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RESEARCH, APPLICATIONS AND DEVELOPMENT

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J. T. Pytlinski
Center for Energy and Environment Research
University of Puerto Rico
Mayaguez, Puerto Rico 00708

EXTENDED ABSTRACT

INTRODUCTION

Fossil fuels are not available in many countries, and these countries are forced to rely on imported oil or coal or nuclear technology in spite of the continuous balance of payment problems which most of them face.

During the last few years, solar ponds have received special attention as one of the solar technologies with the potential to be economically and technically competitive with energy conversion technologies which use fossil fuels (see Fig. 1). In addition to their low cost, solar ponds offer built-in storage which makes them independent of the intermittence of solar radiation. Shallow solar ponds appear to be the most developed and market ready technology [1,2].

The concept of collecting and storing solar energy by means of salt-gradient ponds was derived from research on natural salt lakes [3]. In recent years salt-gradient solar ponds reached the application level, although some aspects of their construction, operation and maintenance are still in the research and development stage [4,5,6]. Some of the most important work done in this area is described by Tabor [7-10], who treats the current status of the technology and the physical and thermal phenomena which occur in the salt-gradient solar ponds, and by Nielsen [11,4], who focuses on research results related to the physics of ponds. Other areas of pond studies are treated by Fynn [12] and Zagrando [13], who describe in detail various aspects of the salt-gradient pond operation and maintenance of salt inventory during the heat extraction mode, and by Cha et al. [14] and Coates et al. [15], who concentrate on pond construction methodology and cost. Some laboratory investigation has also been done on saturated salt ponds [16, 17, 18] and on gel ponds [19,20]. Both of these techniques of solar heat collection and storage are still in the research stage. They do not at present attract the interest and financial support which shallow solar ponds and salt-gradient solar ponds do. Shallow solar pond technology and salt-gradient pond technology are appropriate to build ponds on site, using well known construction techniques and off-the-shelf components. Solar pond applications that have been proposed and studied include commercial and residential space and water heating, low-temperature (between 50°C and 70°C) industrial and agricultural process heat production, electric power generation, pumping irrigation water, and absorption and dehumidification cooling.

The development work on solar ponds is concentrated primarily on the use of large size (up to 50 MW) modular salt-gradient ponds for electricity generation [21-24]. The economies of scale, simplicity of construction and technological readiness make such stand-alone plants especially attractive in areas where natural salt lakes already exist and can be converted into production ponds with a minimum of technical effort and financial support. Selected research, application and development efforts in the field of solar ponds are described below.

RESEARCH PONDS

In the United States, research activities on shallow solar ponds, salt-gradient ponds, salt-saturated solar ponds, and gel ponds are being conducted at several locations. Figure 2 shows a cross-sectional view of a laboratory size research pond at the Brace Research Institute at McGill University [25]. The first shallow solar pond system, designed and operated by Lawrence Livermore Laboratory of California, was built in 1975 in New Mexico. Three prototype ponds 210 sq. m. (2260 sq. ft.) each provided heat for the Sohio Company's uranium processing mill during the several months of successful operation [26]. A cross-sectional view of a typical shallow pond is shown on Fig. 3. A shallow solar pond of 22 sq. m. (240 sq. ft.) and 2.54 cm. (1 in.) in depth is currently being installed on the roof of a high school in Mayaguez, Puerto Rico, to deliver hot water at 57°C (135°F) to the school cafeteria [27].

A salt-gradient solar pond of 200 sq. m. (2152 sq. ft.) area, a depth of 2.5 m (8.2 ft.), and 45° tapered walls has been operating since 1975 at Ohio State University in Columbus, Ohio. In 1976 this pond reached a maximum temperature of 62°C (144°F). Experimental and theoretical research has been done on the physics of this salt-gradient pond and on its operation and maintenance [28]. A second salt-gradient solar pond of 408 square miles (4390 sq. ft.) area was installed at Ohio State University in 1979 [31,32]. This pond is 4.5 m. (14.8 ft.) deep at the center and 1.5 m. (4.9 ft.) deep close to the walls. The walls of the pond are vertical and are made out of wood planks thermally insulated by styrofoam and urethane. The pond is extensively instrumented to yield data on solar input, heat gain by the pond, heat loss to the ground, and heat conducted upward through the gradient layer. A cross-sectional view of a salt-gradient solar pond is shown in Figure 4. Another pond of this type having a 156 sq.m. (1678 sq. ft.) area, a depth of 3.6 m. (11.8 ft.), and vertical wooden walls has been operating successfully on an experimental basis since 1977 providing heat for a greenhouse of the Ohio Agricultural Research and Development Center in Wooster, Ohio [12,29,30]. Although this pond provides heat for a greenhouse, its main purpose is to serve as a research base where various aspects of the pond operation and heat extraction are studied.

A research salt-gradient solar pond of 177 sq. m. (1901 sq. ft.) with a depth of 2.5 meters and walls tapered at 34° was installed at New Mexico University in Albuquerque, New Mexico, in 1975 [13]. In the second year of the pond's operation, the storage layer reached a temperature of 93°C (199°F). Studies on the operational parameters, the criteria for the materials to be used, the cost and performance data, and the physical behavior of the pond exposed to the environment are being performed. Proof of the technical feasibility of heat extraction was obtained by the successful operation of the pond year around and by the extraction of an amount of heat adequate for heating a 185 sq. m. (1990 sq. ft.) house located in the region. The same pond reached a boiling temperature of 108°C (226°F) during the summer of 1980.

Research on gel ponds has also been conducted at the University of New Mexico since 1981 using an experimental pond of 18.7 sq. m. (201 sq. ft.) [19,20]. The effect of the polymer gel thickness upon the performance of the gel pond is being studied. It was found that the surface heat losses from the pond containing a 0.25 m. (0.82 ft.) layer of gel over about 1.22 m. (4 ft.) of low salinity water were approximately half those from a salt-gradient pond with a 1 m. (3.28 ft.) stratified salt zone under the same conditions. For the optimum operation of a gel pond, the research indicates that a 0.15 (0.49 ft.) gel thickness is adequate. The gel chemical formula which is the subject of a patent is not available. The present estimate is that the polymer gel will last three years in a pond under natural solar exposure. Heat is extracted from a gel pond in the same way as it is from salt-gradient and salt saturated ponds; that is, by using "in ponds" or "out ponds" heat exchangers.

Laboratory work on salt saturated ponds has been done by the Desert Research Institute in Nevada using borax as the salt [16,17], and by Inter Technology Company in Virginia using disodium phosphate as the salt [18]. In the former case the size of the pond built in 1979 was 10 sq. m. (108 sq. ft.), and 1 m. (3.28 ft.) deep; in the latter case the pond size was 0.37 sq. m. (3.7 sq. ft.) and 0.91 m. (3.0 ft.) deep. The maximum temperature reached by the Desert Research Institute pond was 47°C (117°F). Reduced maintenance and lower fresh water usage are some of the advantages of using saturated ponds. The saturated pond also has the property of a self established and maintained stable density profile during the heat injection and/or extraction process. A saturated pond may, however, require much more salt than an unsaturated pond which may be a financial disadvantage. Some studies were done on the chemical and biological contamination of saturated ponds, thermal behavior, and operation and maintenance problems. The research performed so far, however, has been restricted to laboratory size ponds and the available data does not cover operating conditions of large size production ponds.

Work on the construction of a salt-gradient solar pond was also initiated in 1971 by the University of Utah, in Utah. The research pond of 850 sq. m. (9146 sq. ft.) and a depth of 1.1 m. (3.6 ft.) was built during 1979 on the southwest side of the Great Salt Lake [33]. The maximum temperature reached by the pond was 55°C (131°F), which was reached after about six weeks of pond operation. At the beginning of 1980, however, a very strong wind of approximately 35.8 m/s (80 m.p.h.) destroyed the salt gradient and emptied almost one-fourth of the pond into the dike surrounding it. The pond was built to investigate the physical processes that occur in a salt-gradient pond and to develop an experimental base for computer modeling of various design schemes for electrical power generation using large size production ponds.

A salt-gradient pond has been operating at the Argonne National Laboratory in Illinois since 1980 [6,14]. The pond has 1075 sq. m. (11567 sq. ft.) and its sides are tapered at an angle of 45° to a depth of 4.27 m. (14 ft.). At the end of 1981 the pond reached a temperature of 63°C (145°F). The major objective of building this pond was to have a research tool to assess the salt-gradient pond as a heat collection and storage system for various types of applications, and to set up an operations base for a future U.S. solar ponds program. This pond is very well instrumented and has already provided data that can be used initially to guide future builders of salt-gradient solar pond systems.

The Tennessee Valley Authority (TVA) installed a 4047 sq.m. (43543 sq. ft.) pond in Tennessee in 1981 [34,35,36]. This pond will work in conjunction with a 2484 sq. m. (26724 sq. ft.) evaporation pond which is 1.2 sq. m. (4 ft.) deep and has walls tapered at 34°. The TVA pond is extensively instrumented, and it will provide important information on pond reliability, operating costs and energy collection efficiency, thus making a significant contribution toward the commercialization of pond technology. This pond is available to outside users as a testing site.

The Center for Energy and Environment Research (CEER) of the University of Puerto Rico in Mayaguez is currently installing a research pond of 39 sq. m. (415 sq. ft.) with a depth of 0.9-1.5 m. (3-5 ft.), and vertical walls [27]. This pond will work in conjunction with an evaporation pond of a similar area. The research pond will be well instrumented to study the physics and engineering aspects of pond operation, maintenance and control. Some computer simulation work will also be performed. This research pond will be a pilot system for a one-half acre production pond to be used to generate process heat for a food processing company in Puerto Rico.

In Israel, research on salt-gradient solar ponds has been underway since 1954, the year the concept was conceived there [9]. After a nine year pause work in this area was revived again in 1975. Because of Israel's almost total reliance on imported fossil fuels, salt-gradient solar pond research is oriented primarily toward electricity generation. In 1977 a 1500 sq. m. (16140 sq. ft.) pond was made operational in Yavne by Ormat Turbine Ltd. The pond reached a temperature of 90°C (194°F) the same year. The pond 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 7500 sq. m. (80700 sq. ft.) and 2.5 m. (8 ft.) deep was installed in Ein Bokek by the Dead Sea in 1978. When the temperature of the storage layer reached 80°C (176°F) the pond started to produce electricity using a 6 kW_e capacity Ormat system. A large Ormat system of 300 kW_e capacity was installed in 1979, and the pond delivered 145 kW_e of electricity the same year operating at 93°-100°C (199-212°F) evaporator temperature and at about 30°C (86°F) condenser temperature. Desalination activities are also planned here as secondary research efforts. The main thrust of the Israeli research effort is toward obtaining a complete understanding of salt-gradient pond technology for electric power production in order to commercialize such systems for domestic and export markets as "turn key" plants.

In Canada, the first research salt-gradient solar pond was installed in 1980 [37]. The pond area is 17 sq. m. (183 sq. ft.) and the depth is 0.86 m. (2.82 ft.). The walls of the pond are vertical. An external, brine to air heat exchanger made out of copper tubing is being used. The maximum temperature reached by the storage layer in 1981 was about 50°C (122°F).

The general objectives of installing this research pond were to obtain first hand practical knowledge of methods and problems associated with construction, operation, and maintenance of solar ponds in preparation for the design and operation of larger ponds. Research is being financed by the National Research Council of Canada to develop equipment and procedures for automating the maintenance of salt-gradient ponds.

<u>In Australia</u>, the first salt-gradient pond was built in Aspendale in 1964. This pond had an area of 106 sq. m. (1140 sq. ft.) and a depth of 0.86 m (2.82 ft.). Locally available clay soil was used to seal the bottom and the walls of the pond; no liner was used. The storage layer reached a maximum temperature of 63°C (145°F) in the summer of the second year of operation. The same year the pond developed a leak which contributed to the discontinuation of the project. The results of this research, which was oriented toward the study of the pond thermal efficiency, the sealing techniques and the control of the salinity gradient, were published in the form of a report [38]. The second salt-gradient solar pond was built by the University of Melbourne in 1981 for research purposes [39]. The pond area is 240 sq. m. (2582 sq. ft.). The research is focused on the stability of salt gradient, methodology of pond filling, and computer simulation of thermal phenomena.

<u>In Saudi Arabia</u>, a research pond of 4 sq. m. (45 sq. ft.) with a depth of 2.3 m. (7.5 ft.) was built in 1981 by the Research Institute of the University of Petroleum and Minerals in Dhahran [40]. This research pond is being used to gain operating experience and to design proper instrumentation for a future large production pond. The activities are focused on computer simulation of pond behavior and on gaining experience in designing and building salt-gradient solar ponds by employing indigenous labor and techniques.

<u>In India</u>, a salt-gradient solar pond of 100 sq.m.(1075 sq.ft.) with a depth of 2.25 m. (7.4 ft.) was built in 1980 by Tata Energy Research Institute in Pondicherry [41]. The pond has vertical walls and works in conjunction with an evaporation pond of 50 sq. m. (538 sq. ft.) area and 0.3 m. (1 ft.) depth. The maximum temperature reached by the pond the same year was 70°C (158°F). The pond is instrumented to provide research results on thermal performance and on the behavior of the stratification layer. Experience was gained about which locally available materials can be used to build a pond and about construction and operation costs in India's rural environment.

APPLICATION ACTIVITIES

The most immediate applications of solar ponds seem to be for space heating and for water heating/preheating for residential, commercial, industrial and agricultural uses where the temperature requirement is in the region of 49°C to 66°C (120°F to 151°F). In tropical climates such as, for example, the Caribbean, salt-gradient ponds may be used in the future for dehumidification cooling as proposed by Bonnet et al. [42].

In the United States a production salt-gradient solar pond of 2044 sq. m. (21993 sq. ft.) was built in 1978 by the city of Miamisburg, Ohio, to supply heat to an outdoor swimming pool in the summer and to a recreational building in the winter [43-46]. The pond depth is 3.0 m. (10 ft.) and the walls are tapered at an angle of 45°. The maximum temperature reached by the storage layer of the pond was 65°C (149°F) during the summer of 1979. The temperature required at the end use is 25°C (77°F). The pond was equipped with a heat exchanger made out of copper tubing of 2.54 cm. (1 in.) diameter which was placed in the pond. The effective surface area of the heat exchanger was 180 sq. m. (1937 sq. ft.). The cost of the pond construction was $35/sq. m. ($3.26/sq. ft.), excluding the land cost. After a successful initial operation of two years, this pond developed a leak in the liner in 1980 and had to be rebuilt.

In 1979 a shallow solar pond system was designed to supply 2000000 liters (528401 gal.) of hot water per day to two army barracks and the laundry at Fort Benning in Georgia [37]. Some 80 shallow pond modules with a total area of 25000 sq. m. (269000 sq. ft.) are being built. The system will be fully operational in 1983. Because of the large size of the installation, the fixed cost of the project will be relatively low. In addition to its size, the project attracted some attention because of some system requirements. For example, the distance between the ponds and the barracks is 2 miles, and very high morning and evening hour peak flows of water had to be accommodated.

In Canada, a production salt-gradient solar pond of 700 sq. m. (7532 sq. ft.) was built in 1981 in Quebec by the Contract Research Company [47]. The pond is 3 m. (10 ft.) deep and has walls tapered at an angle of 45°. During 1981 the pond reached a maximum temperature of about 53°C (127°F). The pond is used to produce heat for a commercial size grain dryer. A brine-to-air heat exchanger made out of copper tubing with aluminum fins is located outside the pond. The frontal area of the heat exchanger is 2.3 sq. m. (25 sq. ft.). The heat extraction rate was over 100 kilowatts during the fall of

1981. The construction cost of this pond was below \$50/sq. m. (\$5/sq. ft.), excluding the land cost.

DEVELOPMENT WORK

The development work at present is taking place mostly in the countries where research and application activities have already gained momentum. As a natural extension of these activities, the development work is focused on stand-alone plants to produce hot water, heat and/or electricity, on selection of materials and components to assure durability and reliability, and on automation of the operation and maintenance. Two typical development projects, one taking place in the United States and one in Isreal, can be mentioned as examples.

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 [48]. 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 will 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 square kilometer(0.4 sq. mi.) and it will cost \$4,000/kW_e. The 600 MW_e commercial plant will cover 120 sq. km. (46 sq. m.) and will cost \$2,000/kW_e installed. On the base of 30 years operation time, the cost of electricity is projected to be \$0.075 to \$0.08/kWh (1980 dollars). The concept of this project is presented in Figure 5. The electric power generation from the low temperature heat provided by a salt-gradient pond can be accomplished by using an organic fluid turbogenerator as shown in Fig. 6 for the proposed Salton Sea plant.

In Isreal the development plan of salt-gradient ponds technology calls for, in the first stage, the use of solar pond power plants interconnected to the power grid as peaking plants, operating between 750 and 1250 hours per year. It is expected that by 1990 solar pond power plants can be built economically to supply intermediate loads. Finally, it is assumed that by 1995 large scale pond-lakes can be built to supply the base load. By following this development plan Isreal will be ready by the end of this century to operate a Dead Sea pond of about 500 sq. km. (190 sq. mi.) which will supply up to 2000 MW_e of electric power by using a series of modular units of 50 MW_e each [21,23].

CONCLUSIONS

Solar ponds are technically feasible and can be economically competitive, as proven by some users. It is important to get direct experience by operating a research pond. More production ponds should be built to gain market acceptability through the reliable and economical operation of large size ponds integrated into an industrial, commercial or agricultural process. The largest salt-gradient production pond in operation has an area of 2044 sq. m. (21993 sq. ft.) and the largest shallow pond, which is in the construction stage, has an area of 25000 sq. m. (269000 sq. ft.). The salt use in a salt-gradient pond is usually sodium-chloride, although in Isreal magnesium-chloride is used. Borax, disodium phosphate and sodium sulphate have been experimented with and studied as possible salts for saturated ponds.

Because of the scarcity of information about metals corrosion in solutions of high salt concentration, an external heat exchanger may be more suitable for the heat extraction system. Copper and brass piping are commonly used as heat exchanger elements. PVC piping is usually used to carry the brine to the heat exchangers. A heavy-duty plastic liner made of a chemically resistant polymer-coated polyester fabric, a vinyl liner, EPDM liner, or XR-5 liner seem to work satisfactorily. Leak detection is one of the most difficult problems in a salt-gradient solar pond. Most often the leaks occur in seams of the liner. Cooper-constantan thermocouples in stainless steel jackets are normally used for pond temperature measurements.

In general the present cost of man-made salt-gradient ponds is in the range of \$50 to \$100 per square meter (\$4.60 to \$9.30 per sq. ft.). Naturally occurring salt lakes can be converted into ponds at a cost much below \$50 per square meter (\$4.60 per sq. ft.). The major capital costs are for salt, excavation, the liner and the heat extraction equipment. The salt cost can be up to half of the total cost. In the case of a salt lake and the construction of an electric power plant, the total cost can be divided half and half between the pond construction cost and the cost of the power equipment. In some locations, for example the Middle East countries, the cost of water may not be negligible, and in some others, such as the Caribbean islands, the cost of land is an important factor. Depths of ponds range between 0.9 m. and 4.5 m. (3 ft. and 14 ft.) with the deeper ponds used in areas where seasonal heating is required. Energy costs between \$6.60 and \$9.50 per GJ (\$7 to \$10 per million Btus) are projected in the case of large size production ponds of over 40000 sq. m. (430400 sq. ft.). The cost of the construction of shallow solar ponds is higher and can be estimated to be in the range of \$150 and \$200 per sq. mi. (\$14 and \$18.5 per sq. ft.).

Although only a few production ponds have been built and operated, the technical simplicity and the research results obtained indicate that the shallow solar ponds technology is market ready while the salt-gradient solar ponds may be on the fringe of market readiness. Whereas the technical/engineering problems related to the pond applications are being addressed by current research and development activities, the environmental, institutional and political issues lag behind and could act as obstacles to the large scale use of solar ponds in the future.

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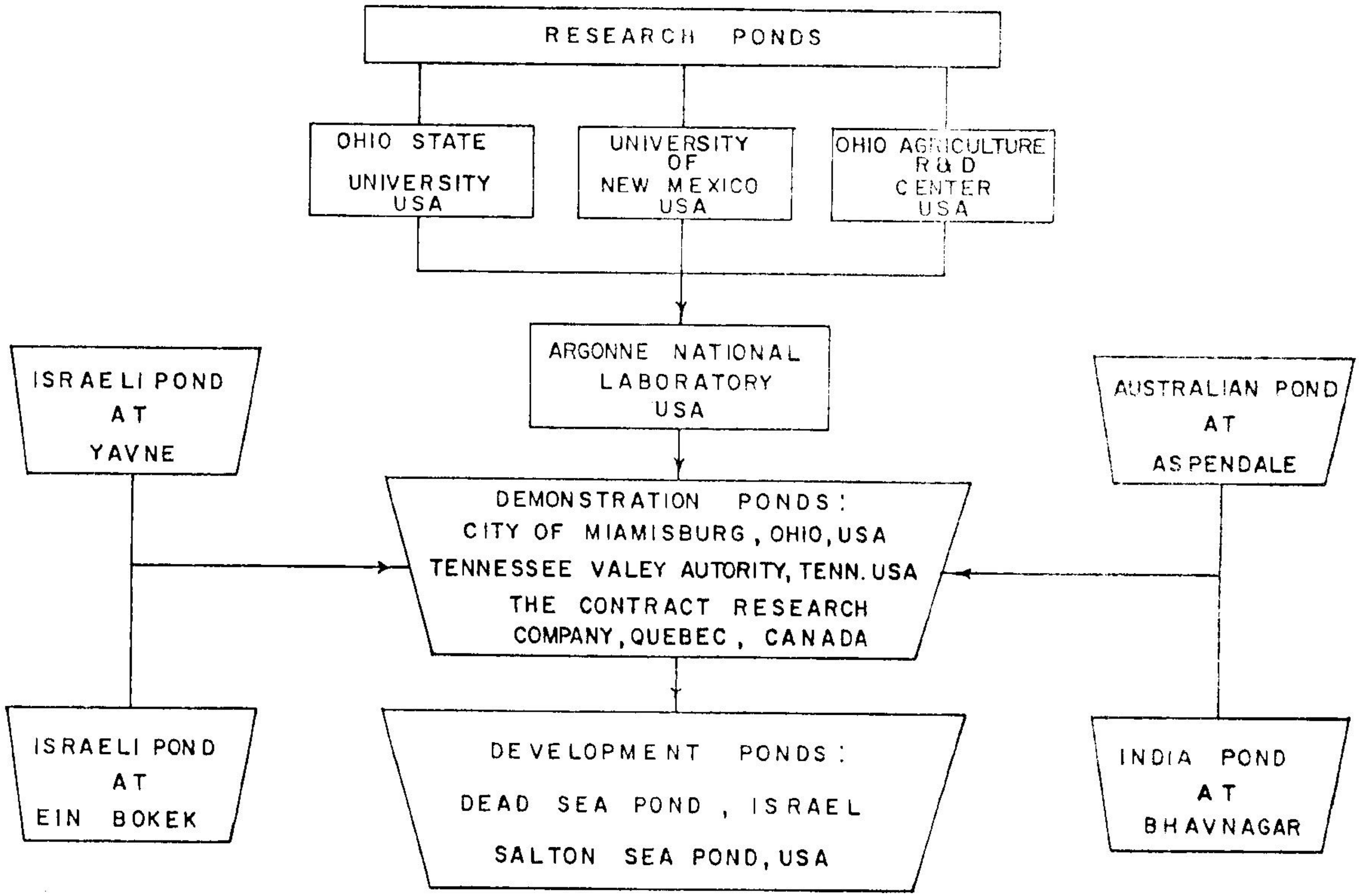

Fig. 1 Solar Pond Activities

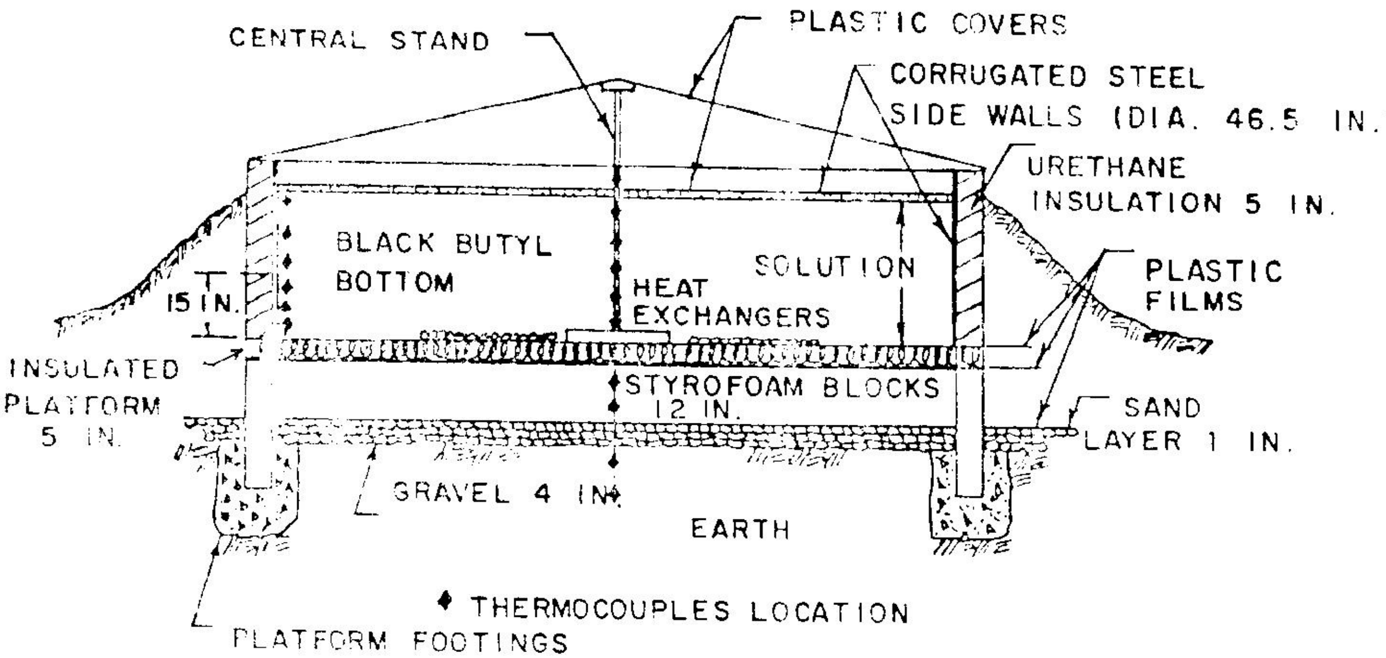

Fig. 2 Laboratory Size Salt-Gradient Research Pond

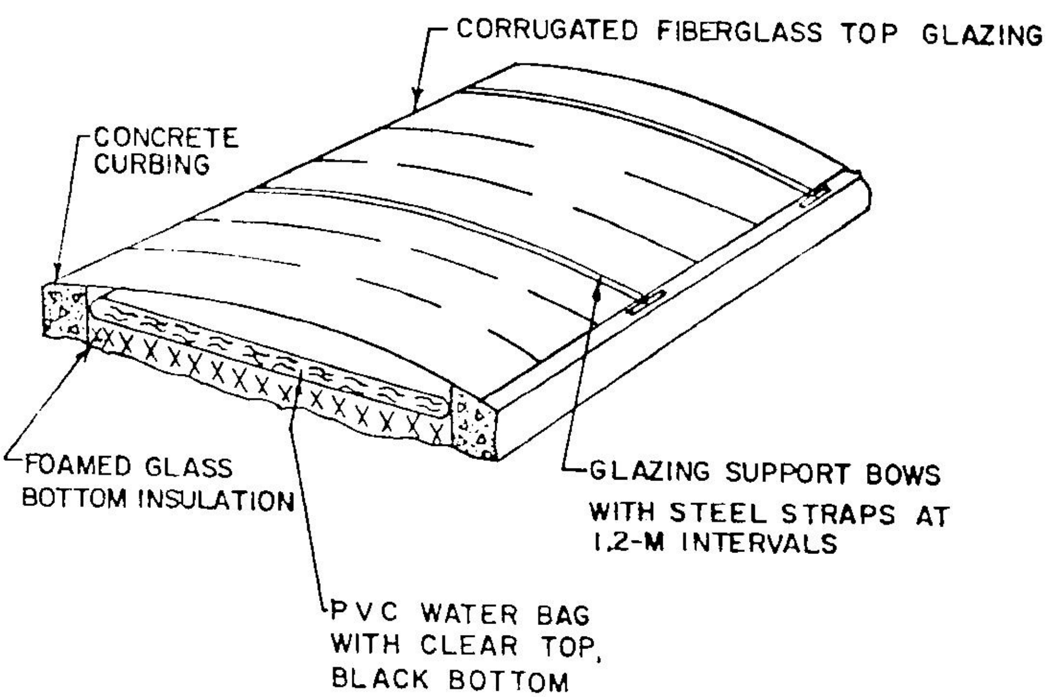

Fig. 3 View of Shallow Pond

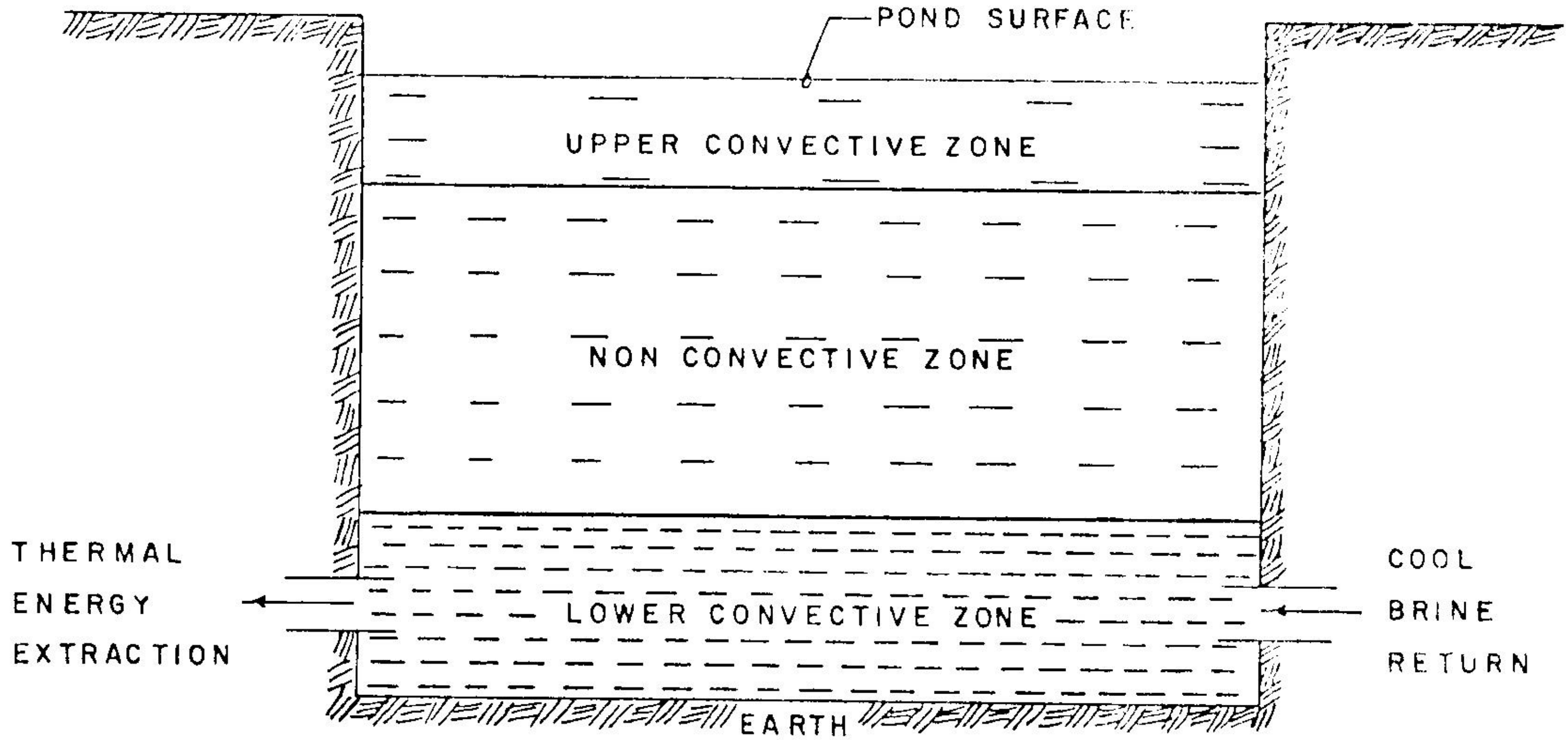

Fig. 4 Cross-Sectional View of Salt-Gradient Pond

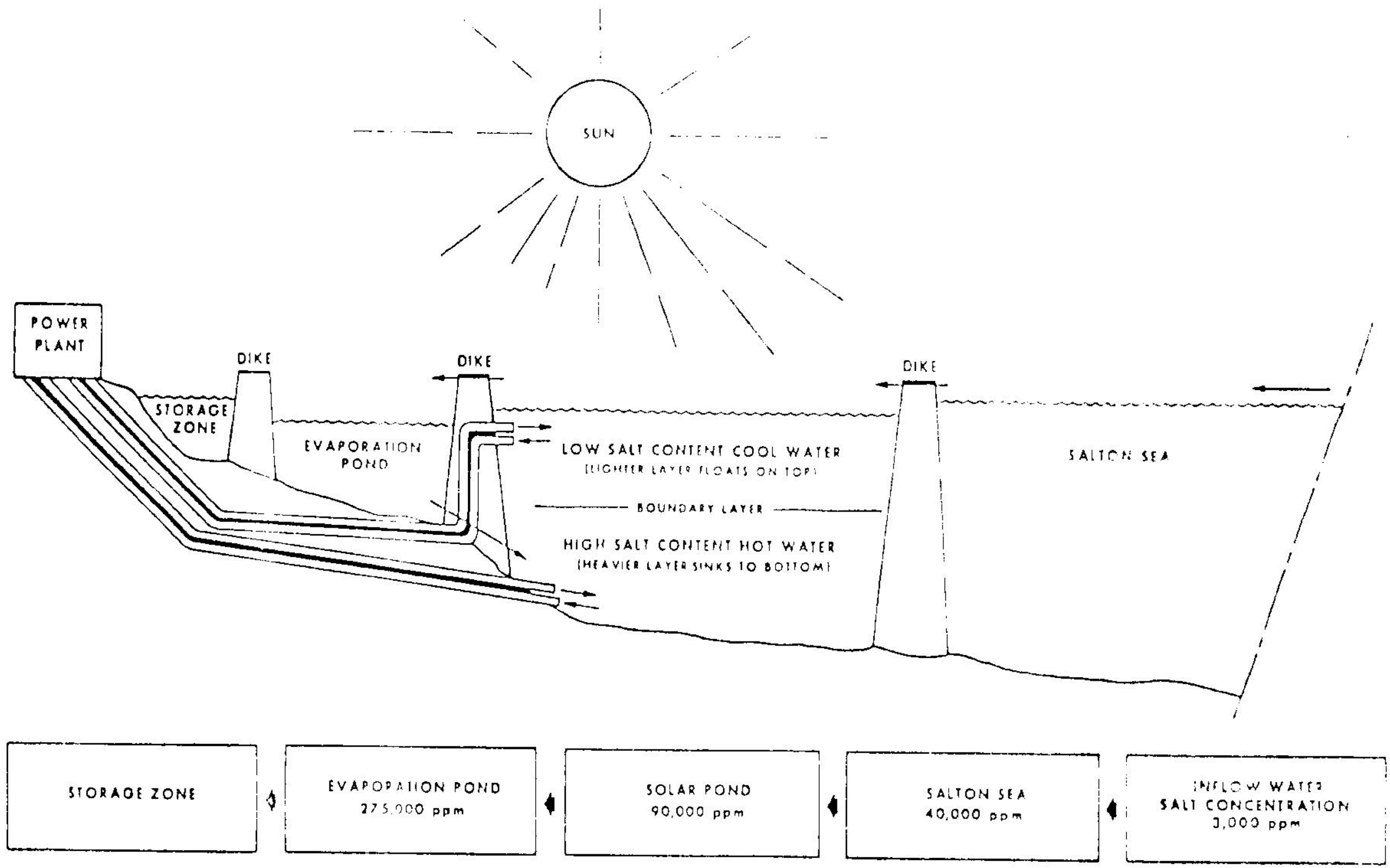

Fig. 5 Cross-Sectional View of Salton Sea Pond

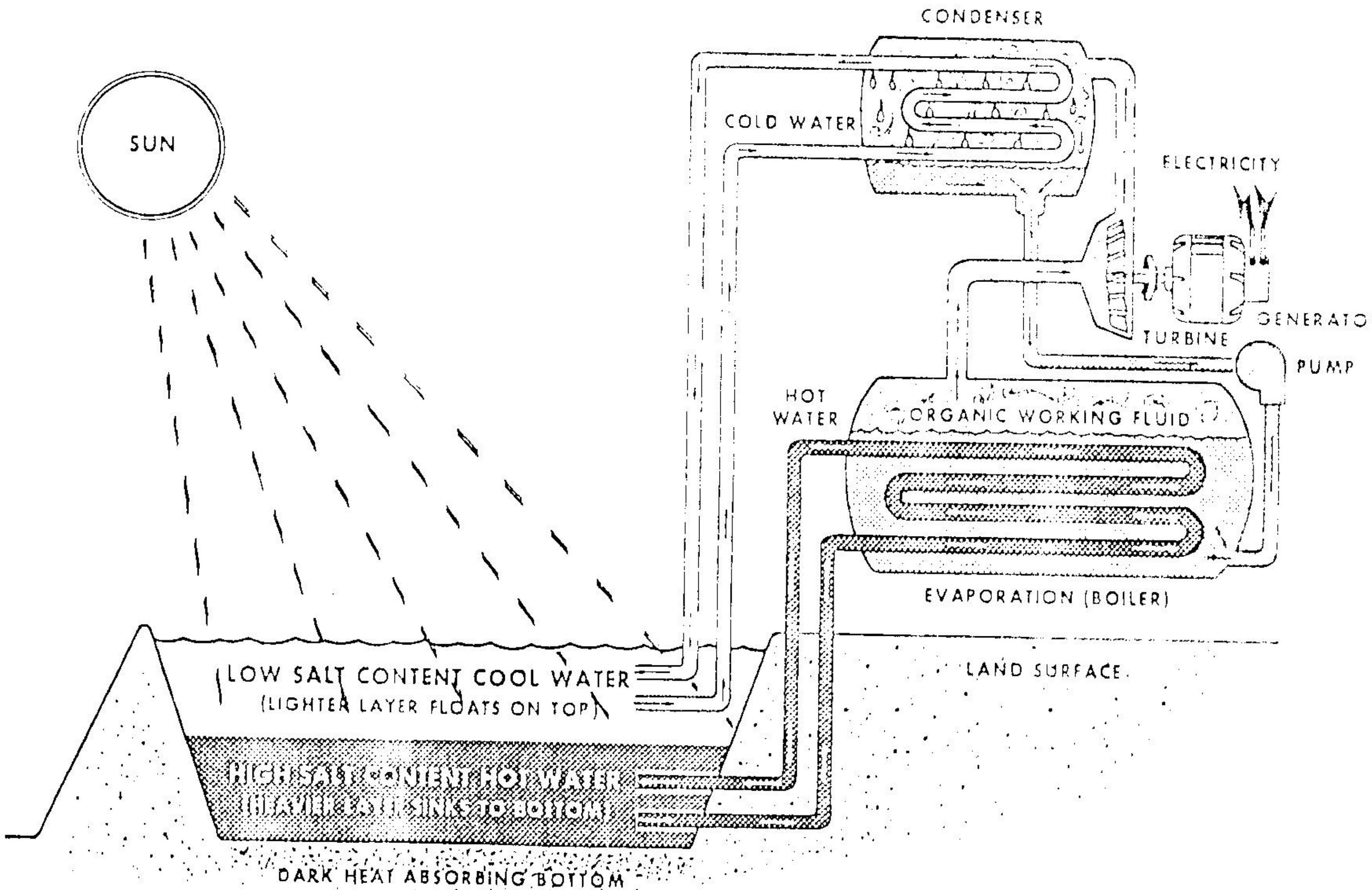

Fig. 6 Electricity Generation System Using Salt-Gradient Pond