to 4 to 7°C at a depth of about 750 metres. There is a ΔT of 16 to 22°C around the coasts of Australia at a 1000 metre depth. Japan, the Philippines and the Chinese coast all have a temperature difference of 22 to 26°C at the same depth.

India's coast line also has a 20 to 22°C temperature difference at a 1000 meter depth. In fact Sir Lanka is already in the process of studying the feasibility of having a pilot OTEC power plant. Good sites for deployment of the OTEC platforms may be approximately 100-150 kilometres away from India's shoreline.

3.3 Basic Open and Closed Cycles for OTEC

3.3.1 The Open Cycle

In the 1920's George Claude built a power plant in which he pulled a vacuum on warm water, boiled it into steam, passed it thru a turbine, and the exhaust was condensed with cold deep seawater. In essence it is the present day open cycle, so called because it uses water itself as the working fluid.

It can be seen that with a temperature difference of 25°C between the hot and cold water and allowing 5°C each in the heat exchange - first while producing steam from warm water and later when condensening this steam thru the cold water, a net temperature difference of 10°C is available for production of power. It gives one a very low Carnot efficiency of about 3%. When account is taken of the losses in the actual system, the efficiency obtainable may not be higher than 2%. This low efficiency is still not a fatal draw back as there is enough of the hot water resource available to be used for generating a given amount of power.

As Claude experienced, water and in turn steam are not good working mediums at that temperature level. At low temperatures, the specific volume of steam is extremely large. This necessitates a large turbine, and, with low Reynold's number, low efficiency. Also the corresponding high vacuum entailed removal of dissolved gases from the water and maintenance of large leakproof connections. Corrosion is another problem when water is used in the plant circuit.

3.3.2 The Closed Cycle

It is surprising that the presently preferred cycle was proposed at first in 1881 by Jacque Arsene D'Arsonval. He proposed the use of warm water to boil ammonia, which would pass through a heat engine to generate power, and then condense on cold water pumped from deep in the ocean. While this cycle requires heat exchangers to transfer heat from the warm water to the working fluid, and to transfer heat from the condensing vapours to the cold water, it has many advantages in being much more compact, and avoiding the need for very large and costly equipment to degas the water. Present day designs talk of using a variety of working fluids - primarily organic refrigerats, e.g. R-22.

A simple form of the closed cycle power plant shall work as follows: warm water from the surface of the ocean is pumped through a boiler at the bottom. This boils the working fluid into vapour. Vapour from the boiler/generator passes up through a turbine driving a generator, and from there passes up the condenser which is cooled by cold water pumped from deep in the ocean. The condenser is placed high enough above the boiler so that the liquid will flow by gravity from the condenser back to the boiler, thereby requiring no pump to force the liquid into the boiler, which is at a higher pressure than the condenser.

Figure shows the schematic of this simple design which, with variations to enhance efficiency and reduce cost, is the one most preferred for generating power at the lowest cost.

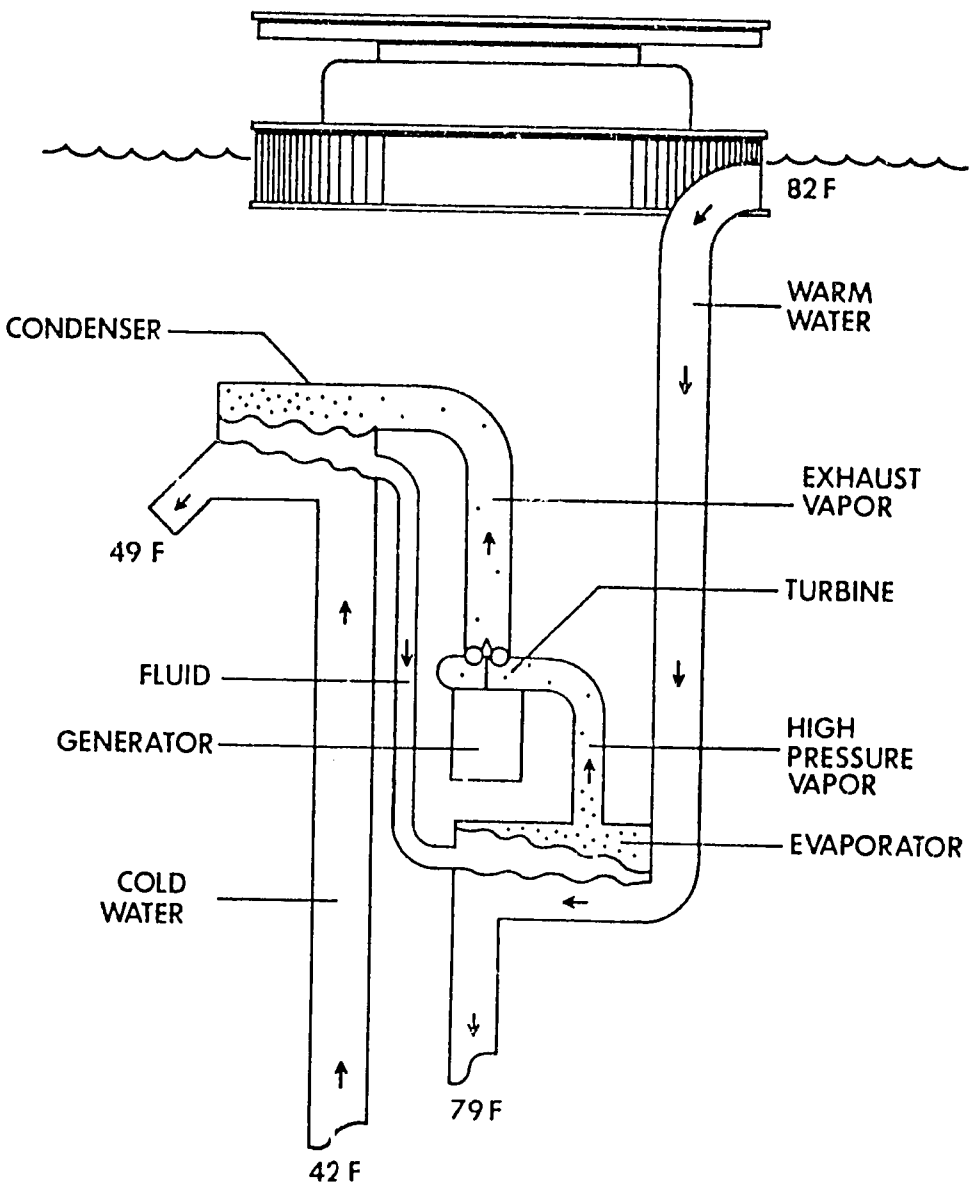

Fig. Schematic of Closed Cycle OTEC Power Plant

3.3.3 Variations /Modifications to the Closed Cycle

Quite a large number of designs talk of submerging the plant under surface (up to 30 to 60 m) to take advantage of water pressure being equal to working pressure of vapour inside the boiler. By doing this the pressure difference between the working fluid and the water outside is very low and this makes it possible to manufacture much lower cost heat exchangers. It also tends to reduce problems from leakage of working fluid into the water or water into the working fluid. As large quantities of warm water is required to generate 100MW of electric power, this warm water must be brought in at a very low velocity to avoid plugging of inlet screens with fish. Moreover one should use the warmest possible water available as each degree Fahrenheit drop in temperature reduces net plant output by approximately 7%.

Contamination of the input water to the boiler by the output water is avoided by taking advantage of the naturally occuring density stratification, at least for plants of up to 700 MW.

Another modification is the high-density power generation without moisture, and the consequent power expenditure in its removal, is obtained by falling film evaporation on vertical tubes (CMU design). Appreciable pressure drop in the large banks of vertical tubes in the boiler and condensers is avoided by proper manifolding. Some designs (University of Massachusetts Design - UMASS) of evaporators and condensers are based on a complete two-phase heat transfer theory which has been synthesised for transfer of heat with ammonia or propane in the 40° to 100°F temperature band. Overall system efficiencies between 1.5 and 1.8% using either ammonia or propane are possible.

Though ammonia shows advantage over propane in all studies, experience with ammonia refrigeration systems has shown the practical problems associated with ammonia to be so large that the less attractive propane will probably receive greater attention.

3.3.4 Types of OTEC Power Plant

Various kinds of OTEC power plant sitings have been proposed. The major types are:

- the land based plant (practical if resource within 5 miles of land)
- floating type. These can be either semisubmersible or moored and/or dynamically-positioned type.

The floating power plant, which would be the OTEC converter shall, in the actual installation, be capable of dynamic positioning. The basic methodology shall be:

dishcarge from the boilers and the condensers is directed through louvres. These louvres are moved by hydraulic pistons of the same type now in use for ship rudders. The louvres shall deflect the jet thrust produced by the water and thereby effect control of the motion of the power plant. The use of heat exchangers effluent for thrust permits the water pumps to act as propellers and eliminates the parasitic power drain that would othrewise be imposed by a separate thrusting system.

Gas turbine or diesel engines totalling about 10 MW will be required for a plant of about 100 MW capacity for auxiliary power for start up and for propulsion during periods when the plant is down for maintenance.

Mooring of the power plant may be provided by a single anchor. A simple gravity type anchor of reasonable cost and requiring construction methods no different from those already in use may be the choice in the early designs. It can be made from reinforced concrete in the form of a concrete barge hull. The interior compartment of the anchor can be so

arranged as to keep it afloat at 15 to 20 feet draft when transiting to the emplacement site; there it becomes a submarine, capable of diving in a controlled manner to the seabed exerting millions of pounds of reaction downward. Pressure proof compartments inside the massive concrete hull may serve as connection points for both electricity and gas pipe line energy collection subsystems, and into which the energy lifeline as the umbilical shall be connected.

A single mooring line from anchor to power - plant is envisaged in the University of Massachusetts' design. In fact they propose using the axial strength of the cold water inlet pipe as a major portion of its mooring line.

3.4 Major OTEC Power Plant Components

3.4.1 Though the major components of OTEC power plant shall essentially function towards a similar end, their designs can vary quite drastically. As no large OTEC power plants have been put in commission, a design which is sponsored by J.H. Anderson & Co., the pioneers of OTEC systems in U.S.A. is discussed as a case. Alternative UMASS and CMU (Carnegie Mellon University) designs shall also be discussed whenever there is a different approach towards design of any major power plant component. The power plant design is for 100 MW of electricity.

3.4.2 Platform

It is a floating platform similar to those used for offshore oil development. The proposal calls for use of aluminium for the entire structure to eliminate electro chemical corrosion that might otherwise occur between conventional steel and aluminium heat exchangers. The platform houses the turbines, electric generators, deaerators, control systems, hydraulics, crew quarters, machine shop etc.

3.4.3 Warm Water intake

Warm water intakes surround the periphery of the platform. Screens remove debris to protect the boilers. The screens are cleaned by trash rakes. The intake screens are sloped to reduce the effects of oncoming waves in stormy weather. This allows the waves to roll up on the deck, and release energy gradually.

3.4.4 Deaerators

Deaerators are large presure vessels into which the inflowing warm water is drawn. Here a vacuum pump removes some of the dissolved gasses. Warm water is continuously stirred to bring undegassed water to surface for effervescing off of the dissolved gases. Degassing removes dissolved oxygen to inhibit both corrosion and fouling of the heat exchange surfaces by organisms.

3.4.5 Warm Water Pump

From the deareators warm water is pumped to the boilers by warm water pumps. These pumps are driven by trubines that are powered by working fluid taken from the main boilers and exhausted into the main condensers.

3.4.6 Boilers

Boilers receive the water from the pumps. There the working fluid, R-22 in this case, is vaporised by the heat from the warm surface water. Anderson's design of boilers and condensers is different from that of conventional shipboard heat exchangers and from some other OTEC designs. Anderson uses heat exchangers of plate-fin construction of a unique mechanical design to minimise cost and weight. The design uses the pressure - balanced plate-fin heat exchangers. As the boiler inside pressure is counter balanced (up to 1/2 bar) by the outside submerged liquid head, minimum strength is required for the heat exchange surfaces and it also reduces leakage.

As this pressure difference is directed inwards the working fluid cannot leak out and only sea water can go in. As sea water and the working liquid, in this case R-22, are immisscible and nonreacting, the two can easily be separated. What it entails is that as the system is now leak tolerant instead of leak tight, it is much less expensive to construct and seal. The passages for sea water and R-22 are formed by simple plates of metal in a cross-flow pattern.

Elimination of large pressure differential permits modular construction of the heat exchangers. Each module can be about 6x2x16 metres and yet contain tens of thousands of square metres of thin sheet as heat exchange surface. For a 100 MW plant, with aluminium as the material, total heat transfer area required for both boilers and condensers would be about 500,000 m^2 of aluminium sheet. The outside of the module would then be of moderate-gauge aluminium plate. Each module

shall consist of a stack of plates separated by spacers and sealed by rubber seals. No precision welding or sealing would be necessary.

One of the greatest advantage of modular construction is that individual modules can be sealed off and removed from service without shutting down the power plant. Each module in turn can be sealed off from the water inlet. It is filled with a slurry of water, sand and detergent. The slurry is circulated at high pressures by a pump. The abrasive action of the sand restores the aluminium surface. Also the modules can individually be replaced.

3.4.7 Turbines & Generators

Single stage turbines (four in this case) receive the vapour from the boilers. Each turbine is rotated at a governed speed to generate 25MW.

3.4.8 Condensers

These are similar to the boilers but with cold water from the deep exchanging heat from the vapour. It should be noted that very high heat transfer coefficients are maintained in the boiler and condenser so that there is as little surface area required as is feasible.

3.4.9 Cold Water Pump

It is similar to the propeller of a ship and can be about 9m in diameter (for this 100 MW plant). Like the warm water pumps, it is driven by a turbine powered by vapour from the main power boilers and condensers. The turbine dirve unit is housed in a sealed pod located behind the pump blades. The entire assembly can be lifted out of its mountings and raised to the deck for maintenance.

3.4.10 Cold water inlet Pipe

For this plant the cold water pipe is about 10 metres in diameter and the length can be upto 1200 m. The pipe is constructed like a stockade fence, using standard size pipes. Tension bands and interlocking joints form the pipes into a strong, weldless structure.

Compartemnts in the pipes are filled with oil or compressed gas to make the entire cold water pipe into a nearly neutrally buoyant object. This greatly reduces the stresses at the connection between the pipe and the rest of the power plant. This neutrally buoyant stockade cold water pipe reduces the cost of the power plant. Other designs which do not use the neutral buoyancy principle tend to be heavy as:

- they require much more expensive support structures
- they must be stronger, since they must transmit supporting forces down the entire length of the pipe

3.4.11 Electricity Transmission to Shore

For all ocean based OTEC plants, undersea electric cables will be necessary. With the experience of installing power cables with seas at quite a few places - the latest being across the English Channel - the use of underwater cable whould present no unreasonable technical or economic difficulties. The practical limits to the length are determined by the transmission voltage, mode (ac or dc) and power level. For short distances ac is more economical as no expense is incurred for ac-dc-ac conversion. For longer distances, as losses in an ac cable due to charging current become high in long cables, it is economical to send dc current. Moreover a given cable can transmit more power as dc than ac. A dc power system needs only one cable, since the conductivity of the seawater can be used to provide a free return. With ac, at least 2 cables, and for 3 phase, 3 cables are required. Several OTEC power plants of 500 MW capacity could share a common power cable hundreds of kilometres in length. Once brought to shore, power can be transmitted by overhead lines for onward transmission.

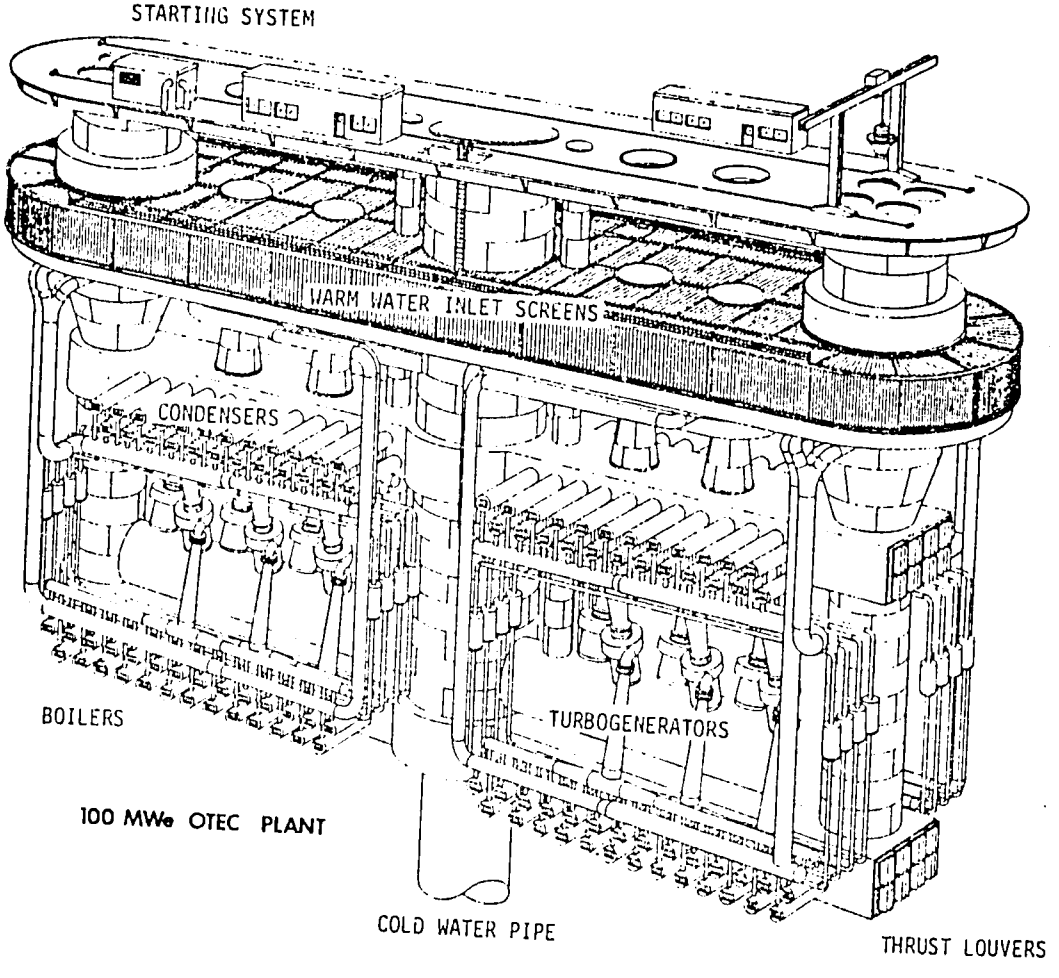

FIG. Semi-Submersivle OTEC Power Plant

3.5 UMASS & CMU Designs

3.5.1 UMASS design

The UMASS Sea Solar Power Plant (SSPP) is designed to be placed in the Gulf Stream 25 km off the coast near Miami. The system assumes a thermal working gradient of 31.5° F and an efficiency of 1.8%. The Mark 1 is a large 400 MWe power plant. The design indicates use of an in-sea-bed energy collection grid, cable and / or pipe line, with connection modes at anchor points, and transmission cables or pipes of at least 15 miles length extending back to shore. Mark 1 contains 16 identical power modules, each delivering about 37.5 MWe. The plant is configured as a semi-submersible ship usually lying in static balance at the end of its mooring with its mass so far beneth the surface that even hurricane season wind-wave motion excitation shall be very small. Present hull configuration is that of a pair of 100 foot diameter cylinders, side by side, each 600 feet long.

The evaporators are carried on top of the hulls to miminise ducting required to bring hot water to them. The turbines and condensers are carried inside the pressure hulls. 90% or more of turbine efficiency is expected. Evaporators and condensers are designed for 2 phase heat transfer. Ammonia or propane shall be WFL. Maintenance on the condensers is possible by individually isolating any condenser and repair against leakage can be done by selective channel plugging or by core replacement with spares.

The cold water inlet pipe is a very large open ended welded aluminium hull whose framing includes enough pressure proof void spaces that neutral buoyancy can be achieved.

3.5.2 CMU design

The CMU power plant is a 200 MWe design for off-shore installation. It operates like the UMASS plant in a closed cycle with ammonia as the working fluid. It is to generate 200 MWe power.

Warm water from above is forced through a vertical tube evaporator, thereby vaporising the working fluid liquid (WFL), falling down as a film on the outside of the vertical tubes. The central cylindrical section of the evaporator serves as a vapor collector. This vapour them flows downwards through an axial gas turbine, which in trun powers a generator. After leaving the turbine, the working fluid vapour (WFV) continues downward into the central cylindrical section of the vertical tube condenser, and condenses upon the surface of vertical tubes cooled by deep water forced up from below. WFL is them pressurised and pumped back into the evaporator.

The warm water flowing downward meets the cold water flowing upward. Since the warm water current is stronger than the cold water current, the resulting stream forms a downward conical jet which disappears below the thermocline boundary. This insures that the exhaust from neither the evaporator nor from the condenser contaminates the water in the warm water intake. Large distance from the cold water intake insures no mixing at the cold water intake.

3.6 Foam & Mist Lift Cycles

The foam and mist lift cycles are rather different from the open and the closed cycles discussed uptil now. These new cycles involve the total flow of the sea water through the turbine. They are based on the air-lift pump which raises water by injecting air into the bottom of a column. Since the foam mixture thus produced is less dense than the water, it is able to rise to a higher level. These cycles substitute low pressure steam for air in the air lift pump. The operation is:

- warm water from surface is collected by an intake
- it is pumped to the foam generator
- here this warm water is subjected to a reduced pressure, which causes the water to boil as a mass
- the resulting foam rises in the expansion vessel
- meanwhile another water pump brings cold water into the condenser
- the foam or mist enters the condenser where the cold water causes it to collapse into a liquid state.
- condesate then flows back down thru a turbine, where power is generated.
- the mixture is finally ejected into the surrounding ocean.

The basic difference between the foam and the mist cycles is that in the latter, the foam is allowed to break up into a fine mist, while in the former, the low density foam is stabilised by a detergent, which must be biodegradable of course. Clarence Zener, the inventor of the foam cycle, has shown that a height of 300m could be achieved in principle and a practical head of 200m could be attained.

3.7 Other Uses of Sea Solar Power

The energy of warm waters can be harnessed not only for producing electricity but could quite readily be used to produce any of the following:

- power in transmission cable
- hydrogen gas via pipeline or liquid hydrogen via barge
- liquid ammonia
- chlorine and caustic soda
- methanol and other alcohols
- synthetic hydro carbons (gasoline, kerosene etc.)
- magnesium

- liquified atmospheric gases such as:
  * oxygen
  * nitrogen
  * carbon dioxide
  * argon
- fresh water

3.7.1 All of the above can be made from air and sea water alone by Sea Solar Power (SSP). In addition many other energy - intensive products can be manufactured on board SSPP from raw materials brought to the plant by ship. Aluminium can be manufactured economically aboard an SSPP. Most electrolytic processes, such as reduction of aluminium oxide to aluminium, are more efficient if plenty of low temperature cooling water is available.

3.7.2 Electrical energy can be converted into chemical form for storage and transmission. The easiest electrochemical process is fresh water electrolysis for production of hydrogen and oxygen. It should be noted that the amount of oxygen in sea water is roughly 34% of the dissolved gases, whereas air has only 23% oxygen. One can thus separate oxygen at a considerably less cost than would be the case in separating oxygen from air. Additionaly cold water available from condensers may reduce the power costs in the separation process as it is required to cool the refrigeration system. During the oxygen separation one obtains carbon dioxide as a by product. It should again be noted that CO_2 is concentrated in much higher percentages than it is in air.

3.7.3 When the warm water is deaerated and it passes through the main heat exchangers, a considerable temperature difference remains between the boiler water discharge stream and the condenser water discharge stream. This can be used to produce distilled water in enormous quantities at low cost by addition of auxiliary equipment. Warm water is allowed to evaporate under a partial vacuum, and the vapour then condenses on a

a heat exchange surface cooled by cold water from the main power condensers. It is estimated that a 100 MWe plant could produce 500 million litres of fresh water per day without any great reduction of power output.

3.7.4 The tropical seas are generally poor in nutrients near the surface. As a result, despite the high influx of sunshine, these waters do not yield much sea food. In the process of generating power, SSPP will bring vast quantities of nutrient-rich deep water to the surface. In the process of producing power and fresh water, this bottom water will be warmed sufficiently for it to float near the surface and mix with the surface water. As a result, there will be a profound beneficial effect on local marine life.

3.8 Environmental Impact

Though no major environmental effects are envisaged due to the very size of the systems it is quite feasible that over a long period of time major ecological changes may take place. Some of the apprehensions are listed.

3.8.1 Since an SSPP operates by removing heat from surface water and by heating large quantities of cold, deep ocean water, questions have been raised as to possible deleterious effects of constructing large numbers of SSPP's in equatorial waters, considering the fact that heat is transferred from the upper ocean to the deep layers with a slight decrease in surface temperature. This lower surface temperature results directly in a corresponding decrease in the atmospheric temperature near the surface. If the incoming solar radiation remains constant, then the reduced surface temperature results in less evaporation and outgoing radiation and a greater net heat transfer to water. The result is presumably increased convection away from the tropical plant location.

3.8.2 SSPP shall produce a lot of carbon dioxide as when the warm surface water is degassed CO_2 is removed. Also by bringing the CO_2 rich cold water from the bottom to the CO_2 depleted surface water, SSPP may be increasing CO_2 level in the atmosphere. So care needs to be taken with CO_2 if it cannot be used. The alternative may be to pump this gas down to the depths where it will dissolve and remain trapped.

3.8.3 Another possible problem with SSPP is the loss of working fluid, especially if these are halocarbons. It is reported that photolysis of these materials releases free chlorine, which catalyses the conversion of ozone back into ordinary oxygen. Ozone is this planet's principal shield against short ultraviolet radiations.

3.9 Economic Analysis

Although presently not enough practical data is available on equipment cost for OTEC power plants, estimates made by various agencies /design organizations seem to indicate that even with the present status of technology, power generation from the oceans may be an economical way. Added to the power generation are of course the various other advantages that accrue due to the utilization of this resource.

The best estimates for cost of an OTEC power plant can be made by using the same cost per ton of weight that is used for semi submersible oil drilling rigs. Fact is, that an oil rig is considerably more complex than an OTEC power plant. At $4000 per metric ton and a weight of 250 ton/MW, the cost would be around $1000/kW. There are other estimates that put the cost between $500 to $3700 per kW. But then these estimates assume a much heavier OTEC plant than can now be designed (2150 tons/MW). With these figures the cost comes to $1720/ton so the assumption of $4000/per ton is quite conservative. Table 2 gives a comparison of power costs by major energy sources in constant 1981 dollars. The analysis has been carried out by Anderson and it seems that OTEC power plant has been favoured in the analysis while unusually

low capacity factors have been taken for oil, coal and nuclear power plants. Still the study does bring out the main point under discussion- the cost of generating electricity by OTEC based power plants can be competitive with the present electricity producing systems. The analysis, though subjective, does highlight that though the system efficiency of SSPP may be 1.5 to 2% it still can vie for funds for electricity generation and once the systems get tested in the field and newer technologies in heat exchanger design, cold water inlet pipe design, turbine design make their effect felt, the price of each kWh of electricity shall reduce while the other resources are dwindling away.

Another evaluation, done by Carlson S. Goss was based on the concept of total energy required to build the plants. OTEC power plants showed a more favorable energy balance than any other form of electricity producing power plant.

	OIL	COAL	HYDRO	NUCLEAR	OTEC POWER PLANT	REMARKS
Capital Cost $/kW	1100	2200	2340	2450	1000	Anderson's estimate for OTEC cost
Fixed change rate	0.20	0.20	0.20	0.20	0.20	
Capacity Factor	0.75	0.55	0.75	0.55	0.90	low CF assumed for Coal & Nuclear
Cost of maintenance-mills/kWh	4	4	3	4	4	
Cost of fuel-mills/kWh	51	12.3	0	11.4	0	oil-$34/barrel coal-$38/ton Uranium-$92.5/kg
Power Cost - mills/kWh	88.5	107.6	71.2	117.1	29.4	

1. Costs are based on 1981 dollars

2. Power cost has been calculated by the formula: Mills/kWh = [1000(FCR) (C/kW)]/[(FA)x8760] + (CF) + (COM)

FCR = fixed charge rate

C/kW = capital investment per kW capacity including financing charges

FA = capacity factor= Actual kWh produced/theoretically possible

CF = cost of fuel in mills/kWh produced

COM = cost of maintenance in mills/kWh

TABLE 2 POWER COST COMPARISON

3.10 Areas for Technology Development

Significant development work needs to be done if the total weight of the power plant and in turn the cost of the electricity produced is to be further reduced. Moreover what is not known as precisely about some of the component designs needs to be throughly investigated and verified so that the predictive results are obtained and the technology of the oceanic energy conversion does not earn a bad name.

Major areas of technology development can be highlighted to improve SSPP.

3.10.1 Heat Exchangers

The costliest item in the OTEC power plant are the heat exchangers-evaporators and condensers. Successful commercialisation of the technology shall depend on the cost and performance of the heat exchangers.

Accepting that the pressure balanced plate-fin exchangers shall be the basic building blocks, it is required that the design, construction and testing of heat exchanger modules be studied carefully. Different working fluids need to be tried and the heat exchangers designed to suit the particular fluid. Effects of fouling and corrosion need to be studied and analysed.

In addition, as the surface area required is huge for an SSPP, equipment for automatic fabrication of heat exchangers should also be developed. This shall help reduce cost.

3.10.2 Cold Water Pipe Support

The most difficult component to design is probably the cold water pipe. Analysis of the stockade type pipe should be pursued. This pipe is perceived to be hooked to the hull structure through a flexible connection. Stress analysis using F.E.M., material selection, construction method and model testing in a wave tank are the requirement for the pipe and the joint.

3.10.3 Power Turbines

Special considerations for which these turbines are to be desinged are:

- low operating head
- tight shaft sealing
- maximum speed for a low-head turbine
- large flow capacity

Efficiency of turbine is an important parameter in the success of an SSPP.

3.10.4 Water Pumps & Trubine Drives

The pumps are the largest piece of machinery to be operated in the ocean. The maintenance free operation is thus of paramount importance. These pumps shall be axial flow type similar to ship propellers due to the large quantity of water and low head under which they have to operate.

3.10.5 Warm Water Outlet System

Warm water-in flow should be from the warmest layers as each degree drop in temperature reduces output by 7-10%. Thus it is necessary to design an inlet that can adjust itself to maintain maximum inlet temperature. Screens are also needed to be very efficient otherwise corrosion and biofouling of the exchangers takes place. Wave damping into the screens should be provided.

3.10.6 Bio fouling

Bio fouling is a major porblem in the system. This is due to the fact that certain organisms have a tendency to cling tenaciously to any surface that offers them a foot hold. This is more likely on the warm water heat exchanger surfaces as warm surface water contains many such organisms. The best way to solve this problem is to deoxygenate the water before it enters the boilers. This prevents growth of fouling organisms. But the methodolgies of degassing water on that massive scale have yet to be proven.

3.10.7 Overall Plant design

A good system design should include the following for an SSPP :

- ease of construction
- logic of arrangement
- effective support of cold water pipe
- optimisation of inlet structure
- maximum use of thermal gradient
- storm resistance
- ease of maintenance

It may be necessary to do model, scaled down version testing in wave tanks and in towing tanks. Integration of the peices into a whole OTEC power plant is very essential. It may be that the overall plant design may offer constraints in the design of individual equipment. But it is preferable to know the limitations and have an optimum design that works than ideally designed components that don't mesh in properly and fail to operate efficiently.

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