

SOLAR ENERGY THERMAL
APPLICATIONS

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ABSTRACT

Solar radiation reaching the surface of the earth is intermittent due to atmospheric conditions and the earth's rotation. This intermittence and variability are guiding factors in solar energy thermal applications. Direct applications of solar thermal energy for industrial process heat generation, for water heating using shallow ponds, for electricity generation using salt gradient ponds, for fruit and grain drying using flat-plate air collectors and for water pumping for agricultural uses using flat-plate and concentrating collectors are described. The design, construction and operation of shallow and salt-gradient ponds are presented. The direct use of solar thermal energy to produce industrial process heat is discussed. The indirect use of solar thermal energy in ocean thermal energy conversion (OTEC) is presented on the base of two 100 kW_e each systems, an experimental one and a demonstration one. Finally, some economic aspects of various solar thermal applications are discussed. References are provided for further reading on the solar thermal applications treated in the paper.

INTRODUCTION

As with any technology, solar energy development from the research stage to market status demands time and money. It took twenty years and many billions of dollars to develop nuclear technology from a research prototype of the first atomic reactor to an electricity generating unit. This does not mean that solar energy development has to take as long and be as costly. A decade of federally supported development, enhanced by state tax incentives and industry involvement, made flat-plate solar collectors a billion dollar per year industry in California alone in 1983. However, neither solar tax incentives in California nor strong federal government support for the development of alternative energy sources is available today. Since 1983 the price of oil has decreased from over \$30 per barrel to below \$15 per barrel. Federal support for solar thermal, photovoltaic, wind energy, biomass and OTEC has decreased as well from a maximum \$570 million in 1980 to about \$70 million now. And, this \$70 million mostly goes to National Laboratories.

This drastic cut in U.S. government funding of work on

solar energy and resulting decrease in competitive grants available for solar research and development (R&D) in the U.S. has caused some important changes in the direction of solar work. In the past, the solar R&D program was based to a great extent on competitive, federally-supported projects whose primary thrust was toward large-scale applications and solar market development inside and outside of the U.S. These applications sometimes demanded technology that was not of immediate interest to individual states. Now, because of new economic and energy policy factors, solar efforts are less centralized and more geographically and locally oriented. Local needs have taken on stronger importance, and attention is again focused on proven concepts and technologies. As a result of economic constraints, smaller solar thermal systems are planned to be built. Innovative solutions to well-known concepts are set according to local needs and limited resources.

In these circumstances, collaborative efforts between countries are necessary to join financial and technical capabilities for the mutual advantage and better use of these resources. This can be done effectively only by knowing the current status and advances made in the solar area in collaborating countries. Thus, this paper reviews selected solar thermal energy applications to facilitate the collaborative efforts of the U.S.-Spain Workshop on Renewable Energy Sources.

1. FLAT-PLATE COLLECTORS BASED SYSTEMS

The basic component of these systems is a flat-plate collector. A flat-plate collector normally consists of a black metal absorber enclosed in an insulated box with a glass or plastic cover. Tubular plastic and synthetic rubber collectors are also available on the market for heating swimming pools. Solar energy (diffuse and direct radiation) is collected by the absorber and transferred in the form of heat to the use point directly or via a storage which contains liquid, rock or another appropriate material. Water and air are the heat transfer fluids most often used.

Because of heat losses, systems which use flat-plate collectors work more efficiently in high ambient air temperatures than in low ambient air temperatures. Flat-plate collectors are usually employed when low temperature heat is required. System efficiency can vary from up to 50% for space heating and water heating systems to below 2% for water pumping when using a Rankine-cycle engine and a refrigerant as the working fluid.

Well-known applications of flat-plate collectors include space heating by using solar assisted heat pumps, direct space air-conditioning (heating and/or cooling), swimming pool heating, domestic water heating, water pumping and agricultural produce drying.

1.1 Water Heating by Shallow Solar Ponds

Concept: A cross-sectional view of a shallow solar pond is shown in Fig. 1. A typical shallow solar pond resembles a thermally insulated, plastic water bag partially filled with water. The bag may have a black bottom for absorbing solar radiation, and a clear top to prevent evaporation and assure the greenhouse effect. The most recent design calls for a black hypalon or polyvinyl chloride (PVC) water bag with a clear fiberglass cover supported by concrete curbs and metal struts. The hot water from the pond is drained down to a storage tank once or several times per day depending on the system requirements.

Applications: The first shallow solar pond system, designed and operated by Lawrence Livermore Laboratory of California, was built in 1975 near Grant, New Mexico [1]. The pond system consisted of two modules of 220 m² (2400 ft²) each, which contained 10 cm (3.9 in) of water. This prototype system was built at a uranium mining and milling plant of Sohio Petroleum Company. The shallow pond modules operated on a stand-alone basis without being interfaced with the plant's hot water system. Each pond module heated 25 tons of water per day to about 54°C (130°F) in summer and to about 35°C (95°F) in winter. A twelve-month performance survey of the system's operation indicated that the solar ponds operated with an annual average energy collection efficiency of about 45% and collected close to 9.37×10^6 Joules/m²-day (825 Btu/ft²-day).

In 1983, a shallow solar pond system was installed to supply 2,000,000 liters (528,401 gal) of hot water per day to the U.S. army barracks and laundry at Fort Benning in Georgia. A total of 80 modules with an area of 25,000 m² (269,000 ft²) were built. Each module contains two water bags made of industrial grade, 0.7 mm (35 mil) thick hypalon. A fiberglass cover over the water bags assures the greenhouse effect. After the system's installation, the water bags were sterilized on site by rinsing them twice with clorox in a four-hour period. An above ground, 1,892,500 liter (500,000 gal) capacity steel tank is used for hot water storage. The system is located 1402-1463 m (4600-4800) ft) from the use point of hot water which is distributed by 15 cm (6 in) diameter PVC pipes.

One of the most recent applications of shallow solar ponds for water heating occurred in 1983-1986 in Puerto Rico. Three ponds were installed to provide hot water for a school cafeteria, for showers of a University campus swimming pool facility, and for general use in a medical campus building. The ponds are similar in construction but vary in size. The largest one of 40 m² (430 ft²) provides hot water for showers of a swimming pool facility. This pond, like the two others, is installed on the building's flat roof and has a reinforced concrete frame and a corrugated fiberglass cover. The system is equipped with automatic operation and control. The system design, shown on

Fig. 2, calls for a water depth in the bag of up to 7.6 cm (3 in) and a delivery of up to 3028 liters (800 gal) daily of solar heated water at 43°C (110°F). For an average annual daily insolation on a horizontal plane of 1430 Btu/ft², the pond's efficiency is in the range of 45%.

The cost of designing and constructing a shallow solar pond is site specific and varies from \$150 to \$205/m² (\$14 to \$19/ft²). The economic aspect of a shallow solar pond application is treated by W.C. Dickinson [2]. The construction methodology of shallow ponds has been presented by A.B. Casamajor et al. [3]. Shallow pond thermal performance testing has been described in detail by several authors [4,5] as has also solar pond use for process hot water heating [6,7]. In addition, a theoretical study on pond sizing and design optimization was performed by simulation and modeling using the TRNSYS program [8].

1.2. Electricity Generation by Salt-Gradient Ponds

Concept: The concept of collecting and storing solar energy by means of salt-gradient ponds, also known as convecting solar ponds, was derived from research on natural salt lakes [9]. Figure 3 shows a cross-sectional view of a typical salt-gradient solar pond. Salt-gradient ponds are large pools of water open to the environment and filled out with salty water in such a way so that the liquid top layer (upper convective zone) has a 1-4% salt content while the bottom layer (lower convective zone) has a content as high as 23-27% salt. In the process of being exposed to solar radiation, the denser bottom layer is heated to a much higher temperature than the surface layer. The heat accumulated in the lower convective zone is "trapped" due to the low salinity nonconvective zone, which separates the high density brine at the pond bottom from the low density brine at the top of the pond. In this way, the use of a salt-gradient pond eliminates the separate thermal storage that is normally required in many solar installations.

Applications: One good example of salt-gradient pond technology is the 234 m² (2518 ft²) pond built in 1982 at Los Alamos National Laboratory in Albuquerque, New Mexico [10]. The pond depth is 3.6 m (11.8 ft) and the walls are vertical. Two liners were used for the pond construction; one 1.2 mm (45 mil) thick main hypalon liner and one 0.5 mm (20 mil) thick secondary polyvinyl chloride (PVC) liner. The second liner was laid over 15 cm (6 in) of sand spread uniformly over the pond bottom. Also, a 6.4 cm (2.5 in) thick layer of sand was spread between the liners. The walls of the pond are thermally insulated with 7.6 cm (3 in) thick polyurethane foam insulation.

To attain brine salinity of 21% at the pond bottom, about 127 tons of 98% pure, granular NaCl were used. The salt was dissolved by using a fire hydrant; further salt mixing was done with two pumps of 400 lit/min (105 gal/min) capacity each. The salt gradient was established by lowering

the diffuser* to a depth of 1.2 m (3.0 ft) from the bottom which corresponded to the chosen thickness of the lower convective zone. With the diffuser at that position, 5.1 cm (2 in) of fresh water was added. The diffuser was then moved up 10.2 cm (4 in), and another 5.1 cm (2 in) of fresh water was diffused into the pond. This procedure was repeated several times until the pond's depth was about 20.4 cm (7.8 in). Another 10 cm (3.9 in) of fresh water was then added at the top of the pond. In this way, the pond reached the chosen parameters of a 1.2 m (3.9 ft) thick lower convective zone, 1.2 m (3.9 ft) thick nonconvective zone and 10 cm (3.9 in) thick upper convective zone. One month after the salt gradient had been established, the salinity and temperature of the pond reached 21‰ and 50°C (122°F) respectively. The heating rate of the pond at that time was about 1.2°C/day (2.8°F/day).

The pond is instrumented with an underwater Eppley pyranometer, two 100 Ohm platinum resistance thermometers (RTD), a platinum point conductivity probe, and an induction salinometer. Four leak detection sensors are embedded in the sand at the pond bottom. Twelve vinyl jacketed copper-constantine thermocouples, in groups of three, are installed in the walls, and six are installed in the pond bottom, to determine heat losses from the pond. A weather station is employed in conjunction with the other pond instrumentation. The station consists of a horizontally mounted Eppley Model 8-48 pyranometer, a wind speed and direction measuring anemometer and a thermally shielded ambient temperature sensor. Data from about 80 channels is processed by a Hewlett-Packard Model 87 desk-top computer. Although this pond was built to do research on the interface between the convection zone and nonconvecting zone, interactions between zones, wind-induced turbulence, and other phenomena can also be studied. With an appropriate system installed the pond could demonstrate process heat generation (see Fig. 4) as well.

The Los Alamos salt-gradient pond works in conjunction with an evaporation pond 257 m² (2765 ft²) in area and 1.4 m (4.6 ft) deep. The walls of this pond are vertical except for the west wall which is sloped at a 16° angle to create a ramp for salt removal and pond maintenance. A detailed description of the design and instrumentation of a research salt-gradient pond is presented in the paper of J. T. Pytlinski et al. [11].

Some of the most important work on salt-gradient ponds was done in Israel by H. Tabor [12-15]; the concept of such ponds generating heat and electricity was introduced there in the mid-fifties. Salt-gradient solar ponds are being considered as a possible means of electricity generation in Israel because of this country's almost total reliance on imported fossil fuels.

*The diffuser is made of two half discs of 2.5 cm (1 in) thick plexiglass.

In 1977, a 1500 m² (16,140 ft²) pond was made operational in Yavne by Ormat Turbine, Ltd. The pond reached 90°C (194°F) the same year and generated electric power output in the range of 6 kW_e using an organic cycle system equipped with a turbine as the prime mover. This closed loop self-contained system employed chlorobenzene as the working fluid. Water at 29°C (84°F) from the surface of the pond was used to cool the condenser.

A larger pond of 6250 m² (67,250 ft²) area and a depth of 2.5 m (8 ft) was installed in Ein Boquek by the Dead Sea in 1978 [16,17]. When the storage layer reached 80°C (176°F), the pond started to produce electricity by using a 6 kW_e capacity Ormat system. The pond was enlarged to cover 40,000 m² (9.9 acres) of the Dead Sea and a larger Ormat system of 300 kW_e capacity was installed in 1979; the pond delivered 145 kW of electricity the same year, operating at 93°-100°C (199°-212°F) evaporator temperature and 30°C (86°F) condenser temperature. A schematic diagram of an electricity generating system using a salt-gradient pond is shown in Fig. 5. An organic fluid turbo-generator is used to generate electric power from the low temperature heat provided by the salt-gradient pond.

The development plan of salt-gradient technology in Isreal calls for, in the first stage, the use of solar pond power plants interconnected to the power grid as peaking plants to operate between 750 and 1250 hours per year. In July 1984, a 5 MW solar pond power station connected to the electricity grid was inaugurated at Beith Ha-Arava; the station uses two Dead Sea based salt-gradient ponds of a combined area of 250,000 m² (62 acres). The ponds provide 5 million kWh_e per year at a construction cost of \$18/m² (\$1.67/ft²). It is expected that by 1990, solar pond electric power plants can be built to supply the base load. By following this development plan, Israel could be ready by the end of this century to operate a Dead Sea pond of about 500 km² (190 mi²) which could supply up to 2000 MW of electric power by using a series of modular units of 50 MW_e each.

In the United States, the Salton Sea Pond Project in Southern California, sponsored by Southern California Edison and the State of California, has been highly publicized [18-20]. The concept of this project is presented in Fig. 6. The project consists of three phases. Phase 1, the concept and feasibility study, was completed in 1981. Phase 2 calls for designing, constructing and testing a 5 MW_e prototype power plant by 1988. Satisfactory results could then lead to the construction of a 600 MW_e plant comprising 20 to 50 MW_e commercial modules.

The 5 MW_e plant will probably cover 1 km² (0.4 mi²) and will cost \$2,000/kW_e. On the base of 30 years of operation, the cost of electricity was projected to be \$0.075 to \$0.08/kWh (1980 dollars).

The interest in salt-gradient solar ponds during recent years has resulted in several review papers and reports on the current status of the technology, cost, and physical and thermal phenomena which occur in salt gradient solar ponds [21-25]. Several papers give detailed descriptions of pond sizing methodology [26,27] and results of modeling and simulation studies [28-30].

In addition to electricity generation, salt-gradient solar pond applications for commercial and residential space heating [31,32], district heating and cooling [33,34], low temperature (between 50°C and 70°C) industrial process heat production [35], agricultural process heat production [36], and greenhouse heating [37-40] have been investigated. Salt-gradient solar ponds have also been used for enhancing salt production [41-43]. Pumping irrigation water is another area in which salt-gradient solar ponds can be used effectively, although this application awaits implementation.

Some laboratory investigations have also been done on saturated salt ponds [44-46] and gel ponds [47,48]. These two techniques of solar heat collection and storage are still in the research stage. They do not attract the interest and financial support that shallow solar ponds and salt-gradient ponds do.

Development work on solar ponds is concentrated primarily on the use of large size (up to 50 MW_e), modular salt-gradient ponds for electricity generation. The economy of scale, simplicity of construction and technological readiness make such stand-alone plants especially attractive in areas with natural salt lakes that can be converted into production ponds with a minimum of technical effort and cost.

1.3. Electricity Generation by Ocean Thermal Energy Conversion (OTEC)

Concept. Ocean thermal energy conversion (OTEC) is a solar technology based on the principle that energy can be attained from an engine operating between a heat source and a heat sink. In tropical latitudes, the heat source for OTEC could be warm surface ocean water $T_w = 27^\circ\text{C}$ (80°F) which absorbs the sun's radiation, and the heat sink could be cold water at 1000 meters (3280 ft) in the ocean deep $T_c = 4^\circ\text{C}$ (40°F). The ideal Carnot efficiency for this $\Delta T = 19^\circ\text{K}$ will be:

$$\eta_c = \frac{\Delta T}{T_w} = 0.063 \text{ (or 6.3\%)} \quad (1)$$

However, this 6.3% theoretical efficiency accounts neither for heat losses between seawater and working fluid in the heat exchangers nor for parasitic power losses (seawater and working fluid pumping and auxiliary power). Allowing approximately 25% of the ΔT for evaporators and 25% for

condensors will leave 50% for the turbine. Assuming an 85% efficiency for the turbine generator and a gross power output relation to the net power produced as equal to $P_g = 1.3 P_n$, the OTEC system's practical efficiency will be:

$$\eta_o = \frac{0.063 \times 0.5 \times 0.85}{1.3} = 0.020 \text{ (or 2\%)} \quad (2)$$

Since in practice this efficiency could be even lower, OTEC systems will operate at very low efficiencies when compared to 35% efficiency for electricity generating fossil-fueled plants.

Although several types of OTEC heat engines have been proposed, one based on a closed-cycle concept and the other on an open-cycle concept are the two best known [49,50]. In a closed-cycle system (see Fig. 7) the warm surface water is pumped into an evaporator where a subcooled working fluid such as ammonia or freon under high pressure absorbs heat and is turned into vapor. The vapor drives a turbine-generator which produces electricity. The vapor is then condensed in a surface condenser cooled by ocean water from the deep. The condensed fluid is pressurized again before being fed into the evaporator, thus closing the cycle.

So far most of the U.S. effort has been directed toward closed-cycle development, and a number of specific designs exist which propose different working fluids, heat exchanger configurations, platform structures, and turbine types. The closed-cycle system requires a smaller turbine and vapor passage size. This advantage is offset, however, by biofouling [51] and corrosion problems, material incompatibility with the working fluid, the requirement of large, costly, high pressure heat exchangers, and parasitic power needs associated with the working fluid.

The second cycle that is seriously being considered for a commercial OTEC power plant is known as an open-cycle system (see Fig. 8) because it uses sea water as the working fluid. Warm surface water is degasified, then evaporated in a vacuum in a boiler to produce low pressure steam that expands in a very large diameter turbine-generator to produce electricity. Deep, cold seawater then condenses the steam in a surface condenser. The advantages of the open-cycle system include possible production of fresh water from the condensed steam, simpler energy producing system, fewer problems associated with biofouling, favorable heat transfer coefficients, and elimination of a potentially hazardous working fluid. The disadvantages include large turbine and steam duct sizes, necessity for deaeration of seawater, need to maintain vacuum conditions in very large volumes, and parasitic power requirements greater than those for closed-cycle systems.

Three other cycles have been proposed, but they are still in the laboratory study stage. Two are lift cycles (Fig.9)

that evaporate warm surface sea water into low pressure steam in a way that traps substantial volumes of water. The condenser, which is located above the evaporator, condenses the vapor. The potential energy of the resulting liquid, which has been raised to the condenser level, is then converted into rotational energy by an hydraulic turbine-generator to produce electricity. Two approaches to the lift cycle are being pursued. The first requires adding a surfactant to the warm water to cause a foam. In the second, the warm seawater is turned into a mist. The principle advantage of the lift cycles is that they use conventional hydraulic turbines and do not require heat exchangers. The last cycle proposed is a hybrid cycle (see Fig. 10) which combines elements from both open and closed-cycle systems. As in the open cycle, a portion of the warm water is converted to low pressure steam by flash evaporation. But then, this low pressure steam is condensed in a heat exchanger which provides energy to vaporize the working fluid of a closed-cycle system. After expansion in a turbine, the working fluid is condensed by cold sea water. The selection of an OTEC system for a commercial power plant will be a complex one governed by engineering design, overall performance, site characteristics, and system size and cost.

Applications: Many applications for Ocean Thermal Energy Conversion plants have been proposed, from the production of electricity to the production of fresh water, ammonia, liquid hydrogen and methanol, by applying different types of cycles and processes. The production of electricity remains, however, the most valid application of OTEC. Despite its low efficiency and large size system, OTEC is an attractive energy source because of the enormous amount of energy that could be captured from the oceans. Estimates indicate that the energy potential of the Gulf of Mexico is $15,400 \text{ MW}_e^*$ and that over $52 \times 10^6 \text{ km}^2$ ($20 \times 10^6 \text{ mi}^2$) of suitable ocean area exists worldwide for OTEC sites with an energy extraction potential of $2.2 \times 10^6 \text{ MW}$ per year (see Table I). The ocean itself is the collector and energy storage medium allowing an OTEC plant continuous operation for 24 hours per day. For this reason, the OTEC concept has often been characterized as a solar system which has the potential to provide base-load power at a cost which may become competitive by the end of the century (see Table II).

One country which has the potential for ocean thermal energy conversion and which recently expressed interest in building a mini-OTEC plant is Indonesia [52]. The plant will be built in cooperation with the Dutch government on the North East coast of Bali. The bathymetric and oceanographic survey of the site was carried out in 1983. This survey revealed that there is a 50 m (164 ft) thick layer

*Based on an OTEC plant efficiency of 1.5% and a capacity factor of 75%.

of 29.5°C to 30°C (85°F to 86°F) warm surface water. At 500 m (1640 ft) depth some 1600 m from the shoreline, the water temperature is 7.4°C (45.3°F). The system design temperatures were taken as 28.5°C (83.3°F) for warm water and 7.5°C (45.5°F) for cold water. Using historical data over a 20-year period, the wave height was taken as 12.5 m (41 ft). The sea-water pipes will consist of a 0.8 m (2.6 ft) diameter, 1600 m (5248 ft) long cold water intake; a 0.9 m (2.95 ft) diameter, 100 m (3280 ft) long warm water intake (both suction pipes); and a 1.2 m (3.9 ft) diameter, 40 m (131 ft) long mixed water discharge. The cold water pipe lay-out is presented in Fig. 11. The plant itself will be located above mean sea level. A land-based closed-cycle system (see Fig. 12) with a net power output of approximately 100 kW has been chosen for the demonstration unit.

The plant parameters are given in Table III. The plant has been designed by Tebodin Consulting Engineers, a Dutch company in the Hague, Netherlands, to allow two modes of operation. When connected to the public grid, the plant will produce 220 kW of gross power, of which 100 kW will be required to drive sea-water and ammonia pumps. In its second mode of operation, the plant will run separately from the grid as an independent test unit and will produce just enough power to drive the pumps. In this case, start-up power from the grid will be required to get the system in operation.

The heat exchangers will be the largest components of the power plant. Each will consist of a 12 m (39.4 ft) long, 1.5 m to 2.5 m (4.9 ft to 8.2 ft) diameter cylindrical shell of carbon steel and a bundle of 19 mm (0.75 in) diameter titanium tubes through which the sea water flows. Ammonia will be sprayed on the tube bundle in the evaporator. As already mentioned, a typical problem associated with heat exchangers using surface water is biofouling, a build-up of a slime-type layer of micro-organism in the heat exchanger tubes. Biofouling reduces the efficiency of heat transfer and consequently the power output of an OTEC-unit.* The biofouling counter-measure will consist of intermittent chlorination of the warm sea-water loop.

The turbine will be the one-stage radial inflow, axial out-flow type. The synchronous generator will be coupled to the turbine via a gearbox. The sea water pumps will be the axial type suitable for large volume, low heat flows.

As the Indonesian OTEC unit is meant to be a pilot-plant and test-unit, it will be well instrumented and equipped with data-logging facilities to enable the system's evaluation.

The Solar Energy Research Institute (SERI), a U.S. Department of Energy laboratory located in Golden, Colorado,

*A 1 mm (0.04 in.) thick slime deposition could reduce an OTEC system's efficiency by 65%.

plans to install and test a 165 kw open-cycle OTEC system at the Natural Energy Laboratory in Hawaii [53]. A schematic diagram of the system is shown in Fig. 13. The system power output and the experiment itself were selected to determine the minimum size required to scale up results to a commercial size OTEC plant of 10 MW_e capacity (see Table IV). Heat and mass transfer, sea-water hydraulics, and noncondensable gas purge dynamics will be studied in this experiment.

The system will use a vertical spout flash evaporator having a field of 10 cm (3.9 in) vertical spouts located on 0.7 m (2.3 ft) centers standing 0.5 m (1.64 ft) high. According to SERI this evaporator will produce 0.5 kg/sec m² (0.10 lb/sec ft²) of steam with a 3.1°C (37.6°F) flashdown and less than a meter of hydraulic head loss.

The condenser design calls for concurrent flow in the first stage and countercurrent flow in the air-rich second stage. A matrix packing provides the liquid/vapor contact with a volume ratio of three to one between the stages. It is expected that this condenser will condense 0.8 kg/sec m² (0.16 lb/sec ft²) of vapor by employing an entering temperature difference of 7°C (44.6°F). The condenser will enrich the air content of the vapor stream from 0.5% to 35%, thus minimizing air-purge power requirements.

Head losses of less than 1 m (328 ft) and 2 m (6.56 ft) will occur in the evaporator and condenser, respectively. Total hydraulic loss in the system on the cold stream side is expected to be 3.2 m (10.5 ft).

Flow velocity in the system conduits will be kept below 50 m/sec (164 ft/sec) to minimize pressure losses from steam fluid dynamics. A special mist eliminator will separate water droplets with minimum pressure loss.

Experimental sea-water desorption studies indicate that up to 90% of the gas dissolved in sea water can be released before the sea water reaches either the evaporator or the condenser. The purge system will vent and maintain the desired vacuum level in the evaporator and condenser. An interstage cooler will remove steam that must be pumped from the condenser, thus reducing the condenser power requirement to a minimum. Normally about 5% of the power produced in an open-cycle OTEC plant will be needed to purge the system of noncondensable gases, and 20% will be needed to circulate sea water through the system. In addition, 25% of the theoretically available power will be lost through steamside pressure losses in the flow path. These effects result from the low pressure of the steam and the high rates of sea water circulation required. As the system is scaled to smaller sizes, the auxiliary power requirements become a larger fraction of the total power produced until eventually they exceed it.

Figure 14 shows the net power produced from an open-cycle

OTEC experiment as a function of cold water flow rate for different diameters of cold water pipes. It is clear that a 0.76 m (30 in) diameter pipe delivering approximately 24.6 m³/min (6500 gal/min) is possibly the smallest pipe size to make the auxiliary power requirement smaller than the gross power produced by a plant of 165 kW capacity.

Figure 15 shows that when using a double rotor turbine, the wheel diameter needed to produce 165 kW for the described system will be 1.4 m (4.6 ft). Thus, this experimental turbine is scaled to about one-eighth of the full-scale size of 11.81 m (38.74 ft) which is required for a 10 MW_e OTEC plant.

The thermodynamic parameters for this experimental OTEC plant of 165 kW capacity are given in Fig. 16. It is obvious that net power produced by the plant is strongly inter-related to the auxiliary power demands of each of the processes of the thermodynamic cycle. A departure from the design value of any one of these processes will influence the others and have a compounded effect on delivered power.

The construction of this SERI experimental OTEC plant will be carried out in two phases. In the first phase, evaporator and condenser modules will be constructed. In the second phase, a turbine and additional heat transfer modules will be added to complete the open-cycle system.

Japan has aggressively pursued a closed-cycle OTEC program [54] and has operated a 100-kW (gross) pilot plant at the island of the Republic of Nauru [55]. France has assessed both open- and closed-cycle OTEC options for the Ivory Coast of Africa and Tahiti. The European consortium EUROCEAN has also been active, and the United Kingdom, Puerto Rico, Netherland Antilles and others have expressed interest in OTEC.

The technology is available to build OTEC-plants in sizes up to 50 MW. The OTEC plant planned for Oahu, Hawaii, of 40 MW_e is in this range. A detailed description of various OTEC systems and hardware, including the plant for Hawaii, is presented in the paper by G. L. Dugger et al. [56]. For countries with less technical and financial resources and much smaller electric power needs than Hawaii, a plant size of 1 MW_e or less may be a more appropriate choice. Before this can be done, however, better knowledge is needed about several engineering, operational and maintenance aspects of a commercial size OTEC power plant. The ongoing research and development will undoubtedly extend this knowledge to the point of commercial readiness of OTEC.

1.4. Agricultural Drying

Concept: The three most common uses of solar energy for agricultural drying are direct, indirect and hybrid. With direct drying, solar energy is absorbed by the produce and

by the internal surfaces of the drying chamber. The generated heat evaporates moisture from the drying produce. It takes 590 cal per gram (1950 Btu per pound) of water evaporated. Water starts to vaporize from the surface of the moist produce when the absorbed energy increases the temperature enough for the water vapor pressure to exceed the partial pressure of the surrounding air. During direct drying, radiation may penetrate the produce and be absorbed by it. Under such conditions heat is generated inside the produce as well as on its surface.

With indirect dryers, solar radiation is not directly incident on the agricultural produce to be dried. Air is heated in a solar collector and then passed to the drying chamber to dehydrate the produce. When the agricultural produce absorbs this heat, evaporation of water from it occurs. In hybrid dryers, energy such as fossil fuel or electricity is used to supplement solar energy for heating.

From the economic viewpoint, maximum drying rates are usually desired. Produce quality, however, must be considered and excessive temperatures should be avoided. Also, since drying occurs at the surface, agricultural produce which has a tendency to form hard, dry surfaces relatively impervious to liquid and vapor transfer must be dried at a rate sufficiently low to avoid changes in the physical and visual quality of the surface. Close control of heat transfer and vaporization rates, either by limiting the heat supply or by controlling humidity of surrounding air, should be provided.

Applications: Solar drying of agricultural produce is practiced in most parts of the world. Direct solar drying by spreading crops on the ground or on a platform is cheaply and successfully used in villages of developing countries. Also, in Australia, direct drying of grapes on racks in an open environment is done. One 50 m (164 ft) drying unit can provide enough rack space to dry fruits from over 11,000 m² (118,360 ft²) of vines during the drying season. However, open sun drying usually results in inferior quality of the final product because of contamination by dirt and insects, degradation of the produce and wastages; furthermore, it is a slow process. Drying under controlled conditions of temperature, humidity and air flow could be a solution to the problems inherent to direct drying in an open environment.

A classical example of direct solar dryers for drying fruits, vegetables and other agricultural produce on a family scale is a solar cabinet dryer [57]. This dryer basically consists of a rectangular container, insulated at its base and at the sides, and covered with a double or single-layered transparent roof (see Fig. 17). Solar radiation passing through this roof is absorbed on the blackened interior surfaces and raises the internal temperature up to 21°C-27°C (70°F-80°F). To provide ventilation, holes are drilled through the base to induce fresh air into the box.

Outlet ports are located on the upper sections of the side and rear panels of the cabinet frame. As the cabinet temperature increases, warm air passes out of these upper apertures by natural convection creating a suction effect and inducing fresh air up through the base. As a result, there is a constant perceptible flow of air over the drying produce, which is placed on perforated trays to facilitate air circulation. This dryer can be constructed very inexpensively using local materials and local labor.

A solar heated grain bin is a different type of dryer which operates under more controlled conditions [58-61]. Crop harvested at high moisture levels should be dried to avoid spoilage during storage and to preserve the quality and nutritive values. Solar heat is used to lower the relative humidity and equilibrium moisture content of the grain. The safe-value of moisture content has usually been considered to be in the range of 14%, depending on the class of wheat and geographical region. However, in very humid climates this moisture content may have to be as low as 11% for some crops, e.g. corn, to avoid spoilage [62].

In the U.S. a typical grain bin is a metal cylindrical structure with a conical roof (see Fig. 18) having a grain storage capacity of 4,400-bushels and equipped with a stirring device. A bin of this type can be converted to solar drying by painting the south-facing wall flat-black and installing a secondary wall of clear corrugated fiberglass. A 10 hp drying fan is enclosed with fiberglass so that air is pulled over the black-painted wall before it is forced into the plenum and up through the grain. The moisture laden air is exhausted to the atmosphere. An 8 m (27 ft) diameter, 5.5 m (18 ft) high bin provides about 37 m² (400 ft²) of solar collector surface. With such a bin up to 50% of drying heat can be provided by solar radiation.

Another type of drying bin is a barn used for grain drying and storage, and hay drying [63]. The barn is aligned longitudinally on an east-west axis with the south-facing side of the roof used as the solar heat collector. The roof structure is painted black to absorb solar energy. A transparent plastic film is supported about 8 cm (0.39 in) above the roof by stretching it over framing members set edge-wise. The air, drawn by a fan, enters the opening along the roof peak and moves through the collector-roof down the south wall into the outside air duct. From there, the fan pushes the warmed air into the inside air duct and through the grain by way of a perforated floor. The fan should be large enough to be able to deliver about 2 m³ (35 ft³) of air per minute for each cubic meter of corn to be dried, when the bin is full. The roof collector is sloped about 30° from the horizontal and designed to produce an optimal temperature rise of 5 to 12°C over the outside air. The barn structure provides about 1 m² (10.76 ft²) of collector area for each cubic meter (35.3 ft³) of grain. This ratio gives an acceptable drying rate for shelled corn.

Solar drying of soybean, prunes, grapes, alfalfa, wheat,

corn, onion and garlic have been successfully demonstrated on the industrial scale [64]. The prune drying system at the Lamanuzzi and Pantaleo plant in Fresno, California [65, 66], is one example. The operation of this system was inaugurated in 1978. At that time, the plant processed 12 tons of grapes per day, producing two tons of raisins. The solar system (see Fig. 13) contains 30 single glazed air collector panels of a total area of 1951 m^2 ($21,000 \text{ ft}^2$) which provide hot air at 66°C (150°F) at the point of use. The panels are tilted at 36° . Two 50 hp air handlers are used to assure a flow rate of 5.7 m^3 (2000 ft^3) per minute through the collectors. This solar heated air is then directed to the drying tunnel or to an energy storage area containing 40 m^3 ($14,000 \text{ ft}^3$) of 2.5 cm diameter river rocks at a temperature of 54°C - 82°C (130°F - 180°F). Hot air can also be delivered to the drying tunnel from the storage area. The drying tunnel is 16.8 m (55 ft) long. A sprinkler system is used to clean the collectors. Parasitic energy consumption by the system is about 11% of collected solar energy. The solar system's overall efficiency is 18%. Process heat supplied by solar energy amounts to 2.4×10^{12} Joules per year, representing 80% of one tunnel's (out of 12) heat requirement. Details about the system design and performance are presented by E. J. Carnegie et al. [67,68]. Solar timber drying has also been demonstrated and described in detail [69,70].

1.4. Pumping Irrigation Water

Concept: Usually mechanical or electrical energy is used to pump irrigation water. The water pumping power is dependent on several parameters such as the pumping head, the flow rate of water, and the pump's mechanical efficiency. Mechanical energy needed for pumping could be obtained by converting solar energy into mechanical power. When flat-plate collectors are used to convert solar-thermal to mechanical energy, usually one of the refrigerants is used as a working fluid. Attempts have also been made to use ammonia, toluene or sulphur dioxide as working fluids. The working fluid is then utilized directly in a prime mover which operates in the Rankine cycle. The next conversion from mechanical to electrical power is accomplished via an AC or a DC generator. Such a solar-mechanical-electrical conversion system with energy storage (see Fig. 20) can provide energy for pumping irrigation water at night or during cloudy days. Normally, since energy storage increases the solar system cost by up to 100%, solar pumped irrigation water is used directly in fields. A description of various cycles and related solar systems for water pumping is given by M. N. Bahador [71].

Applications: Pumping irrigation water is an operation where the intermittance of solar energy is not a drawback since storage is not needed. Thus, many solar systems for pumping water have been demonstrated over the years [72]. One such system was built by the French company SOFRETES in 1976 in Guanajuate, Mexico [73]. The installation used

2499 m² (26,889 ft²) of flat-plate collectors. Water was the primary heat transfer fluid. Heat was transferred from hot water to the working fluid (Refrigerant 11) through a heat exchanger. A vapor turbine and electric generator produced 30 kW of electric power which drove two pumps. The system supplied about 100 m³ (35,300 ft³) of potable water per day to the neighboring community of San Luis de la Paz. Systems capable of producing 25 kW and 50 kW power output were also available from SOPRETES.

In 1979, the same company built a large solar system to supply up to 6400 m³ (225,984 ft³) of irrigation water per day to Bakel, a remote village in Senegal [74]. A schematic diagram of the system is shown in Fig. 21. Water pumped from the Senegal river enters collectors where its temperature is raised to 95°C (203°F), then it is delivered to a heat exchanger to transfer energy to an organic Rankine-cycle thermal loop. The nominal mechanical energy output from the system was designed to be 35 kW and is provided by a partial-admission, axial-flow, impulse turbine at 5.9 bar (86 psia) and 86°C (187°F) and exhausts at 1.55 bar (22 psia). Under these conditions, a shaft output of 32.4 kW (43.4 hp) is attained with a working fluid flow rate of 2 kg/sec (4.4 lb/sec).

The turbine output is strongly dependent upon the temperature of the condenser water that is obtained from the river. Although the yearly average temperature of this water is 29°C (84°F), the plant output varies from a maximum of 6400 m³/day (225,984 ft³/day) in October to a minimum of 4400 m³/day (155,364 ft³/day) in June. This variation is also related to the variation of the water level in the river during this period; the average pumping head is 9.2 m (26.7 ft).

Approximately 1870 m² (20,000 ft²) of flat-plate single glazed solar collectors supply solar heat to run the system. The collector field faces directly south with panels inclined at an angle equal to 15° latitude. In all, a total of 26 panels, each with an aperture of 72 m² (775 ft²) and dimensions of 6.3 m x 13.7 m (20.7 ft x 44.9 ft), are used. The collectors' average yearly efficiency is 36%.

A 320 m³ (11,299 ft³) hot water storage tank is provided in parallel with the collector loop for energy storage. This allows the system to operate up to 12 hrs per day. Two separate water circulation pumps, one in the collector-storage loop, and one in the storage-heat exchanger loop, provide the necessary water flow. The pump in the collector-storage loop is a variable speed pump to vary the flow rate according to available sunshine. The system auxiliary pumps account for 17.4% of the total power output. The useful output from the system is electrical power produced by a 25 kW alternator. Additionally, 20 kWh/day was made available for local use for lighting and refrigeration. The system's efficiency was designed to be 5.6%, but it may be only a fraction of this value because of a lower

hot water temperature than expected.

The performance prediction model for solar pumps is treated by C. L. Gupta et al. [75]. Economic aspects of solar water pumping have also been studied extensively and are presented by J. T. Pytlinski [76] and other authors [77]. Cost comparisons between water pumping with solar energy, wind power, diesel engines and electricity have been the subject of investigations in several countries [78,79]. The use of solar energy for pumping irrigation water is not yet economically competitive with standard pumping techniques such as diesel engines at locations where oil supply/transportation is not a problem.

2. CONCENTRATING COLLECTORS SYSTEMS

The basic component of these systems is a concentrating collector. Concentrating collectors increase the intensity of the energy radiating onto the absorber and hence raise the temperatures that can be achieved. Normally concentrating collectors use direct sunlight (except compound parabolic concentrators, CPC) and must track the sun. Tracking mechanisms can be expensive, and concentrators are more susceptible to wind damage and degradation caused by sand storms than flat-plate collectors are.

Concentrating collectors range from low-concentration devices, which have a concentration ratio of 5 or less and are capable of reaching 150°C (302°F), to high-temperature devices with concentration ratios exceeding 100 that can reach 300°C to 500°C (572°F to 932°F). In addition to producing higher temperatures and more useful energy, concentrators can have economic advantages in applications which demand high temperatures since a system's thermodynamic efficiencies improve as the working fluid temperature increases. But, there is little incentive to attempt to achieve temperatures above 1093°C (2000°F). Temperatures significantly above 538°C (1000°F) require expensive materials and make energy storage and control of the system more difficult. Also, heat losses from collectors and engines become more severe at high temperatures.

Three generic types of concentrating collectors can be distinguished, corresponding roughly to low, intermediate, and high degrees of concentration. These are nonfocusing concentrators such as compound parabolic concentrators (CPC), trough or line focusing concentrators that track the sun by rotating along one axis, and two axis tracking concentrators such as a spherical or parabolic dish. The current designs use concentrating reflectors made from polished metal, metallized glass, plastics and composite materials. A wide range of absorber materials is used with these collectors. One axis and two axis tracking collectors are used when a high operation temperature is required as in Brayton and Sterling cycle engines.

When deploying concentrator based systems in areas where technical support and training are in short supply, the simplicity, durability and reliability of equipment, and ease of repair should be taken into consideration in addition to other factors such as the system's overall efficiency and temperature requirements.

2.1. Industrial Process Steam Generation

Concept: The concept and basic components of a solar industrial process heat system are similar to those of a hot water or hot air solar system: solar collectors, controls, valves, energy storage and heat exchangers. A variety of solar systems can be employed to supply the heat required for industrial processes. The system chosen, among other considerations, depends on the service required and the process temperature needed. In general, double loop systems are used; one loop consists of collectors and a heat exchanger and the other loop of a heat exchanger and boiler. A special heat transfer fluid in the collector loop produces steam in the boiler via the heat exchanger.

An industrial solar heat generating system must ensure that heat is available for the process at all times. This requirement for durable and reliable operation of components and the overall system is of paramount importance in industrial applications. The system must incorporate sufficient thermal storage and collector capacity to guarantee uninterrupted operation during inclement weather; and, a backup system is a standard requirement. To make a conceptual design for a solar industrial system, operating data of the plant and processes, plant layout and flow diagrams are needed.

Applications: The industrial sector is the largest user of energy in the United States. This sector uses 37%, while the agricultural sector uses only 2%. According to the U.S. Department of Energy (DOE), the industrial sector is classified as mining and petroleum extraction, contractual construction, and manufacturing. As much as 22% of thermal heat used in U.S. industry is required at temperatures below 182°C (360°F).

Many solar industrial applications have been demonstrated in the United States [64] and other countries [80,81]. Solar process steam generation has been demonstrated at several industrial plants. A flash boiler process steam system that uses solar energy was installed at the Johnson & Johnson plant in Sherman, Texas. In this system pressurized solar heated water from the collectors at 215°C (420°F) is pumped to a boiler where it is flashed to obtain steam at 174°C (345°F) and 125 psia. The peak steam flow rate is 727 kg/hr (1600 lbs/hr). This solar produced steam is directed to the plant main through a pressure regulating valve. The 8.9 m³ (314 ft³) flash boiler has enough thermal storage capacity to protect the collector field from freezing in cold weather. The system was

designed to operate 7 days per week and supply 1.58×10^{12} J/yr (1.5×10^9 Btu/yr). The process steam is used for gauze bleaching.

Another solar process steam generating system was installed at the Dow Chemical Company plant in Dalton, Georgia. A freeze-resistant heat transfer fluid (Dowtherm-LF) circulates through the collectors where it is heated to 177°C (350°F) before entering a heat exchanger in the boiler to produce steam. An accumulator tank is installed in the fluid loop to serve as an expansion tank and dump tank. The solar produced steam is used for latex production.

A schematic diagram of a solar system which generates steam for oil refining (stripping) at the Southern Union Refining Company in Hobbs, New Mexico, is shown in Fig. 22 [82]. The solar steam generating system consists of collectors, heat transfer fluid and pump, heat transfer fluid expansion tank, steam generator, blowdown heat exchanger, and several control valves. The solar system is a two loop system; a heat transfer oil circulates in the collectors' loop while steam is generated in the steam generator loop. Saturated steam at $190^\circ\text{C}/12 \text{ kg/cm}^2$ ($375^\circ\text{F}/175 \text{ psia}$) is generated by 936 m^2 ($10,080 \text{ ft}^2$) of parabolic trough collectors having a 16X concentration ratio. The heat transfer fluid temperature at the collectors' exit varies from 190°C to 260°C (375°F to 500°F). The collectors, mounted on the ground, form 12 arrays with 6 collectors in each array. The arrays are east-west oriented and interface with the refinery system through a steam generator. Solar radiation absorbed by the collectors is converted into the heat of the heat transfer fluid (Therminol T-55), then transferred through the heat exchanger and the second loop to the steam generator. The steam generator transfers the heat from the heat transfer fluid to the incoming feedwater, thereby producing steam. The cool incoming feedwater is preheated by the blowdown heat exchanger, thus making it possible to recover some of the wasted energy in the blowdown. Although the blowdown system wastes a fraction of the collected solar energy, it is necessary in order to control corrosion and scaling in the solar system.

The solar process steam generating systems described above were built in 1980. The construction cost of solar thermal systems at that time (excluding solar ponds) was $\$279/\text{m}^2$ to $\$1,234/\text{m}^2$ ($\$26/\text{ft}^2$ to $\$114/\text{ft}^2$) depending on the type of application, the solar system's complexity and the quality of construction and equipment. The trend of cost variation with system size is shown in Fig. 23. The economics of solar industrial process heat generation is treated in several papers [83-85] as well as in a technical feasibility study [86].

Unfortunately, a number of problems have occurred with some of the solar industrial demonstration systems. For example, flat-plate collectors developed leaks or their plastic glazing deteriorated. Although the air systems

operated well with good efficiency, large parasitic power losses occurred. Poor system design led to very low overall system efficiencies. Evacuated tube collectors suffered frequent failures due to thermal shock. Other problems were seal leaks in pumps, improper pump selection, leaks around flare fittings, wetting of insulation, and peeling of selective coatings on some absorbers.

To increase reliability and durability, solar industrial systems should have highly reflective, durable mirrors for concentrators; absorbers with high absorptivity, low emissivity, and low heat loss; simple durable and reliable tracking mechanisms; and flexible couplings that can withstand high temperature, pressure and rotation of flowing fluid. Substantial improvement of concentrating collectors' and systems' durability, reliability and efficiency and a reduction in cost have to occur to make systems using concentrators acceptable to industry.

2.2. Pumping Irrigation Water

Concept: Solar systems for pumping irrigation water which use concentrating collectors are technically very similar to pumping systems which use flat-plate collectors. Because the one axis and two axis tracking collectors can deliver relatively high temperatures, Brayton or Sterling engines could be used as prime movers. Thus higher overall system efficiency can be obtained. The prime mover drives a pump or alternator which generates electric power for pumping water. Since two axis tracking systems are limited in size because of wind loading and the tracking itself, it is believed that a single collector of this type may be limited to a Sterling engine with a capacity ranging up to 25 kW_e. The concentrator dish diameter to generate this power would be 11 m - 13 m (36 ft - 43 ft). However, solar systems that use Sterling engines are still in the research and development stage.

Applications: Several solar water pumping demonstration systems which use concentrating collectors were built in the United States in the period of 1977-1979. In April 1977, a large installation for pumping irrigation water was put into operation on Gila River Ranch near Phoenix, Arizona [87]. The system is equipped with parabolic tracking collectors having a total area of 554 m² (5960 ft²). The collector design efficiency is 55% while the actual field efficiency is 44-50%. Water which circulates through the collectors reaches 149°C (300°F) and is used as the primary heat transfer fluid. To deliver more water on a daily basis the collector axis is north-south during the summer months, instead of east-west as in some installations. The installation's Rankine-cycle power unit, consisting of a radial-inflow turbine/gearbox, boiler, condenser, regenerator and preheater, is capable of developing 37 kW (50 hp) power output and of pumping 38 m³ (1342 ft³) of irrigation water per minute at peak operation. The overall system was designed to deliver full

power when operating between working-fluid temperatures of 138°C (280°F) and 32°C (90°F). The prime mover is an 11.9 cm (4.67 in) diameter radial-inflow turbine which develops 30,500 rpm. This speed is reduced by a gearbox to an output shaft speed of 1760 rpm. Refrigerant 113 is used as the working fluid. The system's performance generally correlated well with the design values. The overall power output has been less than projected, however, because the collectors have not produced the heat output for which the system was designed (mainly due to dust on the glass tubes of the absorbers which decreased the absorptivity values of solar radiation), the cooling water temperature in the condenser was not as low as expected, and additional pipe bends and a flow meter resulted in flow losses for the irrigation pump.

In September 1979, a solar water pumping system was put into operation in Coolidge, Arizona [88]. This 150 kW (112 hp) solar powered deep-well irrigation system uses 2140 m² (23,040 ft²) of line-focus parabolic trough collectors arranged in eight loops oriented north-south. A schematic diagram of the system is shown in Fig. 24. The purpose of this solar energy application was to demonstrate the feasibility of providing cost-effective, reliable solar-thermal generated electricity. In this particular application 150 kW of electrical power are supplied to operate irrigation pumps. The solar energy is converted to electrical energy by an organic Rankine cycle unit and a 440 VAC, 60 Hz generator. Toluene is used as the working fluid.

The system was designed around three heat transfer loops. One loop extracts warm heat transfer oil from the bottom of a thermal storage tank, circulates it through collectors, and returns the hot oil to the top of a thermal storage tank of 189 m³ (6673 ft³) capacity. Caloria HT-43 is used as the heat transfer fluid. The second loop extracts hot oil from the top of the storage tank, circulates it through a vaporizer heat exchange unit, then returns the oil to the bottom of the storage tank (or directly to the collector field inlet). The third loop circulates toluene through the vaporizer heat exchanger unit to vaporize it, then expands the toluene vapor through a one-stage impulse turbine in the power conversion module to extract energy for electrical power generation. The cycle is completed by condensing the expanded low-enthalpy vapor and pumping the liquid back to the vaporizer. The system is equipped with control and data acquisition equipment, as is routinely done. The test results indicated that the prime mover efficiency is 15.9%. The results from performance tests of the thermal storage and power generation subsystems compare favorably with design predictions.

A well-known solar powered irrigation plant was installed near Willard, New Mexico, in June 1977 [89]. Figure 25 shows a schematic diagram of the system. Parabolic trough collectors oriented north-south having a total area of 625 m² (6720 ft²) were used to provide energy for the system's operation and for storage. The capacity of the heat

transfer fluid storage tank was 52 m³ (1836 ft³). The Rankine cycle engine operated at a peak temperature of 163°C (325°F). The working fluid Refrigerant 113 at 255 psia and the heat transfer fluid Caloria HT-43 at 216°C (420°F) were used. The condenser operated at 30°C (86°F). A single-stage radial inflow reaction type turbine was used. This specially built turbine had a 9.9 cm (3.9 in) diameter and ran at 36,300 rpm. The turbine's rotational speed was reduced to 1760 rpm at the output shaft of the gearbox. Other system elements such as valves, fittings, heat exchangers, etc., were off-the-shelf units. The plant could operate in three modes: solar energy to storage, solar energy to power system and energy from storage to power system. The water output of 2.6 m³/min (91.8 ft³/min) from the pump provided irrigation to 405 m² (4358 ft²) of land. The overall system efficiency was between 5 and 6%.

Although the system operated for several years, the collectors' control equipment and the feed pump of the working fluid malfunctioned, leaks in the working fluid piping and degradation of the collectors' reflecting surfaces occurred, and significant maintenance time was expended on the collector and the power systems throughout the operational period of the plant. A few years ago, shortly after the system caught fire due to a leak of heat transfer fluid through a break in an outlet line, the system was dismantled and the demonstration terminated.

CONCLUSIONS

Solar energy in the form of heat, mechanical power or electricity can perform a multitude of tasks as has been demonstrated in the United States and many other countries. Most of these demonstrations were realized through government funding or cofunding. There are no technical obstacles for solar energy use in performing the tasks presented in this paper; but, widespread use of solar energy depends upon market forces, and as long as other energy sources are cheaper and locally available, neither solar energy nor any other alternative energy source will assume an important role in a country's energy supply. Thus, ongoing and future research activities should concentrate on developing simpler systems and lower cost solar devices which could operate with reliability and durability by using innovative concepts and new materials and technologies.

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TABLE I. POWER POTENTIAL OF OTEC PLANTS AT VARIOUS SITES

	Area in square nautical miles	Power potential MW ^a	Percent of U.S. electric generating capacity ^b	Number of 500 MW OTEC's required to produce electric power
140° to 170° East Long., 20° to 30° North Lat.	900,000	69,400	13.0	139
Micronesia	3,000,000	231,400	43.6	462
40° to 50° West Long., 5° to 15° West Long.,	360,000	27,800	5.2	53
Gulf of Mexico	200,000	15,400	2.9	31

^aOTEC plant efficiency = 1.5 percent; capacity factor = 75 percent

^bU.S. electrical generating capacity = 530,000 MW.

TABLE II. COST ESTIMATES FOR OTEC POWER

Site Location	Range of Capital Cost Estimates 1980 \$/kW	Range of Cost of Electricity Estimates Mills/kWh
Gulf of Mexico	1,980-5,300	42-79
U.S. Islands	1,583-4,300	31-96
Grazing	1,584-2,300	34-70

TABLE III. MAIN PARAMETERS OF OTEC PLANT

Parameter	220kW Experimental OTEC Plant	
Thermal input (kW)	9000	
Electrical output, gross (kW)	220	
Electrical output, net (kW)	110	
Flow rate (m ³)	0.73	
Temp. in (°C)		
Pipe diam. (m)		
Pipe length (m)		
	Warm Water	28.5
		0.8
		1600
Flow rate (m ³ /s)	0.53	
Temp. in (°C)		
Pipe diam. (m)		
Pipe length (m)		
	Cold Water	7.5
		0.9
		100

TABLE IV. COMPARISON OF 165kW OPEN-CYCLE EXPERIMENTAL SYSTEM AND 10 MW OTEC PLANT

Parameter	165kW Experimental System	10 MW OTEC Plant
<u>Turbine (double rotor)</u>		
Diameter (m)	1.41	11.81
Gross power (kW)	165	13400
<u>Vacuum vessel</u>		
Evaporator area (m ²)	10.9	680
Condenser area (m ²)	6.9	480
<u>Exhaust compressors</u>		
Number of stages	3	6
Power requirement (kW)	29.6	1074
<u>Pipe diameters (m)</u>		
Warm	0.762	5.07
Cold	0.762	4.58
Discharge	1.078	5.21
<u>Pipe lengths (m)</u>		
Warm	250	315
Cold	1675	2235
Discharge	500	615
<u>Flow rates (kg/s)</u>		
Warm	585	41300
Cold	410	29550
Barometric head loss (m)	3.75	0.0
Pumping power requirement (kW)	86.3	2310
NET POWER (kW)	49	10016

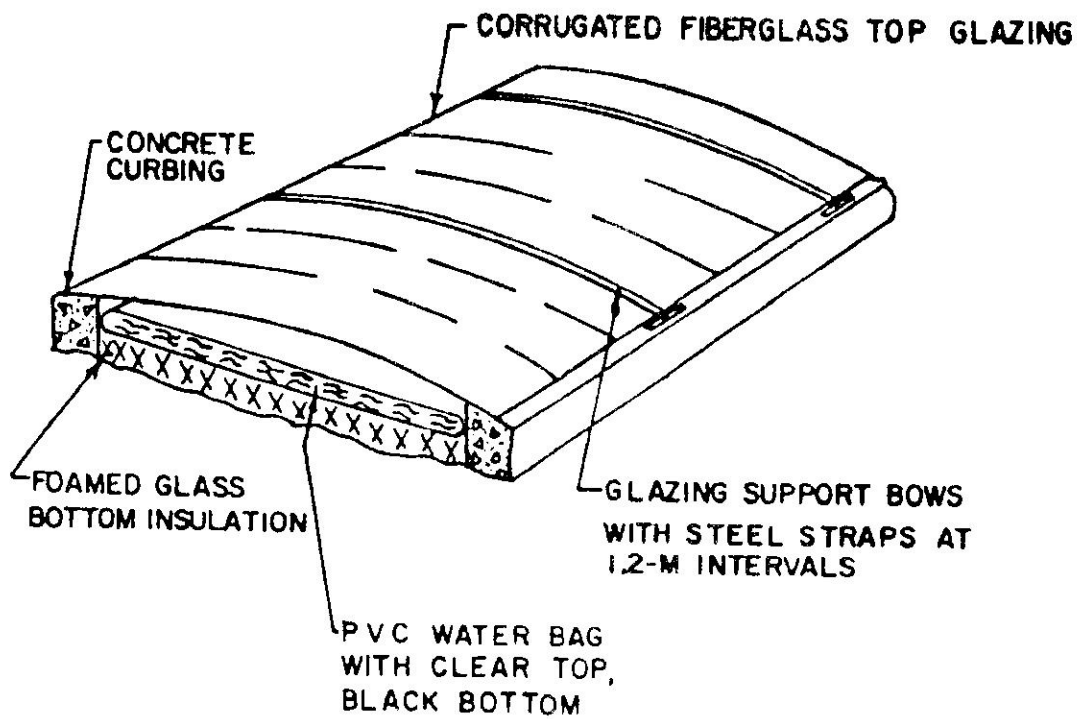


Fig. 1. Cross-Sectional View of Shallow Solar Pond.

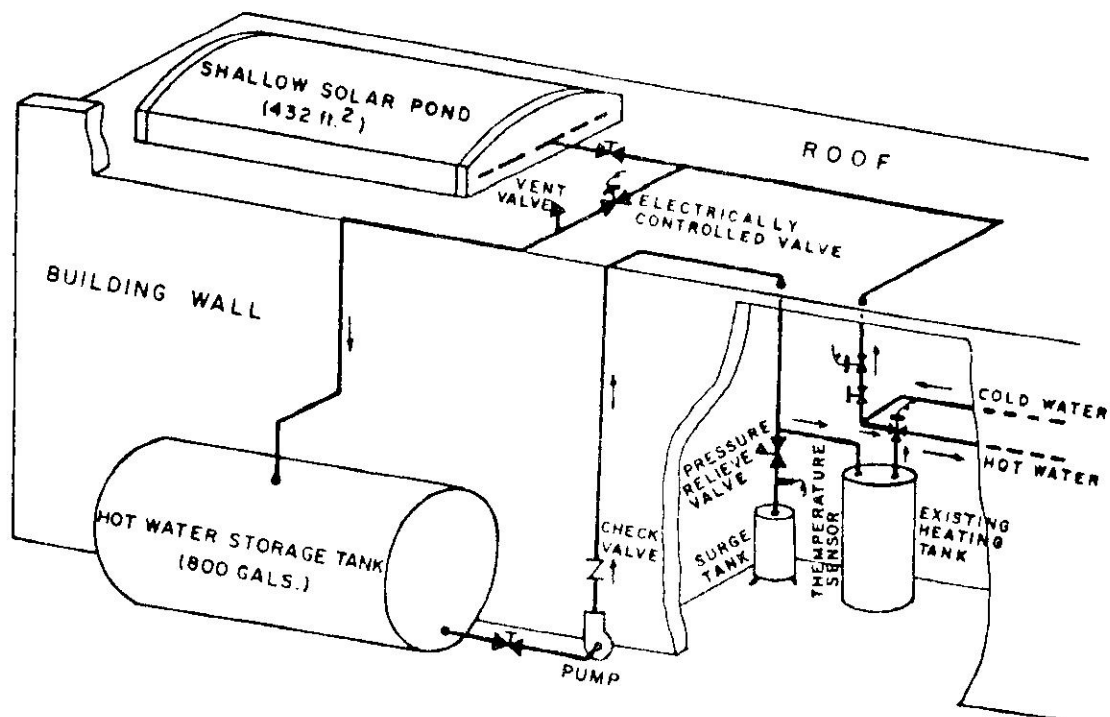


Fig. 2. Shallow Solar Pond System for Water Heating.

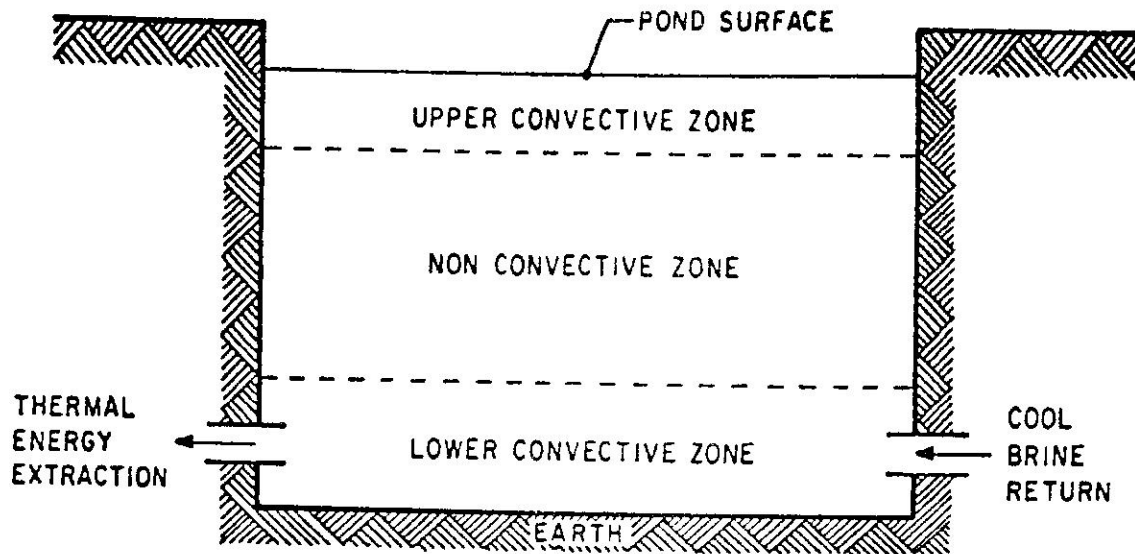


Fig. 3. Cross-Sectional View of Salt-Gradient Solar Pond.

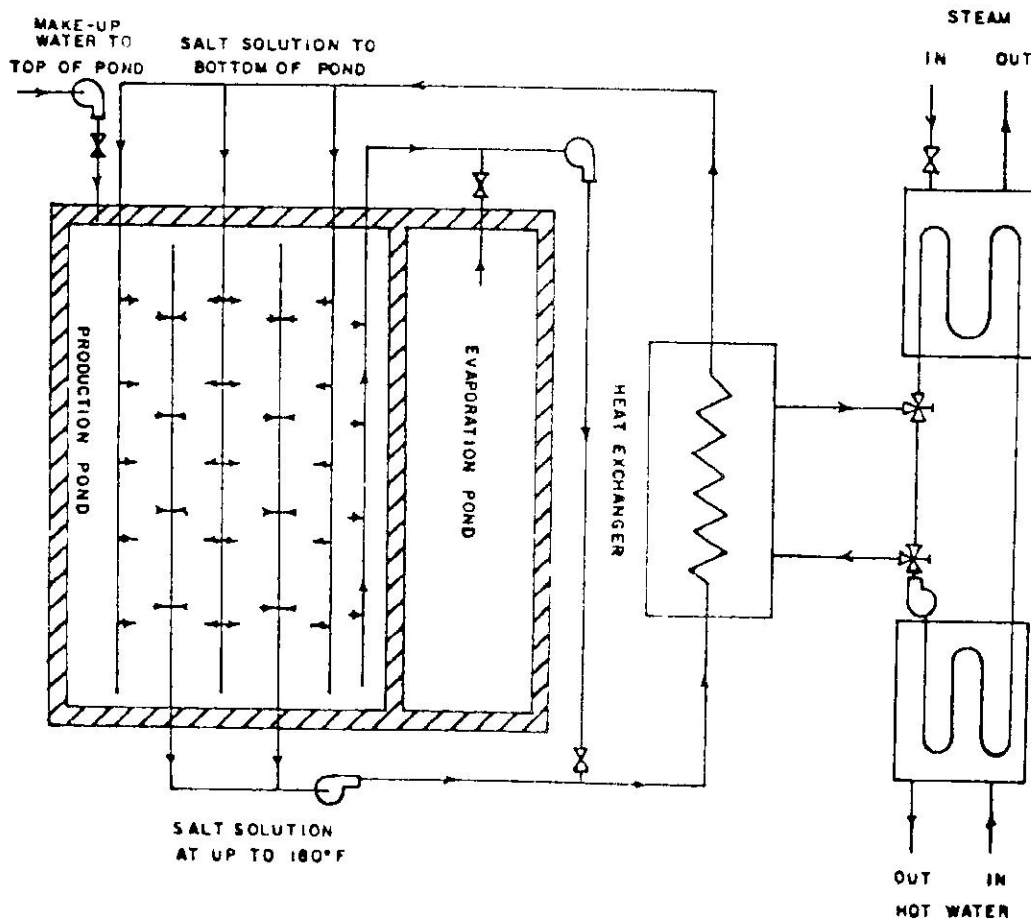


Fig. 4. Schematic Diagram of Process Heat Generation by Salt-Gradient Solar Pond.

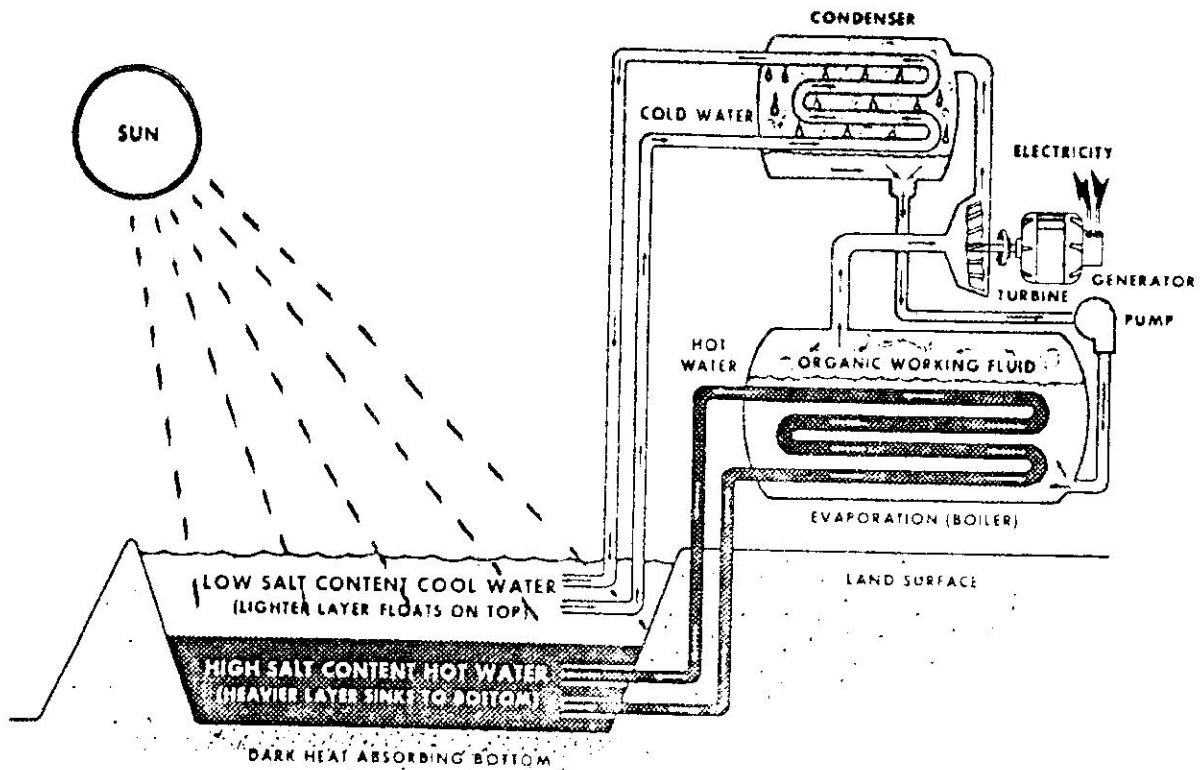


Fig. 5. Schematic Diagram of Electricity Generation by Salt-Gradient Solar Pond.

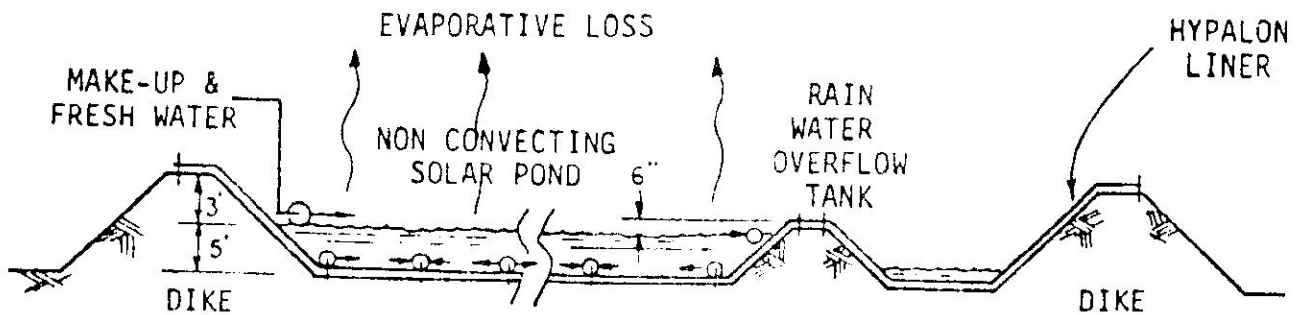


Fig. 6. Concept of Salton Sea Pond Project in the United States.

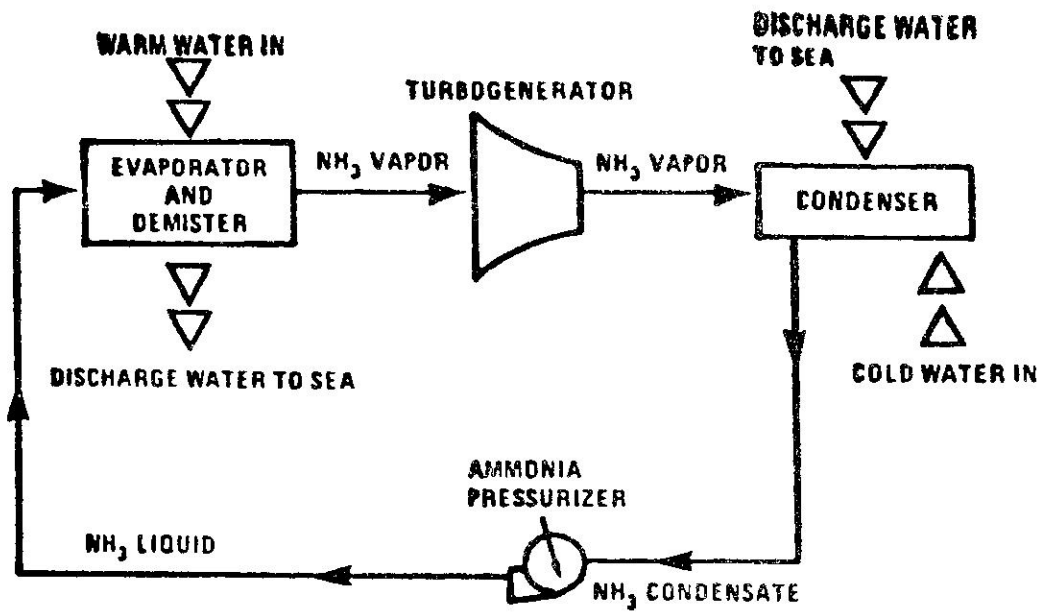


Fig. 7. Schematic Diagram of Closed-Cycle OTEC System.

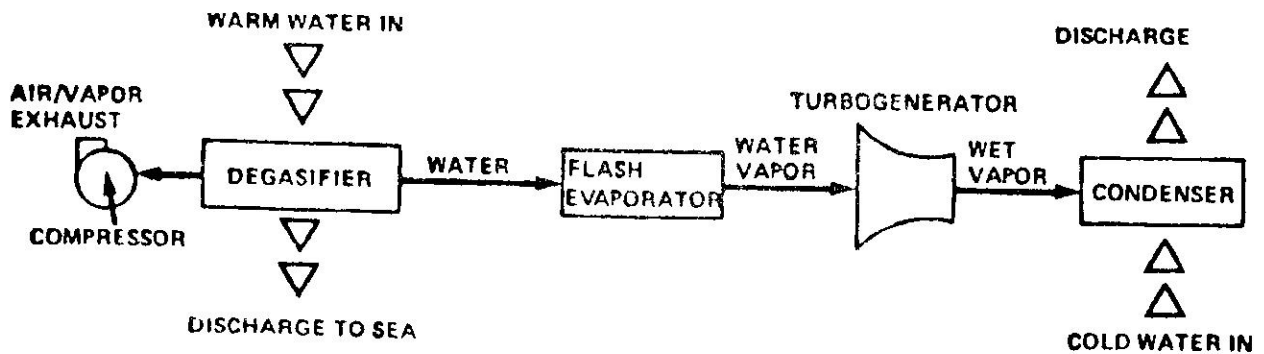


Fig. 8. Schematic Diagram of Open-Cycle OTEC System.

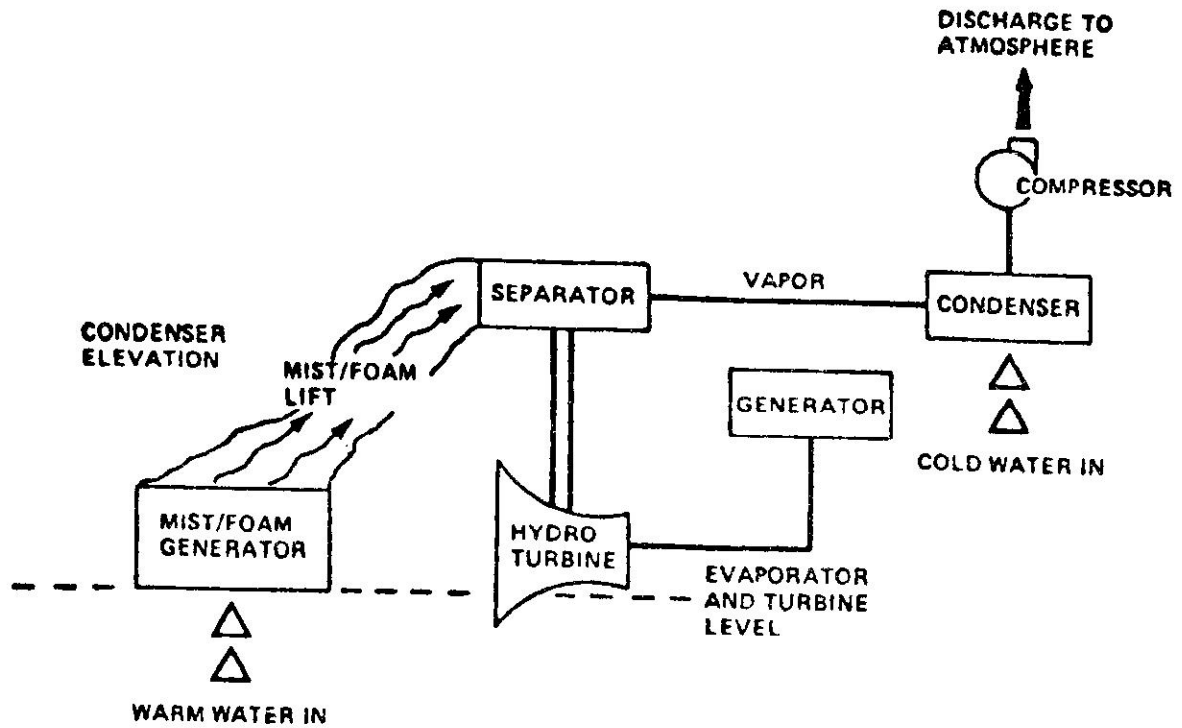


Fig. 9. Schematic Diagram of Lift-Cycle OTEC System.

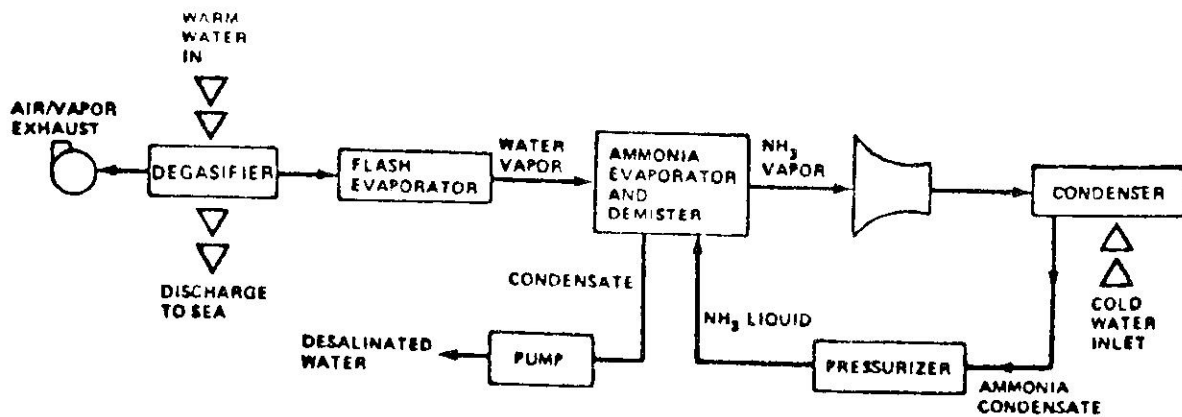


Fig. 10. Schematic Diagram of Hybrid-Cycle OTEC System.

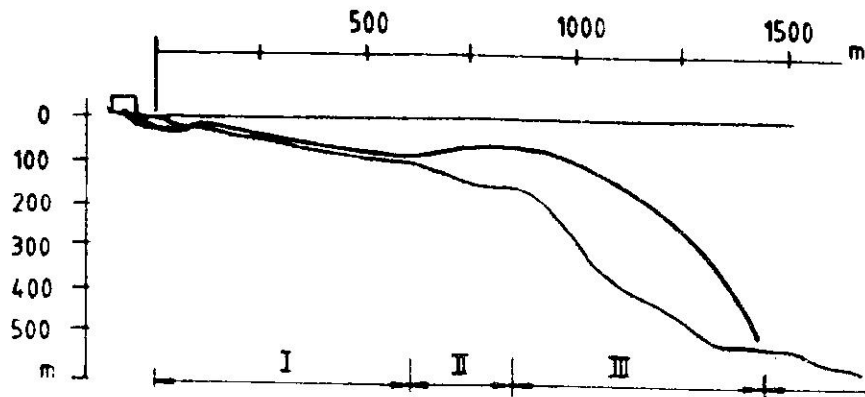


Fig. 11. Cold Water Pipe Lay-Out for OTEC Plant for Bali, Indonesia.

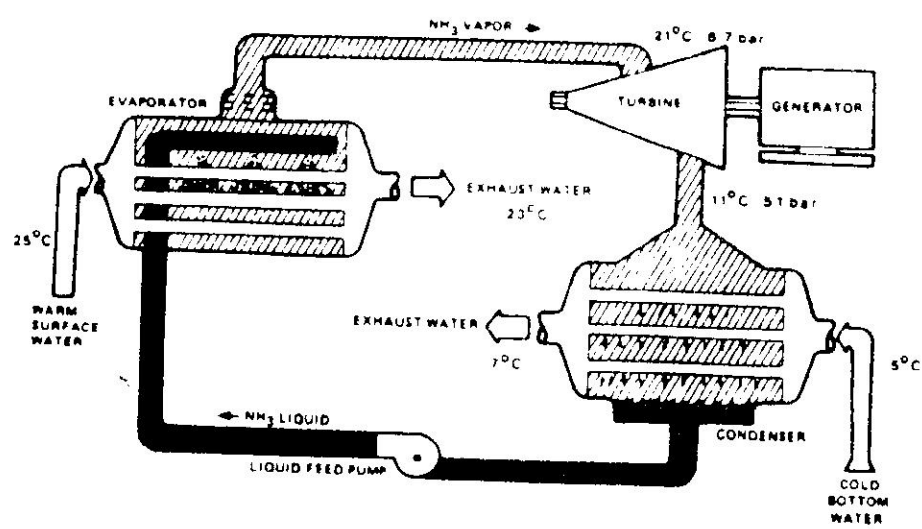


Fig. 12. Closed-Cycle System of OTEC Plant for Bali, Indonesia.

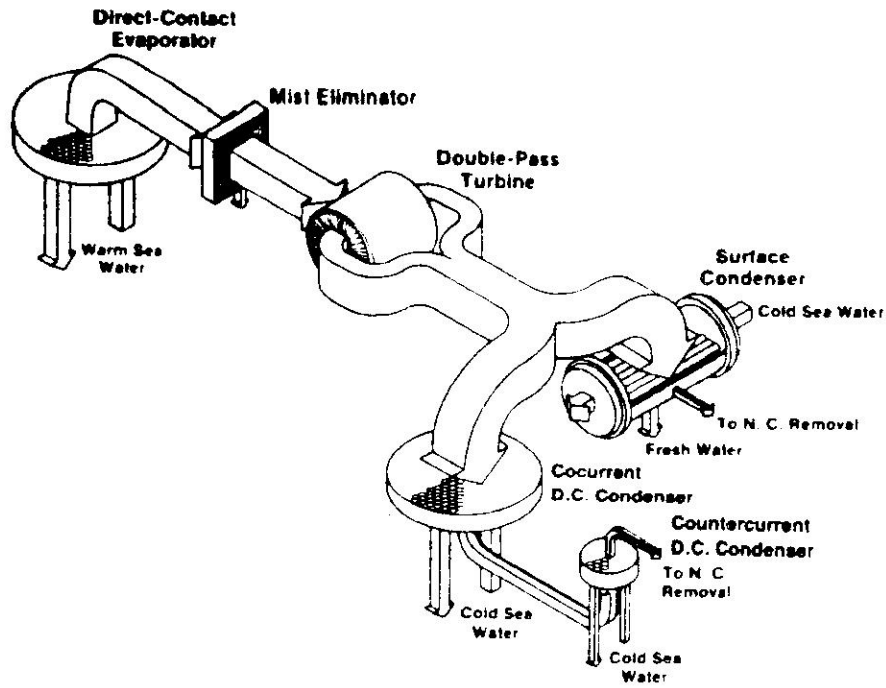


Fig. 13. Schematic Diagram of Experimental Open-Cycle OTEC System of 165 kW Power Output.

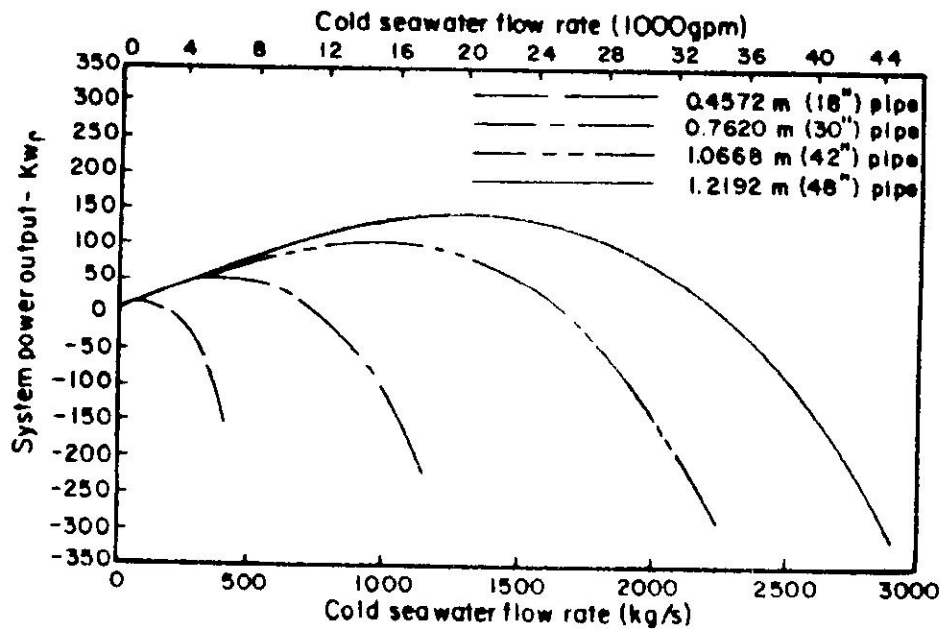


Fig. 14. Power Output vs Cold Water Flow Rate for Open-Cycle OTEC System.

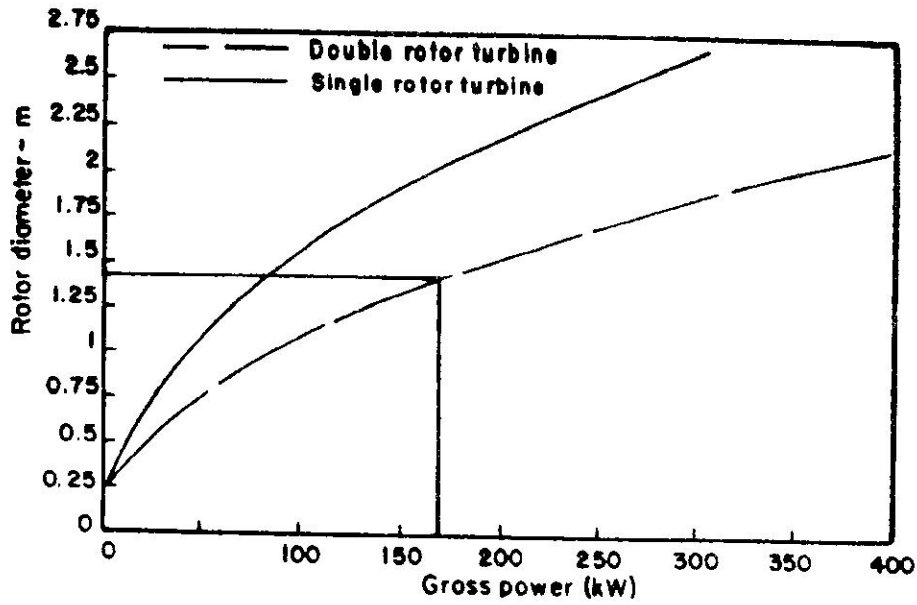


Fig. 15. Power Output vs Turbine Diameter for Open-Cycle OTEC System.

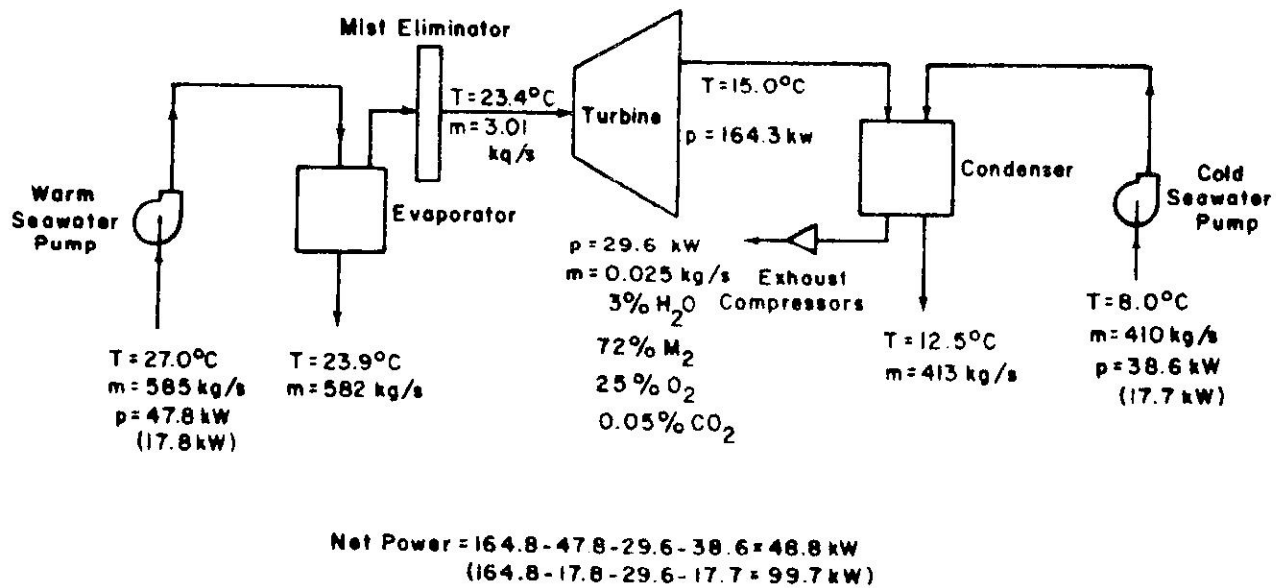


Fig. 16. Thermodynamic Parameters of 165 kW Experimental Open-Cycle OTEC System.

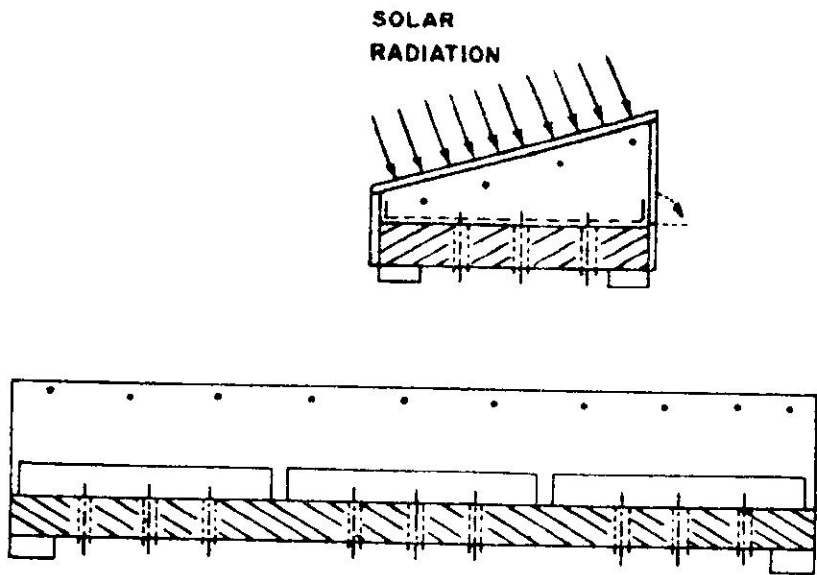


Fig. 17. Cross-Sectional View of Solar Dryer.

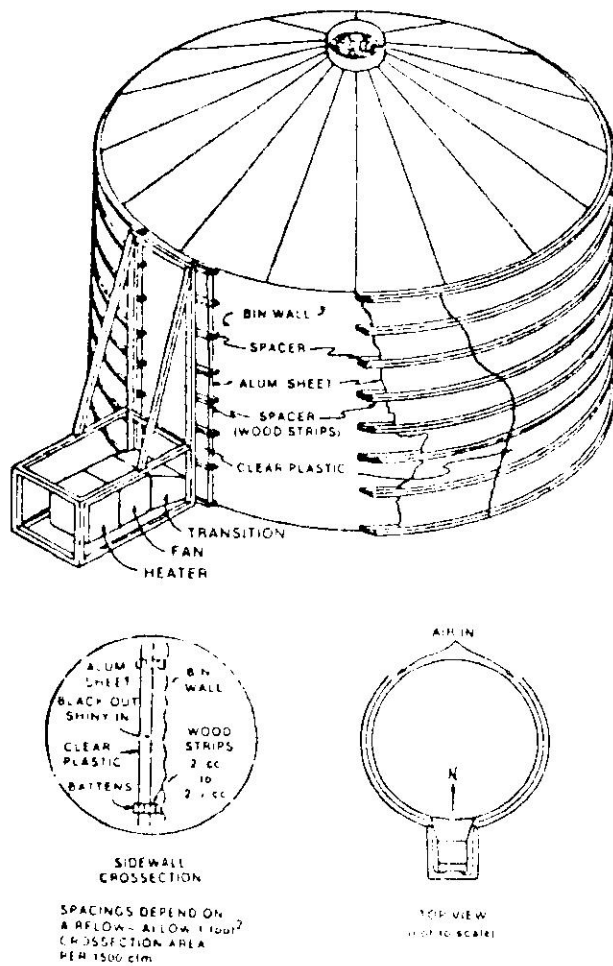


Fig. 18. Overall View of Grain Storage Bin for Solar Drying.

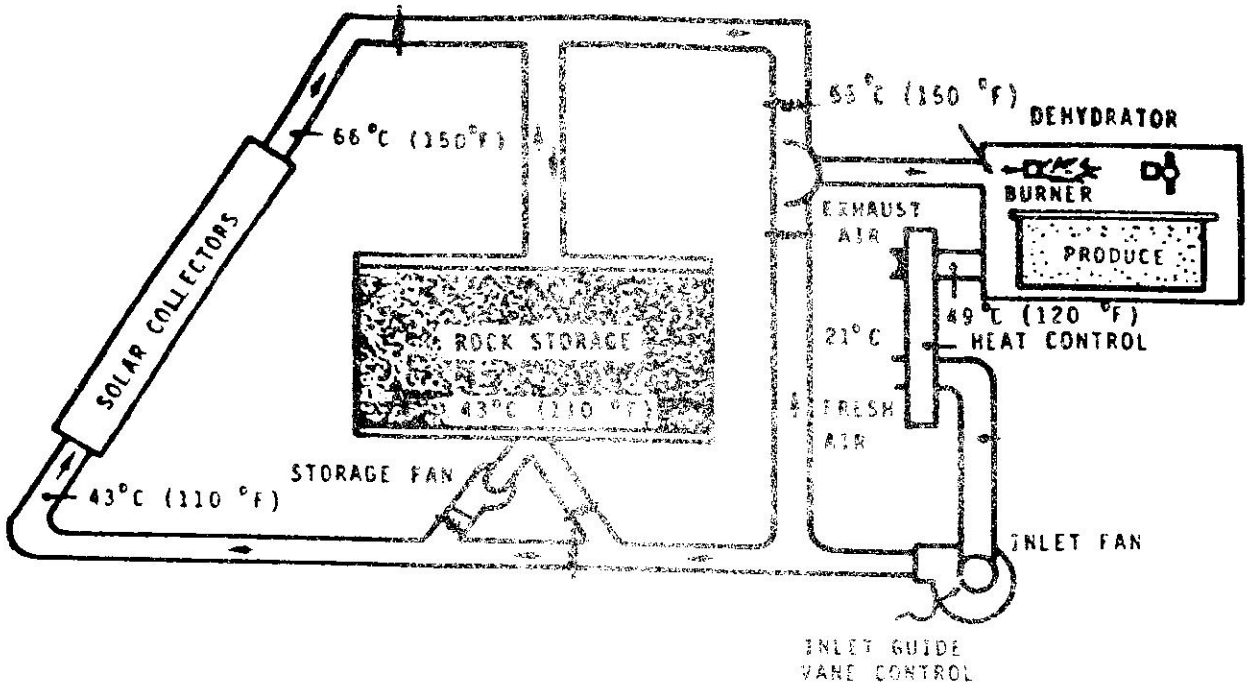


Fig. 19. Schematic Diagram of Solar Industrial System for Prunes and Grapes Drying.

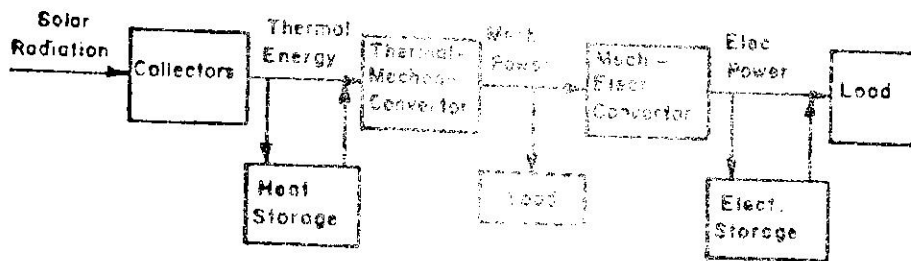


Fig. 20. Block Diagram of Solar Energy Conversion Into Mechanical Power.

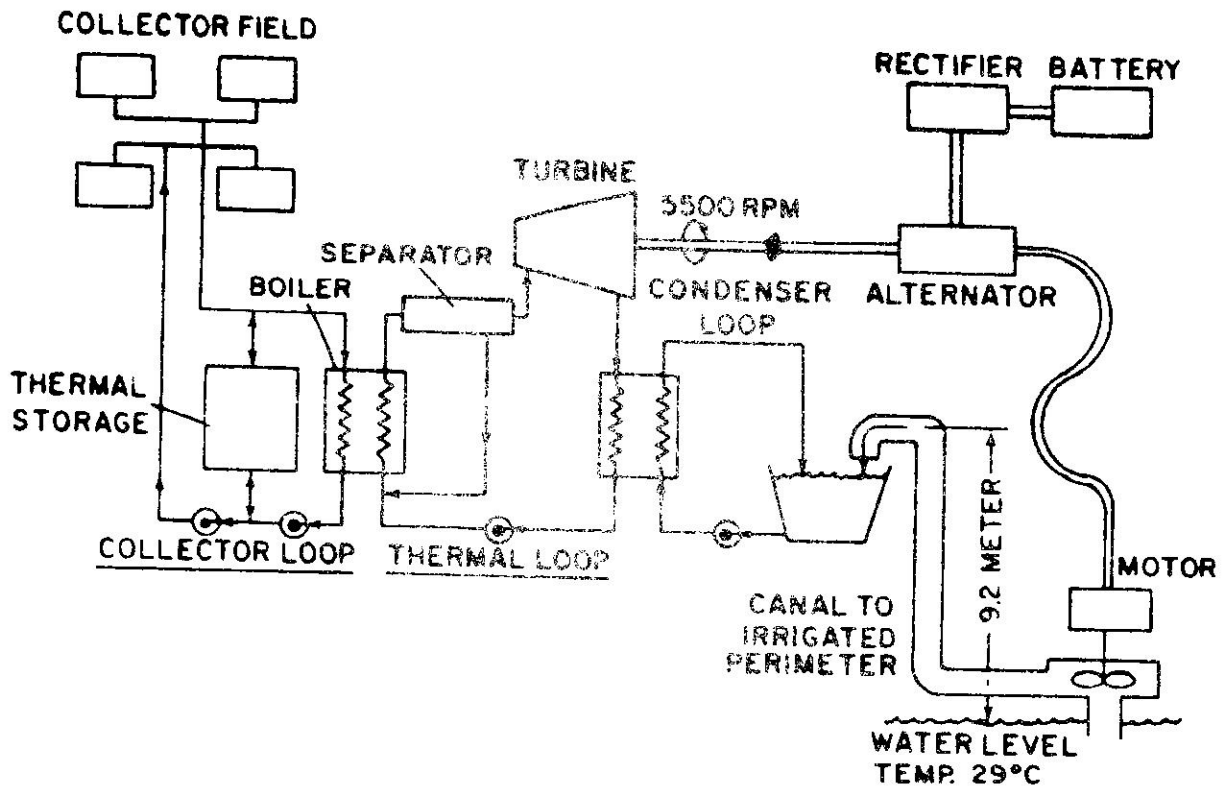


Fig. 21. Schematic Diagram of Solar System for Pumping Irrigation Water in Senegal, Africa, by Using Flat-Plate Collectors.

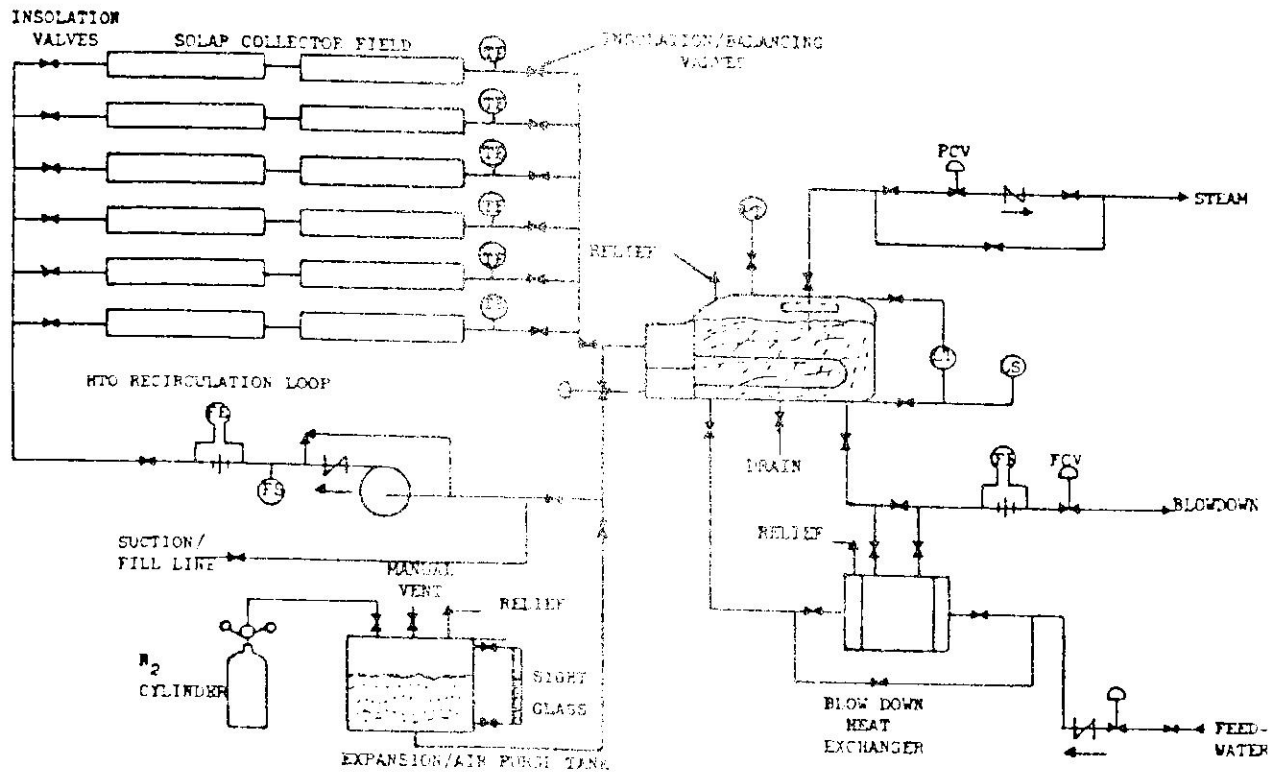


Fig. 22. Schematic Diagram of Solar System for Process Steam Generation for a Refinery.

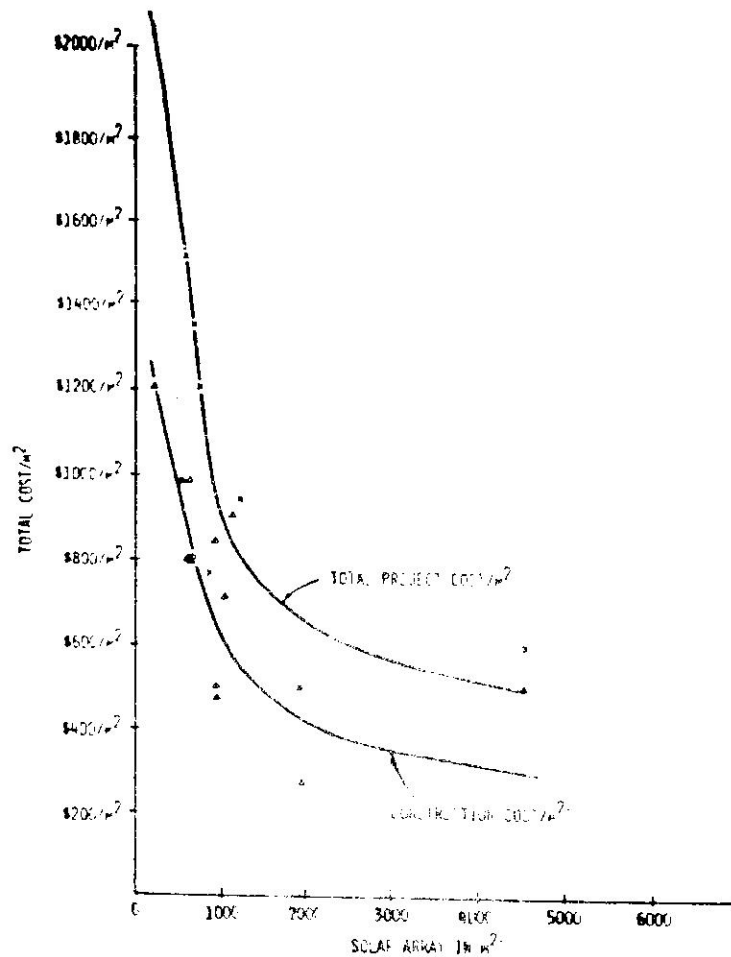


Fig. 23. Solar System Cost vs Collectors Area.

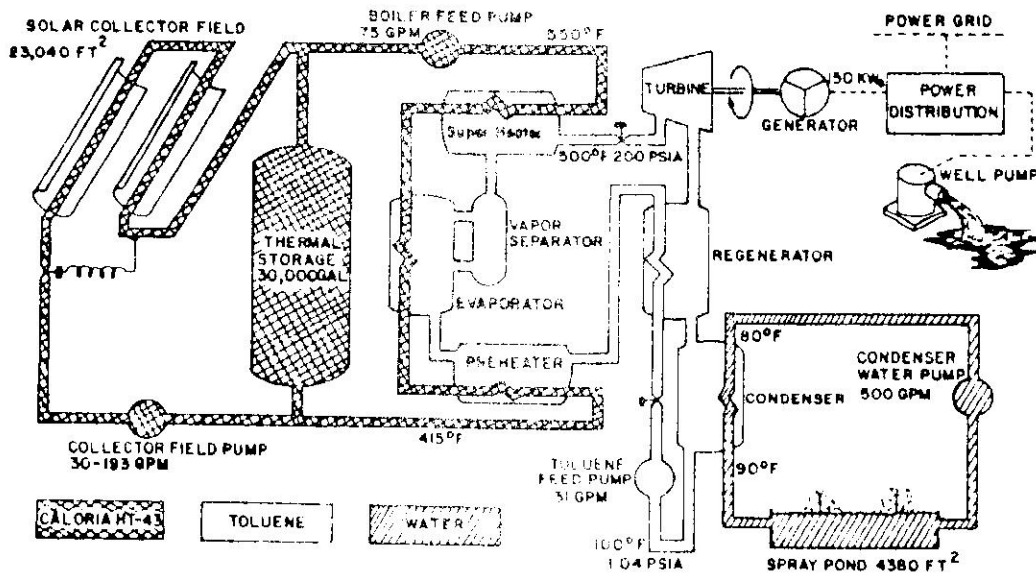


Fig. 24. Schematic-Diagram of Solar System for Pumping Irrigation Water in Arizona (Coolidge), the United States, by Using Concentrating Collectors.

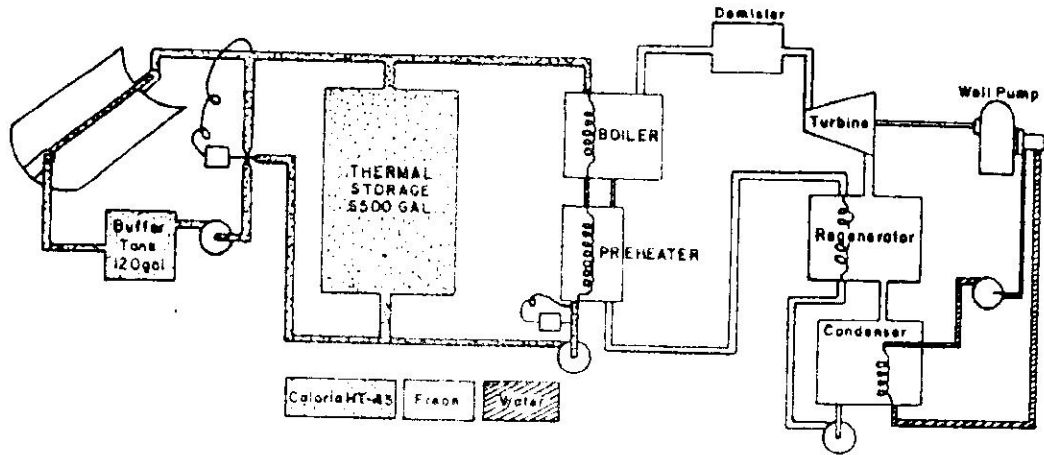


Fig. 25. Schematic Diagram of Solar System for Pumping Irrigation Water in New Mexico (Willard), the United States, by Using Concentrating Collectors.

