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SOLAR PONDS: RESEARCH, APPLICATIONS AND DEVELOPMENT

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ABSTRACT

A description of the status of solar pond research applications and development is provided. Shallow ponds, gel ponds, saturated ponds and salt-gradient ponds are discussed, and many existing ponds in various countries are described. Ongoing field and laboratory work associated with solar ponds is discussed in relation to residential, commercial, industrial and agricultural applications of pond generated heat. Other present or future applications of salt-gradient ponds such as electricity generation, irrigation water pumping and the more recent absorption and dehumidification cooling are presented. Pond construction and operation, including costs, are discussed and schematic diagrams are used to illustrate textual explanations. An extensive list of references treating theoretical and practical aspects of pond research, applications and development is also provided.

1. INTRODUCTION

Fossil fuels do not exist as a natural resource 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 most of them face. Solar ponds, during the last few years, have received special attention as one of the solar technologies which have the potential to be economically and technically competitive with energy conversion technologies which use fossil fuels (see Fig. 1). Solar ponds could, therefore, improve the energy situation of some countries.

In addition to their low cost, some solar ponds such as the salt-gradient type offer built-in storage. This makes them independent of the intermittence of solar radiation. Yet, it is the shallow solar ponds, first introduced in the mid-seventies by Lawrence Livermore Laboratory of California, that appear to be the most developed and market ready as illustrated by several publications on the theoretical and practical aspects of shallow solar pond use, including applications for generating industrial process heat [1-6]. The construction methodology of shallow ponds [7] and their thermal performance testing have been described in detail [8,9]. In one innovative concept that has

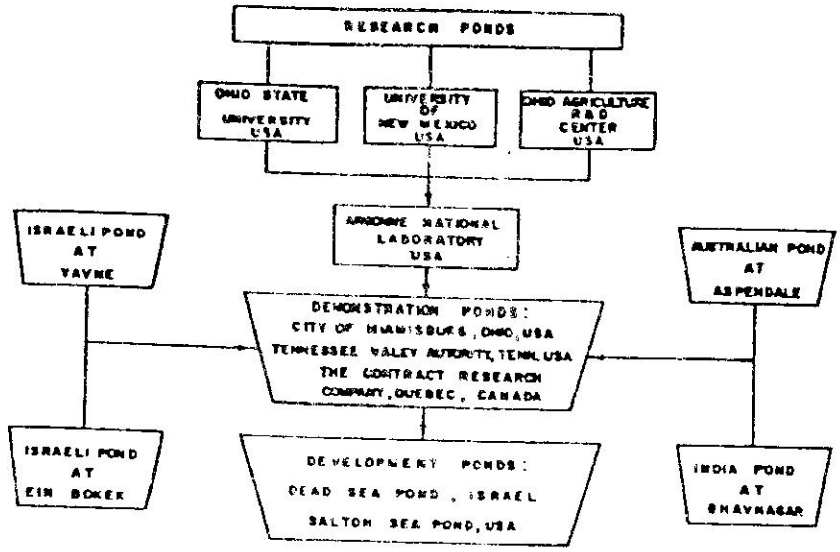

Fig.1. Solar Pond Activities

been tested a shallow solar pond's performance was enhanced by placing a mirror on its north side [10]. In a theoretical study on pond sizing and design optimization, the simulation and modeling of a shallow solar pond was performed by using the TRNSYS program [11].

Although the economics seem to be in favor of shallow solar ponds [2,12], the demonstration program for them was limited since applications are restricted mainly to users in the South and the Southwest of the U.S. . For this reason shallow pond technology does not contribute much toward developing the mass production of solar equipment and the commercialization of solar technology. However, a renewed interest in shallow solar ponds seems to be taking place, particularly for applications in the Caribbean.

The concept of collecting and storing solar energy by means of salt-gradient ponds, also known as nonconvecting solar ponds, was derived from research on natural salt lakes [13]. Salt-gradient solar ponds reached the application level in recent years, although some aspects of their construction, operation and maintenance are still in the research and development stage. Some of the most important work on salt-gradient ponds was done in Israel [14,15]; the concept of ponds generating process heat was introduced there in the mid-fifties. The continuation of this work in Israel and elsewhere resulted in several review papers and reports that treat the current status of technology, the cost, and the physical and thermal phenomena which occur in salt-gradient solar ponds [16-21]. The physics of salt-gradient solar ponds is the subject of theoretical and experimental studies [22,23]. Detailed descriptions of pond sizing methodology [24,25] and knowledge of material selection, site preparation and pond construction techniques are available for medium and large size ponds [26-48] and small laboratory ponds [49-52], because of the work of many researchers. Experimental aspects of salt-gradient pond instrumentation have been investigated [53] and theoretical studies of modeling and simulation have been performed [54-62]. In addition, several innovative pond concepts have been proposed [63-68].

Salt-gradient pond applications that have been studied and/or implemented include absorption and dehumidification cooling [68], commercial and residential space heating [69-71], district heating and cooling [72,73], low temperature (between 50°C and 70°C) industrial water heating [74], agricultural process heat production for grain drying [75], and greenhouse heating [76-79]. Other applications include using salt-gradient solar ponds for salt production enhancement [80-82] and electricity generation [83-87]. The pumping of irrigation water is another area in which salt-gradient solar ponds can be used effectively.

Some laboratory investigations have also been done on saturated salt ponds [88-91] and gel ponds [92,93]. Both of these 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.

The 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 [94-99]. The economics 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 cost. Selected research, applications and development efforts in the field of solar ponds are described below to provide a comprehensive description of the present status of solar pond work.

2. 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.

A cross-sectional view of a shallow solar pond is shown in Figure 2. 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.

The first shallow solar pond system, designed and operated by Lawrence Livermore Laboratory of California, was built in 1975 near Grant, New Mexico [2,3,12]. The pond system consisted of two modules of 220 sq. m. (2400 sq. ft.) 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

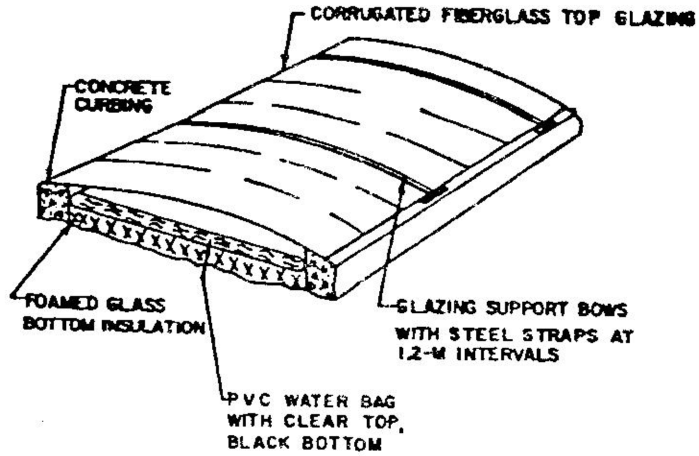

Fig.2. Cross-Sectional View of Shallow Solar Pond Module.

shallow pond modules operated on a stand-alone basis without being interfaced with the plant hot water system. Each pond module heated 25 tons of water per day to about 54°C (130°F) in the summer and to about 35°C (95°F) in the winter. A twelve-month performance survey of the system operation indicated that the solar ponds operated with an annual average energy collection efficiency of about 45 percent and collected close to 9.37 x 10^6 Joules/m^2-day (825 Btu/ft^2-day).

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 percent salt content while the bottom layer (lower convective zone) has a content as high as 23-27 percent 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 upper convective zone. In this way, the use of a salt pond eliminates the separate thermal storage that is normally required in many solar installations.

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 in relation to some of the physical phenomena occurring in the pond, and on the pond operation and maintenance [28]. A second salt-gradient solar pond of 408 sq. m. (4390 sq. ft.) area was installed at Ohio State University in 1979 [35,36]. 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

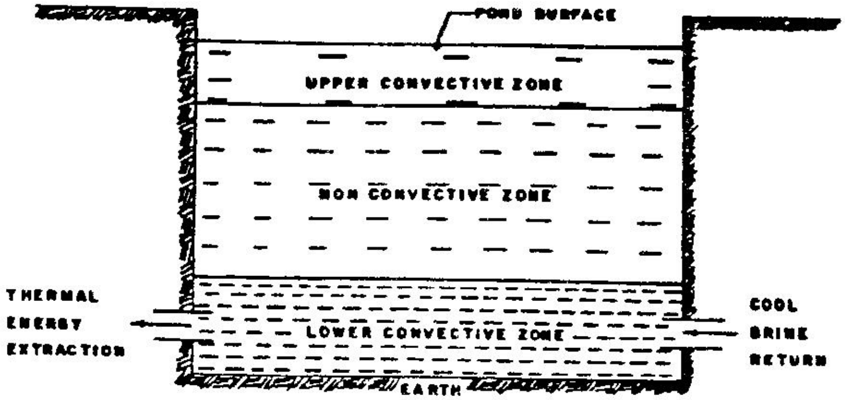

Fig.3. Cross-Sectional View of Salt-Gradient Solar Pond

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.

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 [76-78]. 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 [27]. 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 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 Southwest region. The same pond reached a boiling temperature of 108°C (226°F) during the summer of 1980.

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 Great Salt Lake [34]. 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 mph) 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 [25,42]. The pond has an area of 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 base to assess the salt-gradient pond as a heat collection and storage system for various types of applications, and to set up an operation for a future U.S. solar ponds program. This pond is very well instrumented and has already provided data that can be used 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 [34,37,43]. This pond works in conjunction with a 2484 sq. m. (26724 sq. ft.) evaporation pond which is 1.2 m. (4 ft.) deep and has walls tapered at 34°. The TVA pond is extensively instrumented and 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.

One of the most recently installed ponds is a 234 sq. m. (2518 sq. ft.) salt-gradient solar pond that was built in June, 1982 at Los Alamos National Laboratory in Albuquerque, New Mexico [48]. The pond depth is 3.6 m. (11.8 ft.) and the walls are vertical. Two liners were used for the pond construction; the first one is 1.2 mm. (45 mil) thick main hypalon liner and the second one is 0.5 mm. (20 mil) thick 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 a brine salinity of 21 percent at the pond bottom, about 127 tons of 98 percent pure, granular NaCl were used. The salt was dissolved by using a local fire hydrant; further salt mixing was done by using a couple of pumps of about 400 liters/min. (105 gal./min.) capacity each. The salt gradient was established by lowering the diffuser to a depth of 1.2 m. (3.9 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 2.4 m. (7.8 ft.). At this point another 10 cm. (3.9 in.) of fresh water was added at the top of the pond. In this way the pond reached the chosen a priori parameters of a 1.2 m (3.9 ft.) thick lower convective zone, a 1.2 m. (3.9 ft.) thick nonconvective zone and a 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 percent 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 imbedded 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. The pond is mainly used to study the boundary layer structure at the interface between the convecting and nonconvecting zones, interactions between the zones, durnal heating effect, and wind-induced turbulance.

The Los Alamos salt-gradient pond works in conjunction with an evaporation pond of 257 sq. m. (2765 sq. ft.) and a depth of 1.4 m. (4.6 ft.). All the walls of this pond are vertical except the west wall which is sloped at a 16° angle to create a ramp for salt removal and pond maintenance.

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 0.9-1.5m. (3-4 ft.), and vertical walls [74]. This pond will work in conjunction with an evaporation pond of the same area but of half the depth. 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.

Salt-gradient solar pond research is also being done at the Massachusetts Institute of Technology. The work here is primarily directed toward the development of a numerical model to predict time-dependent vertical temperature and salinity profiles in salt ponds. Wind mixing is also being studied by using a one-dimensional numerical model DALT1 [60].

Laboratory research work on salt saturated ponds has been done by the Desert Research Institute in Nevada using borax as salt, and by Inter Technology Company in Virginia using disodium phosphate as salt [90]. In the former case, the area of the pond built in 1979 was 10 sq. m. (108 sq. ft.) with a depth of 1 m. (3.28 ft.); in the latter case, the pond area was 0.37 sq. m. (3.7 sq. ft.) with a depth of 0.91 m. (3.0 ft.). 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 ponds tested had the property of being self-established and maintained a 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 could 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 the operating conditions of large size production ponds.

Experiments using disodium phosphate in a saturated pond in a laboratory environment were also conducted in 1982 at Inter Technology Company under a contract with Jet Propulsion Laboratory [91].

Research on gel ponds has been conducted at the University of New Mexico since 1981 using an experimental pond of 18.7 sq. m. (201 sq. ft.) [92,93]. 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 a pond containing a 25 cm. (9.9 in.) 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, research indicates that a 15 cm. (6 in.) 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 internal or external heat exchangers.

<u>In Israel</u>, research on salt-gradient solar ponds has been underway since 1954, the year the concept was conceived there [20]. 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.) area and a depth of 2.5 m. (8 ft.) was installed in Ein Bokek by the Dead Sea in 1978 [94,96,97]. When the temperature of the storage layer reached 80°C (176°F) the pond started to produce electricity by 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 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 at the Brace Research Institute in Montreal [50]. A cross-sectional view of this pond is shown in Figure 4. The same year an experimental pond was implemented by the National Research Council of Canada. 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 a solar pond in preparation for the design and operation of a larger production pond. The National Research Council of Canada finances this research for developing equipment and procedures for automating the operation and maintenance of a salt-gradient pond.

In Australia, 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 studying the pond's thermal efficiency, the sealing techniques and the control of the salinity gradient, were published in the form of a report [26]. The second salt-gradient solar pond was built by the University of Melbourne in 1981 for research purposes [40]. The pond area is 240 sq. m. (2582 sq. ft.). Research is focused on the stability of the salt gradient, the methodology of pond filling and the computer simulation of thermal phenomena. In 1981 a 2000 sq. m. (21520 sq. ft.) salt-gradient solar pond was built in Alice Springs.

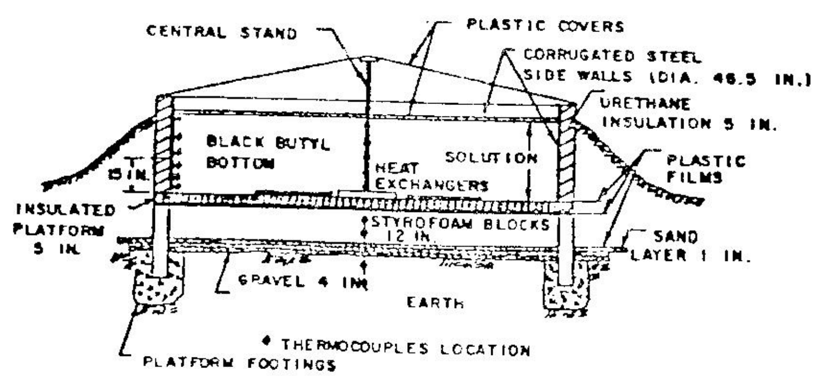

Fig.4. Cross-Sectional View of Salt-Gradient Research Pond

In Saudi Arabia, a research pond of 4 sq. m. (45 sq. ft.) and 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 [52]. 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.

In India, a salt-gradient solar pond of 100 sq. m. (1075 sq. ft.) and a depth of 2.25 m. (7.4 ft.) was built in 1980 by Tata Energy Research Institute in Pondicherry [38]. The pond has vertical walls and works in conjunction with an evaporation pond of 50 sq.m. (538 sq. ft.) area and a depth of 0.3 m. (1 ft.). 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 the behavior of the stratification layer. Experience was gained about which locally available materials can be used to build a pond and about pond construction and operation costs in India's rural environment.

3. APPLICATION ACTIVITIES

The most immediate applications of solar ponds seem to be for space heating and for water heating/reheating 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). A schematic diagram of a possible salt-gradient solar pond system is shown in Figure 5. In tropical climates such as the Caribbean, salt-gradient ponds may be used in the future for dehumidification cooling as proposed by Bonnet et al. [68].

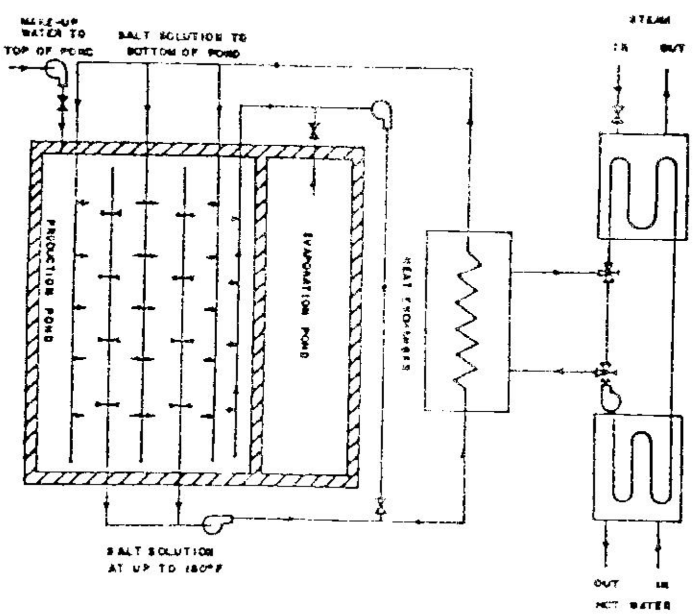

Fig. 5. Schematic Diagram of Salt-Gradient Solar Pond System

In the United States in March, 1983 a shallow solar pond system was installed to supply 2000000 liters (528401 gal.) of hot water per day to two army barracks and the laundry at Fort Benning in Georgia [19]. A total of 80 modules having an area of 25000 sq. m. (269000 sq. ft.) 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, 1892500 liter (500000 gal.) capacity steel tank is used for hot water storage. The system is located 1402-1463 m. (4600-4800 ft.) from the end use and the hot water is distributed by 15 cm. (6 in.) diameter PVC pipes. The installed system cost was $4110000 with a construction cost of $4000000 and a design cost of $110000 which gives a total cost of $164/sq. m. ($15.28/sq. ft.).

A shallow solar pond of 22 sq. m. (240 sq. ft.) and a depth of 2.54 cm. (1 in.) was installed in January 1983 on the roof of a high school in Mayaguez, Puerto Rico, to deliver daily 40 liters (150 gal.) of hot water at the temperature of 60°C (140°F) to the school cafeteria [74]. Another shallow solar pond of 40 sq. m. (430 sq. ft.) area and a depth of 7.6 cm. (3 in.) is planned to be built to heat water for showers at the swimming pool facility at the Mayaguez Campus of the University of Puerto Rico. The project specifications call for heating 3028 liters (800 gal.) of water to a temperature of 43°C (110°F) daily. The solar pond system could reduce the electricity consumption of the electric water heater by 75 percent. A schematic diagram of a typical shallow solar pond system is shown in Figure 6.

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 [30,31,33,41]. The pond depth was 3.0 m. (10 ft.) and the walls were tapered at an angle of 45°. Polymer-coated polyester liner XR-5 0.7 mm. (35 mil.) thick and sodium chloride as salt were used. The energy storage layer had a thickness of 1.75 m. (5.7 ft.) and contained brine of 18.5 percent concentration. The temperature required at the end use was 25°C (77°F). The maximum temperature reached by the storage layer of the pond was 65°C (149°F) during the summer of 1979. The pond was equipped with a heat exchanger made out of copper tubing of 2.54 cm. (1 in.) diameter which was placed at the bottom of 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 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 [75]. 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 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

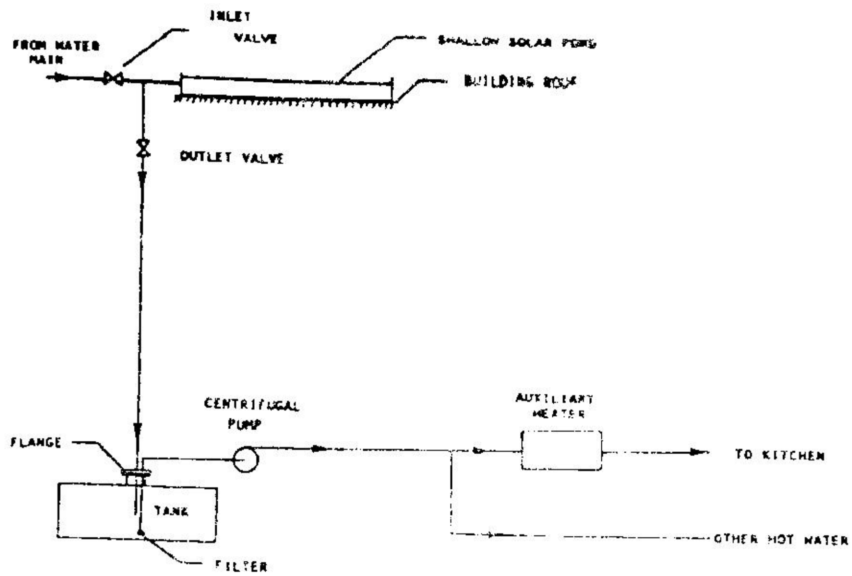

Fig.6. Schematic Diagram of Shallow Solar Pond System

100 kilowatts (3.4 x 10^5 Btu/hr) during the fall of 1981. The construction cost of this pond was below \$50/sq. m. (\$4.6/sq. ft.), excluding the land cost.

In Portugal, a salt-gradient solar pond was built in Lisbon to heat a greenhouse complex belonging to the Portuguese Ministry of Agriculture [79]. The pond has an area of 1024 sq. m. (11018 sq. ft.), a depth of 3.60 m. (11.8 ft.) and walls sloped at a 45° angle. The pond uses 1 mm. (40 mil.) thick hypalon liner and sodium chloride as salt. A heat exchanger, used to extract heat from the pond, consists of four sections, 2.4 m. x 5.0 m. (7.9 ft. x 16.4 ft.) each, made out of galvanized 2.54cm(1 in.)O.D. iron pipe. The heat exchanger was designed for an expected peak energy extraction rate of 50 kW. A diffuser that is used for maintaining the salinity gradient consists of a galvanized iron tube of 7.6 cm. (3 in.) O.D. welded to a 1.2 m. x 1.2 m.(3.9 ft. x 3.9 ft.) plate attached to another plate of the same dimension in such a way as to form a space of 1.6 cm. (0.6 in.) between both plates. The pond is extensively instrumented with thermocouples, salt solution and soil conductivity probes, underwater and surface pyranometers and wind measuring instrumentation. A 16 sq. m. (172 sq. ft.) evaporation pond was built as part of the overall salt-gradient pond system.

In Argentina, a 400 sq. m. (4304 sq. ft.) salt-gradient solar pond was built in 1982 in Salta to purify sodium sulphate salt by using a natural evaporation process [82]. The pond has vertical walls, a depth of 2.4 m. (7.9 ft.) and a solution depth of 1.5 m. (4.9 ft.). The pond was instrumented by placing several thermocouples in the solution at different depths at three locations across the pond. To detect leaks an electric wire mesh was formed by two layers of wire under the pond. This wire mesh shortcircuited, because of water condensing under the pond, and could not be used to detect leaks. A layer of clay was used to smooth out the pond walls, and 10 cm. (3.9 in.) of sand was put on the pond bottom before installing two layers of black polyethylene, each 0.25 mm. (10 mil.) thick. The pond was filled with 50 cm. (1.6 ft.) of water, and then 250 tons of mineral salt to be purified were thrown into the pond. To establish, and later control, the salt gradient a diffuser consisting of two metal plates, separated by a 0.25 cm. (1 in.) space and shaped as a half disk 45 cm. (1.47 ft.) in diameter, was used. To establish the salt gradient the diffuser injected 2.5 cm. (1 in.) of fresh water several times, moving up 5 cm. (2 in.) each time. The water velocity was about 1 m/sec. (3 ft/sec.). About 10 kg. (22 lbs) of copper sulphate was added to the pond to eliminate algae growth. After twenty days the pond solution was very clear again. After forty days the pond bottom reached a temperature of 46°C (115°F), and a linear density gradient of 1.32 g/cm^3 at the bottom and 1.05 g/cm^3 on the surface was established. The water evaporation rate from the pond has been 3 to 5 mm. (0.12 to 0.2 in.) per day. The pond produces 8.5 tons of industrial grade sodium sulphate salt every three days.

4. DEVELOPMENT WORK

The development work at present is taking place mostly in 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 large amounts of hot water, heat and/or electricity, on selection of materials and components to assure durability and reliability, and on automation of operation and maintenance. Two typical development projects, one taking place in Israel and one in the United States, can be mentioned as the most advanced.

In Israel the development plan of salt-gradient pond technology 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. It is expected that by 1990 solar pond electric 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 Israel could be ready by the end of this century to operate a Dead Sea pond of about 500 sq. km. (190 sq. mi.) which may supply up to 2000 MW of electric power by using a series of modular units of 50 MW_e each [94,96,97].

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 [95,98,99]. The concept of this project is presented in Figure 7. 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. Electric power generation from the low temperature heat provided by the salt-gradient pond can be accomplished by using an organic fluid turbogenerator as shown in Figure 8. The 5 MW_e plant will

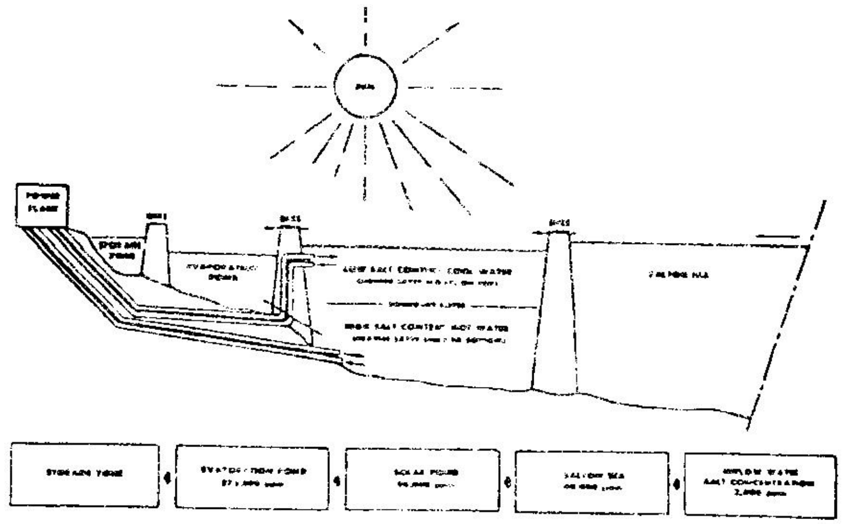

Fig.7. Cross-Sectional View of Salton Sea Pond

probably cover 1 sq. km. (0.4 sq. mi.) and cost \$4,000/kW_e. The 600 MW_e commercial plant will cover 120 sq. km. (46 sq. mi.) and cost \$2,000/kW_e. On the base of a 30-year operation period, the cost of electricity is projected to be \$0.075 to \$0.08/kWh (1980 dollars).

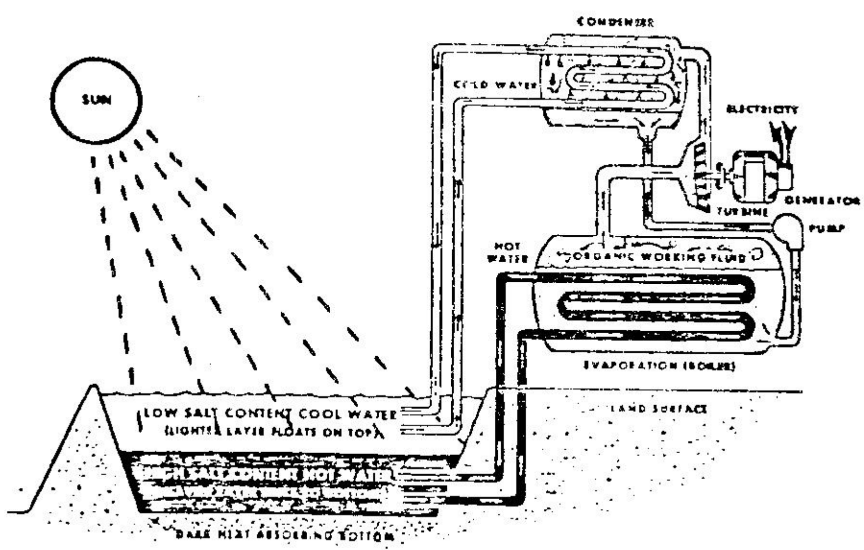

Fig.8. Schematic Diagram of Electricity Generation System Using Salt-Gradient Solar Pond

5. CONSTRUCTION, OPERATION AND COST

The largest salt-gradient production pond in operation has an area of 2044 sq. m. (21993 sq. ft.). The largest shallow pond constructed has an area of 25000 sq. m. (269000 sq. ft.). Pond shapes vary from circular, for small size salt-gradient research ponds, to rectangular (east-west oriented) or square, for large ponds. The latter are usually built in modular units to provide the required thermal/electrical capacity. Before building a pond, a 6-9 m. (20-30 ft.) core sampling should be made to test the soil composition and permeability. The thermal conductivity of the soil around the pond can vary between 1 and 2.5 Watts/m°C. It is recommended to test the soil thermal conductivity and to determine the existance of movable underground water.

Borax, disodium phosphate and sodium sulphate have been experimented with and studied as possible salts for saturated ponds. Sodium-chloride is the salt usually used in salt-gradient ponds, although magnesium-chloride is being used in Israel since it is commonly available there. Refined salt of 95 percent or more purity should be used. The type of salt is of significance (NaCl, MgCl, CaCl, etc.) because of the brine transmissivity factor, and because the salt solubility changes with temperature. About 45 kg. (100 lbs.) of salt per approximately 0.1 sq. m. (~1 sq. ft.) of pond area are needed to obtain the right salt concentration in the lower convective zone. Out of this 0.45-0.90 kg. (1-2 lbs.) per 0.1 sq. m. (~1 sq. ft.) per year will diffuse upward.

Diffusers are used to establish the vertical salinity gradient. This is done by lowering the diffuser to the boundary limits of the lower convective zone; this zone should be previously established by dumping salt at the pond bottom and mixing it with fresh water. In the next step, a layer of fresh water a few centimeters thick (5-10 cm.) is added. This procedure is repeated until the water level in the pond reaches the mark chosen as the pond depth. A similar process is used to maintain and repair the salinity gradient.

A diffuser can be made out of two 1 meter (3.28 ft.) diameter disks made of a noncorrosive material such as plexiglass a few centimeters thick. The gap between the disks and the supply water flow rate should be such as to assure a water velocity from the gap in the range of 0.25-1.0 m/sec. (0.7-3 ft/sec), depending on the pond size. For a 1/4 acre size pond two diffusers located in opposite corners of the pond may be adequate to perform the gradient maintenance work, but in the case of a 1/2 acre pond four diffusers may be necessary. The amount of solar radiation penetrating to the pond bottom can vary between 20 and 40 percent. The thermal efficiency of a large size (1/2 acre) salt-gradient solar pond is usually in the range of 15 to 20 percent, although it could be as low as 9 percent for small size laboratory ponds where high heat losses occur. An operational pond temperature of about 60°C (140°F) with temperature fluctuations of ±10°C (±23°F) can be expected. The pond upper convective layer usually has 1-4 percent of salt and the lower convective layer has 23-27 percent of salt by weight.

When an internal heat exchanger is used the rule of thumb is that about 37 m. (122 ft.) of heat exchanger piping length is needed for every 20 kW of thermal power extraction from the pond. The heat exchanger piping should form a serpentine configuration and be located in the lower convective zone. Copper and brass piping are often used as heat exchangers. To assure the reliability of heat extraction from the pond and equipment durability, a stainless steel heat exchanger and leak proof pump may be recommended. A galvanized iron pipe heat exchanger will corrode easily when the saturated solution level comes down below the heat exchanger and exposes the piping to a non-saturated water-salt solution. Because of the scarcity of information about metal corrosion in solutions of high salt concentration, however, an external heat exchanger may be more suitable for a heat extraction system, especially for large size ponds. If an external heat exchanger is used, an effort should be made to prevent any air leaks in the external piping or in the pump, because air bubbles will be introduced into the lower convective zone. A continuous injection of air bubbles could destroy the salinity gradient in the pond. To assure the effective maintenance of the salinity gradient zone, the injection of 2-5 kg/sq.m.(4.4-10 lbs/sq.ft.) of salt per month may be required. This should be done just below the boundary of the upper convective zone since this zone has a tendency to grow thick, a process which leads to the destruction of the temperature gradient in the pond. Usually PVC valves and PVC piping are used to carry the brine to an external heat exchanger.

Another rule of thumb is that 1-2 kg. (2.2-4.4 lbs.) of chlorine per week per each 1000 sq. m. (10760 sq. ft.) of pond area may be needed to prevent algae build-up in the pond.

An evaporation pond often works in conjunction with the production pond. The evaporation pond, up to half the size of the production pond, serves to produce highly concentrated brine which is injected into the production pond to maintain the salinity gradient. The evaporation pond can also be used to take care of the rain water overflow from the production pond. Both ponds may have vertical walls or 45° sloped walls. The latter, however, can increase heat losses through thermal convection at the walls.

Heavy-duty plastic liner made from chemically resistant polymer-coated polyester fabric, vinyl liner, EPDM liner, or XR-5SP hypalon fiberglass reinforced liner seem to work satisfactorily. The second liner (back-up liner) is usually thinner and also cheaper. Beach sand is recommended for use in a 10 cm. (3.9 in.) thick layer at the bottom of the pond and between the liners. The pond bottom and/or walls sometimes are thermally insulated as well. Floating PVC pipes can be used to suppress wind disturbances on the pond surface.

Detecting and locating leaks is one of the most difficult problems in a salt-gradient solar pond. Most often the leaks occur in seams of the liner. To locate a leak in the pond either a scuba diver is used or the following method could be employed: a length of perforated rubber or plastic hose in a serpentine arrangement is buried in the sand layer between the liners during the pond construction. The hose is plugged at the buried end and runs above ground at the other end. Upon suspecting a leak, by routinely checking the salt inventory in the pond, compressed air or nitrogen is introduced into the hose with sufficient pressure to equal the hydrostatic pressure at the bottom of the pond. The leak locations are found by locating gas bubble streams on the pond surface. A sump pump could be connected to the hose to evacuate the leaking solution from beneath the liner. The same pump can also be used to evacuate the brine from the lower convective layer to the evaporative pond; usually it is necessary to empty the pond to patch up the liner.

Recalibrated platinum electric conductivity probes are used for salinity gradient measurement. Probes of the same type are used for leak detection between liners. Copper-constantan thermocouples in stainless steel or vinyl jackets are normally used for ground temperature measurement. Platinum resistance thermometers, e.g. 100 Ohm RTDs, are used for pond temperature measurement.

Generally the present cost of man-made salt-gradient ponds is in the range of $50 to $100/sq. m. ($4.60 to $9.30/sq. ft.). Naturally occurring salt lakes can be converted into ponds at a cost much below $50/sq. m. ($4.60/sq. ft.). The major capital costs are for salt, liner, excavation and heat extraction equipment. The salt cost can be up to half of the total cost. When a salt lake is used as a solar pond for 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, such as countries in the Middle East, the cost of water for the pond make-up operation may not be negligible, and in others, such as the islands of the Caribbean region, the cost of land may be an important factor. Pond depth ranges from 0.9 m. to 4.5 m. (3 ft. to 14 ft.) with deeper ponds being used in areas where seasonal heat extraction is required. Energy costs between $6.60 and $9.50/GJ ($7 to $10 per million Btu's) are projected for large size production ponds with an area of 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 to $205/sq. m. ($14 to $19/sq. ft.).

5. CONCLUSIONS

Solar ponds are technically feasible and can be economically competitive, as proven by some users. Building an experimental pond may be a necessary first step to gain direct experience and to demonstrate engineering proof of the concept. However, out of the 25-30 small and large demonstration ponds which have been built around the world, only about seven are production ponds. Therefore more production ponds should be built to gain market acceptability through the reliable and economical operation of large size ponds integrated into industrial, commercial or agricultural processes.

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

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