MASTER

THE 1980 INTERNATIONAL SYMPOSIUM ON SOLAR ENERGY UTILIZATION

MLM-2770 (OP)

CONF-800871--1

AUGUST 10-24, 1980

AT

THE UNIVERSITY OF WESTERN ONTARIO
LONDON, ONTARIO, CANADA

SALT-GRADIENT SOLAR PONDS: DESIGN, CONSTRUCTION AND POWER PRODUCTION

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ABSTRACT

Salt-gradient solar ponds are combined solar energy collectors and thermal storage systems. The ponds are made non-convective by the formation of a density-gradient composed of salt solutions whose concentrations increase with depth. The depth of the various layers of the pond determine the efficiency and thermal storage capacity of the system. The construction of the largest such pond in the U.S., 2000 m^2, was completed in 1978 for approximately $\$35/m^2$. The pond is estimated to produce 1015 GJ/yr of low-temperature heat at a cost of \$8.95/GJ, when the installation costs are amortized over 15 yr. Construction changes are suggested to improve the reliability of the system. Electrical power generation by the use of Rankine cycle turbogenerators connected to solar ponds has been demonstrated in Israel. Feasibility studies are in progress to propose electricity production of up to 2,000 MW for projects near the Dead Sea in Israel, and 600 MW in a proposed project at the California Salton Sea.

KEYWORDS

Solar ponds; salt-gradient; solar collector efficiency; thermal storage; construction; cost evaluation; performance; electrical power production; Dead Sea; Salton Sea.

INTRODUCTION

The solar ponds considered here are bodies of water of sufficient depth that they are combined solar energy collectors and thermal storage systems. Such solar ponds must be made non-convective, otherwise the water temperature closely follows the ambient air temperature. The ponds are made non-convective, in this instance, by the dissolution of salts whose concentration and density increase with depth.

Natural salt-gradient solar ponds have been located in several areas of the world. The utilization of artificial solar ponds as a renewable energy source was described

*Mound Facility is operated by Monsanto Research Corporation for the U. S. Department of Energy under Contract No. DE-AC04-76-DPO0053.

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by H. Tabor (1963) in Israel. An adequate physical model of the solar pond was given by Weinberger (1964). Experimental work in Israel ceased for a period but has been recently revived with the construction of a 7500 m^2 pond near the Dead Sea. The hot water from this source has been used to power a Rankine cycle turboelectric generator.

Studies of solar ponds for the heating of buildings were introduced by Rabl and Nielsen (1975) in the U.S.A. approximately ten years ago. Dr. Nielsen (1980a) constructed several research ponds at the Ohio State University. Another research pond has been in operation at the University of New Mexico (Zangrando and Bryant, 1978). The utilization of such a pond for agricultural purposes is being demonstrated at the Ohio Agricultural Research Center (Short, Badger and Roller, 1979). The largest pond in the U.S., 2000 m^2, was constructed by the City of Miamisburg, Ohio, in 1978 for use in a recreational complex (Bryant, Bowser and Wittenberg, 1979).

This article will briefly review the physics of these ponds; describe the construction and initial operation of the Miamisburg pond; and indicate some of the large-scale projects being proposed for such ponds.

PHYSICS OF SOLAR PONDS

Hydrodynamic stability. The concept of such ponds relies upon the formation of non-convective layers; solar radiation, which is transmitted through these layers, heats the water near the bottom of the pond but this hot water cannot rise to the surface. As a result, the solar energy is stored in the form of hot water near the bottom of the pond. In order to establish the non-convective layers, salt solutions of various concentrations are formed so that the density of the water increases with depth (Fig. 1). Stability in such a pond is obtained, therefore, when the density gradient (of the salt solutions) exceeds the thermal expansion of the hot water. This is expressed by the relationship (Weinberger, 1964).

$$\frac{d\rho}{dx} = \frac{d\rho}{ds}\frac{ds}{dx} + \frac{d\rho}{dT}\frac{dT}{dx} \geq 0 \qquad (1)$$

where ρ = density
x = depth (m)
s = salt concentration
T = temperature (K)

Because $(d\rho/dT)$ is negative for most common salt solutions, it is desirable to have (ds/dx) as large as possible. One method of achieving a large concentration change with depth is to select a salt whose solubility increases rapidly with temperature and, then, operate near the solubility limit. A review of candidate salts, Fig. 2, (Edesess, Benson, Henderson and Jayadev, 1979) indicates that over limited temperature ranges, sodium sulfate and sodium carbonate would be likely candidates for use in "saturated salt-gradient ponds;" however, only limited experiments have been performed with such salts. Nearly all ponds constructed thus far have used sodium chloride, because it is relatively cheap and widely distributed throughout the world; however, the ponds in Israel which use water from the Dead Sea are predominantly magnesium chloride brines.

Returning to Eq. 1, one finds that for sodium chloride solutions (which will be considered in the remainder of this paper), the density gradient can support a temperature differential of 100°C when the concentration increases approximately 5 wt % from the top to the bottom. A pond constructed on this stability criterion is shown, however, to be unstable to oscillatory motions which are induced by the diurnal heating of the pond or severe wave action at the surface. A pond must be stable, therefore, both hydrodynamically and diffusionally, to the double-diffusive actions of heat and salt. The relationship between these variables can be expressed as (Weinberger, 1964),

$$(\nu + \alpha) \frac{d\rho}{dT} \cdot \frac{dT}{dx} + (\nu + \alpha') \frac{d\rho}{ds} \cdot \frac{ds}{dx} \geq 0 \quad (2)$$

where ν = kinematic viscosity
α = thermal diffusivity
and α' = salt diffusivity.

For most salt-water solutions the ratio $\alpha/\alpha' > 10^2$. As a result, the solution returns to thermal equilibrium much faster than to salt concentration equilibrium so that the oscillatory motion increases in amplitude with eventual destruction of the density gradient. For these reasons, the salt concentration required for dynamic stability is much larger than the simple relationship expressed by Eq. 1. Based upon recently compiled values for the physical properties of saline waters, it has been estimated (Elwell, Short and Badger, 1977) that a concentration difference of 12% is required to stabilize a temperature difference of 100°C in a pond.

An idealized pond, in which the density gradient varies continuously from top to bottom, and which is exposed to wind action and diurnal heating by the sun, is unstable, however, and divides into three horizontal layers, as shown in Fig. 1. An upper convective zone, UCZ, develops which is usually 20-30 cm thick and whose temperature follows the air temperature. In order to maintain the salinity gradient, the surface of the UCZ must be flushed with fresh water. Below the UCZ is the nonconvective zone, NCZ, approximately 1 m thick. Below this NCZ is the lower convective zone, LCZ, where the thermal energy is stored. The thickness of the LCZ can be varied in order to change the thermal storage capacity of the pond. The NCZ effectively forms the insulation for the LCZ.

Additional hydrodynamic instabilities occur at the UCZ/NCZ and NCZ/LCZ boundaries, as a result of the convective flow in the two convective layers. This erosion is much larger (at these boundaries) than the stability criteria implied by Eq. 1 or Eq. 2. Because no suitable model has been developed to describe the instability, Nielsen (1979) has derived an empirical relationship based upon numerous observations of his research ponds and small tanks. His relationship for stationary boundaries is approximated by,

$$G_T = 5 \times 10^{-3} (G_C)^{1.6} \quad (3)$$

where G_T = temperature gradient (°C/m)
and G_C = concentration gradient (kg NaCl/m^4)

By use of this relationship, one finds that sustaining a temperature gradient of 100°C/m requires a concentration gradient of 30% saline solution, which exceeds the solubility limit for NaCl solutions. In order to make the zone boundaries as stable as possible without requiring excessively high saline solutions for the entire pond, Nielsen is conducting experiments with the injection of high concentration saline solutions just at the zone boundaries.

Thermal Performance. Thermal performance evaluation must consider the pond both as a solar collector and thermal storage system. Because the mass of the storage system is so large compared with the daily insolation, variations in the daily insolation or heat use are not important. Only monthly averages are needed to calculate the thermal performance.

Heat is supplied to the pond only by the solar radiation which penetrates the UCZ and the NCZ and is absorbed by the LCZ. Heat is lost from the LCZ either by being removed as useful heat, or by thermal diffusion upward through the NCZ or to the ground at the

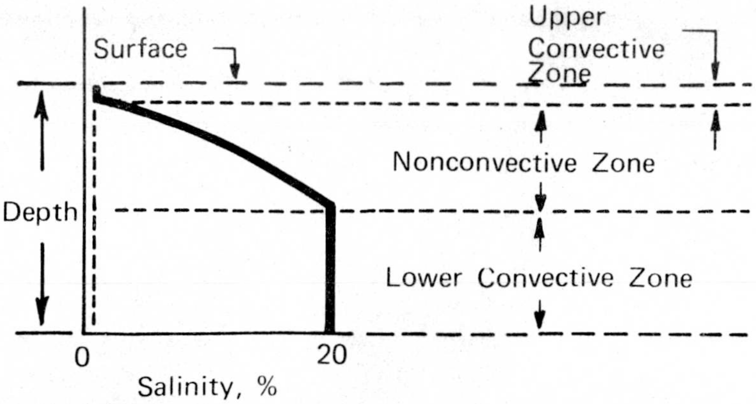

Fig. 1. Schematic cross-section of a salt-gradient solar pond.

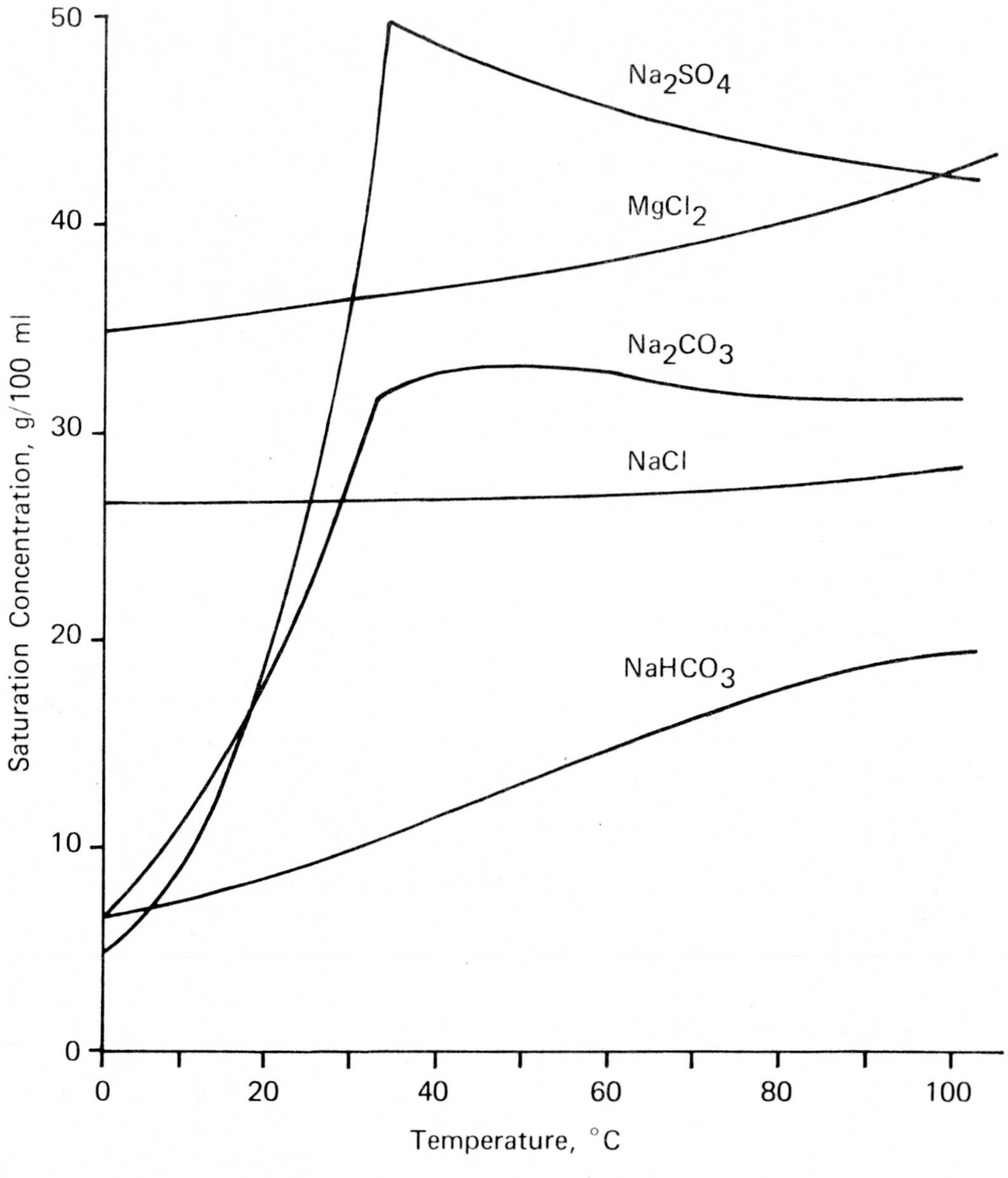

Fig. 2. Aqueous solubility of some common salts as a function of temperature (Edesses, 1979).

sides and bottom of the pond. For the moment, we will ignore the losses to the ground and consider only the steady-state, which is approximated in most large ponds over a period of several days. Let x_1 = the depth of the UCZ/NCZ boundary, x_2 = the depth of the NCZ/LCZ boundary and x_3 = the total depth of the pond. Then, q, the net heat flux into the LCZ (W/m^2 of surface area) is given by the relationship (Kooi, 1979),

$$q = Hh(x) - K_w (dT/dx)_{x_2} \tag{4}$$

where H = solar insolation (W/m^2)
h(x) = the fraction of H that remains at depth x
and K_w = thermal conductivity of water (W/m.K)

The fraction h(x) as a function of depth decreases very rapidly near the surface, as shown by the solid line in Fig. 3, because the long wavelengths of sunlight have a high absorption coefficient in water. The pond is heated, therefore, not only by solar radiation which penetrates beyond x_2, but also the NCZ is heated by the solar radiation absorbed between $x_2 - x_1$. Integration of Eq. 4 leads to the relationship,

$$q = \frac{h'(x)}{(x_2 - x_1)} H - \frac{K_w}{(x_2 - x_1)} \left[T_{x_2} - T_{x_1}\right] \tag{5}$$

where $h'(x) = \int_{x_1}^{x_2} h(x)\,dx$

T_{x_1} = temperature of the UCZ, normally at ambient air temperature,

and T_{x_2} = temperature of the LCZ, usually determined by the heat removal system.

The integral h´(x) has been plotted conveniently by Nielsen (1980b). Additionally, the insolation must be corrected for reflection at the air-water surface and for refraction which increases the path length of the sunlight in the water when the angle of incidence is >°0. Rabl and Nielsen have shown, however, that at latitude 40°N, these corrections reduce the insolation only 5-6% during the months of highest insolations.

It has been shown (Kooi, 1979) that Eq. 5 corresponds to the Hottel-Whillier-Bliss equation for the performance of a solar collector written in the form,

$$q = a\tau\, H - U_L [T_{x_2} - T_{x_1}]. \tag{6}$$

where the absorptivity-transmissivitiy product ($a\tau$) is the same as the first right-hand term of Eq. 5 and the loss factor $U_L = K_w/(x_2 - x_1)$. It is possible, therefore, to plot the efficiency, η, of the two types of collectors on the same graph. At low values of $\Delta T/H$, Fig. 4, the efficiency of a flat plate collector is greater than that of a solar pond because a large fraction of the solar radiation is absorbed in the UCZ and NCZ of a solar pond. At high values of $\Delta T/H$ the solar pond is more efficient, however, because the factors which contribute to losses from a high temperature flat plate collector, emissivity and thermal conductivity to the environment, are not present in a solar pond.

The thicknesses of both the UCZ and the NCZ greatly influence the efficiency of a solar pond. Once the UCZ has been made as thin as possible, the thickness of the NCZ is important because of the trade-off between an increase in thermal insulation but a simultaneous decrease in the solar radiation penetrating into the LCZ as the

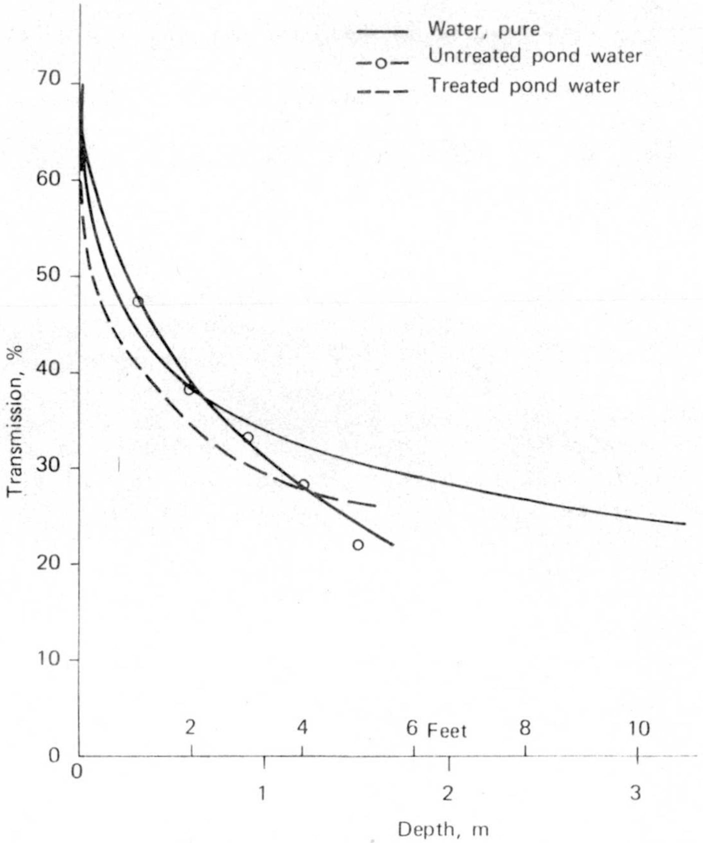

Fig. 3. Transmission of solar radiation as a function of depth into pure water and pond water.

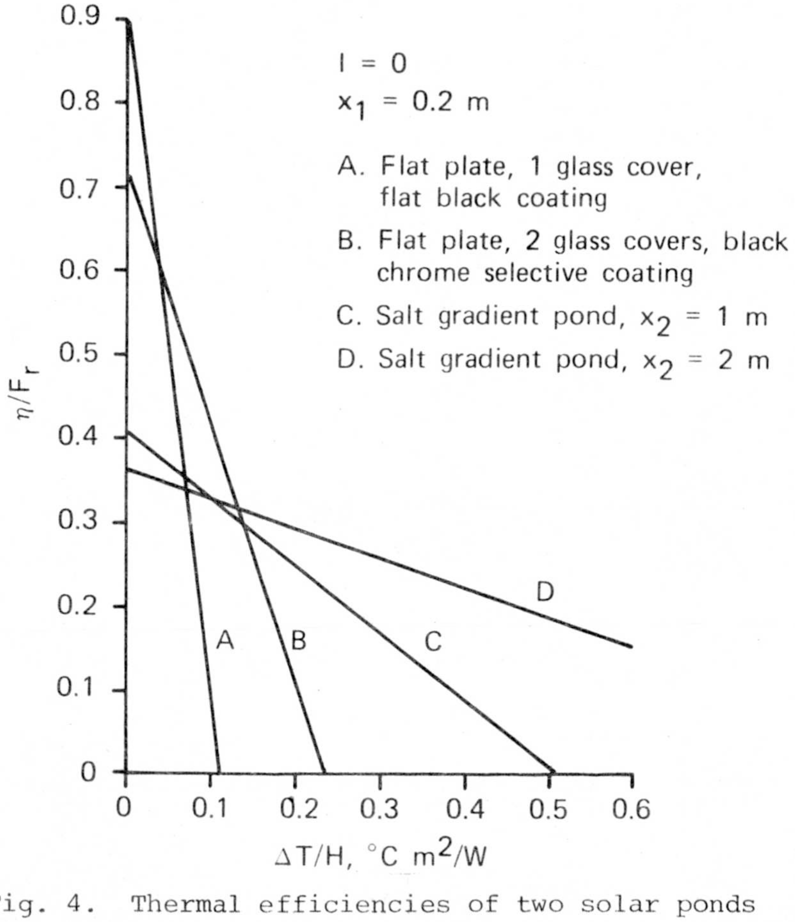

Fig. 4. Thermal efficiencies of two solar ponds compared with two flat-plate collectors (Kooi, 1979).

thickness of the NCZ increases. For every value of $\Delta T/H$ there is, therefore, an ideal thickness for the NCZ which yields the highest efficiency for the pond. For a specific value of $\Delta T/H$ the optimum value occurs when (dT/dx) at the NCZ/LCZ boundary is exactly zero as is illustrated, Fig. 5; consequently, no heat is absorbed or lost from the LCZ to the NCZ at the depth for maximum efficiency, x_2^m.

The thickness of the UCZ affects the efficiency because of the high absorptivity of infrared radiation at the surface of the water. If x_1 (the thickness of the UCZ) were zero, then the NCZ would extend to the surface and the solar radiation absorbed in the surface layer would contribute to the heating of the solar pond. When $x_1 > 0$, the amount of heating produced in the UCZ is lost to the environment by either evaporation or heat transfer to the air. The efficiency of the solar pond markedly decreases, therefore, as x increases for each value of $\Delta T/H$, as shown in Fig. 6. At the present time, several investigators are studying techniques which may be useful to reduce the depth of the UCZ. The factors which appear to influence the depth of x_1 are the diurnal heating by the sun, wind and wave action and the strength of the salt gradient (Nielsen, 1979). Various designs of wave suppressors are being tested as part of this study.

Once the steady state performance of the pond has been considered, we can now consider ponds located on either side of the equator in which the insolation and ambient air temperature display annual cyclical variations. In this case the heat flux, q, per unit area of surface must be replaced by a term for useful heat withdrawn, U, which may also vary with time; consequently, our Eq. 4 becomes (Nielsen, 1980b),

$$H(t)h(x,t) = U(t) + K_w \frac{d}{dx} T(x,t) + S(x,t) \tag{7}$$

U = heat removed (W/m^2 of surface area)

The quantity $S(x,t)$ is necessary in order to account for the heat capacity of all media below x; however, the addition of this term makes it impossible to solve the differential equation. If the heat stored in the NCZ and the ground below the pond is ignored then $S(t)$ can be evaluated and has the value,

$$S(t) = C_s \frac{d}{dt} T_w(t) \tag{8}$$

where C_s = heat capacity of the storage layer (LCZ) per m^2

and T_w = temperature of the storage layer. Because $C_s \left(\frac{J}{m^2\ K}\right) = C_p \left(\frac{J}{m^3\ K}\right) x$ Depth(m), depth of the storage layer becomes a variable.

Integration of the complete Eq. 7: as described by Nielsen (1980b) yields the following solution (with rearrangements of terms),

$$C_s \frac{dT_w}{dt} = \frac{h'(x)}{(x_2 - x_1)} H(t) - K_w \frac{(T_w - T_a)}{(x_2 - x_1)} - U(t) \tag{9}$$

where T_a = air temperature

All of the variables in this equation, such as H, T_w, T_a and U, usually display a sinusoidal function of annual time; consequently, each variable can be written as an average term plus an oscillatory term. At any instant, however, all the terms on the right hand side of Eq. 9 have a finite value so that the term (dT_w/dt) is inversely dependent upon C_s. In order to get dT_w/dt to be small, C_s, the depth of the pond must be large. This is expensive, however, because the excavation must be

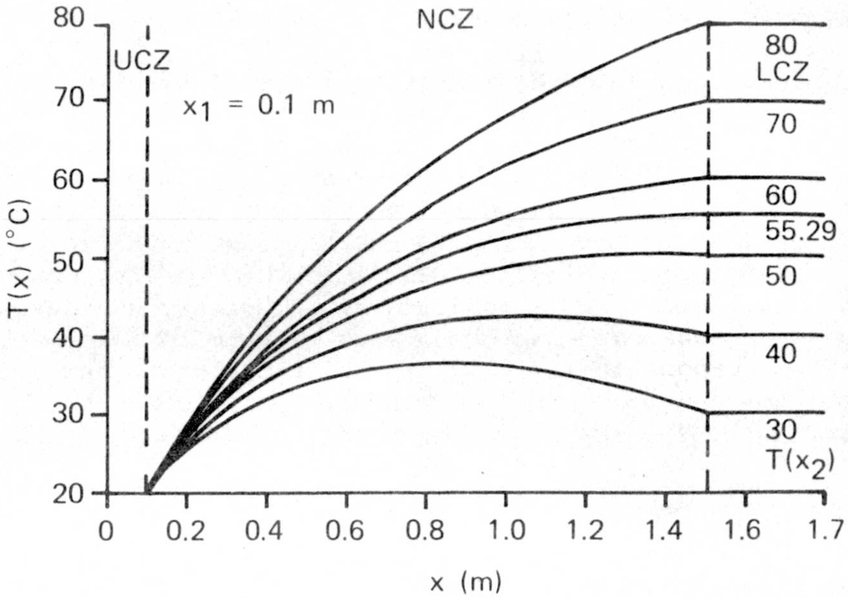

Fig. 5. Temperature profiles in the NCZ as a function of depth and temperature of the LCZ zone, $\Delta T/H$ constant (Kooi, 1979).

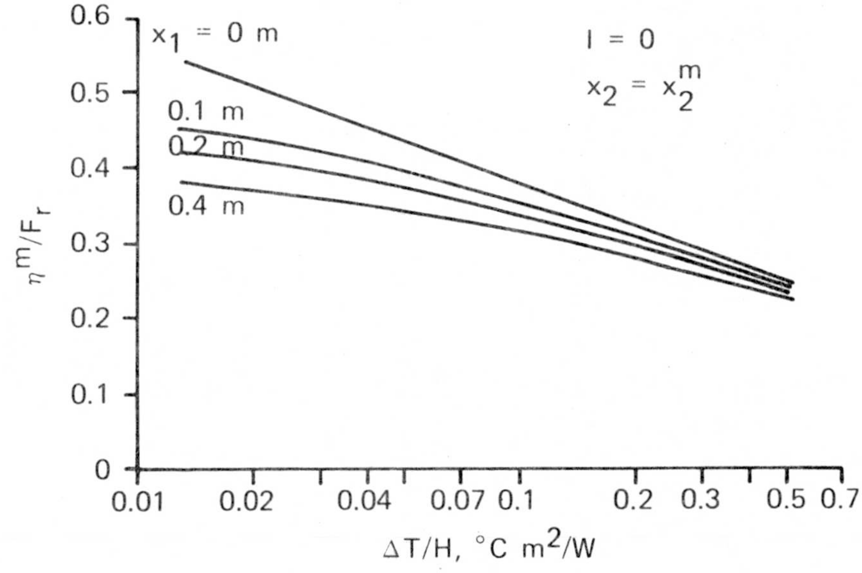

Fig. 6. Maximum efficiency as a function of $\Delta T/H$ for several thicknesses of the UCZ (I = incidence angle) (Kooi, 1979).

deeper, and more liner material and salt solutions are needed. The minimum value for the permissable temperature cycle in the pond, (dT_w/dt), becomes an economic and an engineering decision, therefore.

Rabl and Nielsen have evaluated Eq. 9 for typical values of H and T_a for Columbus, Ohio. The value of H is maximum at the summer solstice, T_a is one month out of phase while U is 6 months out of phase with T_a. For a solar pond of 160 m^2 and a NCZ of one m and various depths in the pond, the data, Table 1, show that the phase angle is rather insensitive to depth between 87 and 94 days; however, the amplitude of T_w varies significantly, from 28 - 42°C.

For engineering studies, we have modified Eq. 9 slightly and evaluated it for periods of a week or a month because the heat use, U, is often not a smooth oscillatory function. For our purpose we multiply all terms in Eq. 9 by A, the area of the pond surface (and bottom) and by the time interval (t_2-t_1) so that the relationship becomes,

$$C_A\,(T_{w_2} - T_{w_1}) = A\,\frac{h'(x)}{(x_2-x_1)}\,H_t - AK_w\,\frac{(T_w-T_a)\;(t_2-t_1)}{(x_2-x_1)} - U_t - AK_G\,(dT_G/dx_3)\,(t_2-t_1) \tag{10}$$

where C_A = total heat capacity of the LCZ (J/K)

$(T_{w_2}-T_{w_1})$ = the change in temperature of the LCZ from time t_1 to t_2

H_t = integrated insolation from time t_1 to t_2 $(\frac{W.s}{m^2})$

U_t = total heat removed from time t_1 to t_2 (J)

K_G = thermal conductivity of the ground. (W/m.K).

TABLE 1 Dependence of Temperature and Phase on Depth of Lower Convective Zone (LCZ)[a]

Depth of LCZ (m)	Temperature of LCZ (°C) Avg.	Temperature of LCZ (°C) Amplitude	Phase LCZ (days)
1.8	72.3	42.2	87.2
2.2	72.3	36.1	90.1
2.6	72.3	31.5	92.3
3.0	72.3	27.9	94.0

[a]For a 160 m^2 pond with constant NCZ of 1.0 m (Ref: Rabl & Nielsen, 1975).

The term dT_G/dx_3 provides for heat loss into the ground and can be obtained from thermocouples buried in the ground or approximated from suitable heat flow considerations (Wittenberg and Harris, 1979a). Recent heat flow calculations indicate the heat loss per m^2 through the sidewall may be twice as large as that through the bottom (Bartzis, Domanus and Sha, 1980). A term for that loss may be added, if desired.

Eq. 10 can be easily programmed on a small computer and the sensitivity of the variables can be examined during the design of a pond. After the pond is operational, it can then be used to determine if the observed performance of the pond meets the design specifications.

CONSTRUCTION AND OPERATION OF A SOLAR POND

The City of Miamisburg, Ohio, initiated construction of the largest, salt-gradient solar pond in the U.S. during 1977 as part of its Community Park Development Project. The pond was designed to supply thermal energy to an outdoor swimming pool in the summer and to a recreational building during the winter. Construction of the Miamisburg pond was completed (Bryant, 1979, Wittenberg and Harris, 1979b) in August 1978, and the first useful heat was removed (Harris and Wittenberg, 1979) during July-September, 1979.

Design and Construction

The Miamisburg solar pond is 54.5 m x 36.4 m (180 ft x 120 ft) at the top with sides tapered at an angle of 45° (a 1:1 slope) to a depth of approximately 3.0 m (10 ft). The site selected for the solar pond was a settling pond area adjacent to an abandoned power house. This area was drained, and mixed fill added in many places. After the excavation work for the solar pond was completed a 10-15 cm (4-6 in.) layer of sand was spread on top of this rough base to serve as a cushion for the heavy-duty plastic liner.

The plastic liner, 0.7 mm thick, made of a chemically resistant polymer-coated polyester fabric has been tested by the manufacturer in outdoor exposure tests to 117°C. It should out-perform the 8-10 yr lifetime of vinyl-coated fabrics. The fabric was supplied by the manufacturer in 1.42-m widths and of sufficient lengths to extend across the width of the solar pond. A fabricator assembled these strips into four large sections by making heat-weld seals along the edges of the stripes with 3.75 cm overlaps. These four sections were laid in the pond excavation and three heat weld seams were made on-site by an installation contractor. A 3% excess of liner material was laid in the excavation in the form of large wrinkles in the liner especially at the corners.

The pond was partially filled with water, approximately 1.5 m deep, and truck loads of salt, approximately 25 tonnes each, were dumped directly into the pond. When all of the salt was in the pond (nearly 1100 tonnes), sufficient water was added to bring the depth to 2.4 m. A large portable water pump, with a flow capacity of 0.1 m^3/s, was used to circulate the pond water and dissolve the remaining salt. After nearly four weeks, the salt concentration approached 18.5% at all locations and depths in the pond.

A new technique was employed for the formation of the salt gradient. In this procedure, a circular water distributor (1.2 m diameter) was placed 460 mm below the surface of the salt water. High pressure water was pumped through a 3.2 mm slit at the edge of the distributor at the rate of 7.4×10^{-3} m^3/s. The velocity of this water, 0.6 m/s (2 ft/sec), was sufficient to inject a horizontal layer of fresh water across the width of the pond at the same depth as the distributor. Successive layers of fresh water were added in this fashion to give the necessary salt-gradient, approximately 1 m thick. The top 150 mm of the pond was covered with fresh water.

A heat exchanger was placed in the north end of the pond for heat removal. It consisted of two tiers of pipe mounted at the 1.5 and 1.8 m levels above the bottom of the solar pond. Each tier was approximately 12.12 x 6.06 m and had eight circuits connected to a central supply and return header. A typical circuit consisted of 16 lengths of 25.4 mm diameter (type M copper) x 6.06 m long tubes connected with U-bends. The total heat exchanger area was approximately 138 m^2 with internal water flow rates up to 6.7 liters/s. The supports for the heat exchanger, fabricated from 51 mm diameter copper tubing, rested on the bottom of the pond.

The construction costs for the pond, Table 2, indicate that the liner and the salt represent the largest capital investment, although no expense has been included for land use.

TABLE 2 Solar Pond Construction Costs (1977 Dollars)

Salt, 1,100 tons @ $17.60/ton	=	$19,400
Liner plus installation	=	22,000
Heat Exchanger	=	6,800
Miscellaneous supplies	=	11,800
Labor (excavation, etc.)	=	10,000
Total Installation	=	$70,000

Instrumentation

During the construction of the pond, appropriate instrumentation was installed to monitor the performance of the pond. For this purpose, temperature sensors were placed at various depths and locations to measure the heat stored in the pond and the ground beneath the pond. Instrumentation was also provided to measure meteorological information, the incident solar radiation and solar energy transmitted as a function of depth in the pond. An automated data collection system records the data on a pre-arranged schedule and stores the information for later digital computerized retrieval.

Routine Maintenance

In order to obtain the maximum solar radiation transmission into the storage layer, the clarity of the water is of vital importance (Wittenberg and Harris, 1980). Algae growth in the surface convective layer and scattered debris floating on the surface absorb the solar radiation and must be removed. Dissolved copper sulfate has been useful to prevent algae growth; however, the water must be kept in the pH range of 5-6 in order for the copper to remain in solution. Several times during the year, the acidity of the water has to be readjusted by the addition of concentrated hydrochloric acid. This procedure, together with frequent skimming of debris from the surface, has maintained good water clarity.

The loss of salt is another consideration in pond maintenance. Small amounts of salt, approximately 2% per year, diffuse continually upward. This salt is removed through the overflow pipe whenever it rains or the surface is washed with fresh water. Disposal of this dilute salty water must be considered based upon local environmental considerations.

Non-Routine Maintenance

Periodic measurements of the salt inventory of the pond has proven advantageous to determine possible salt losses. For this purpose, a density profile of the pond is experimentally determined, such as shown in Fig. 7, and the salt content of each 150 mm layer of the pond is calculated. After one such inventory in August 1979, an abnormally large loss of salt was discovered. A leak in the liner was suspected and although several techniques were tried to locate it, none was successful. When the pond cooled sufficiently, a scuba diver inspected the liner and determined that a 250 mm long section of a seam had separated. This seam was along one side wall and in tension at a right angle to the seam. This seam was repaired by the scuba diver under 2.4 m (8 ft) of water, without draining the pond. Subsequently, the liner has been inspected by two scuba divers who located and repaired another seam leak and determined that the first repair was leak tight.

Additionally, due to the corrosive nature of the hot, concentrated brine solutions, the integrity of the heat exchanger system must be determined periodically. Except for the heat exchanger, only plastic parts, such as PVC pipe, etc., are in contact with the salt solution.

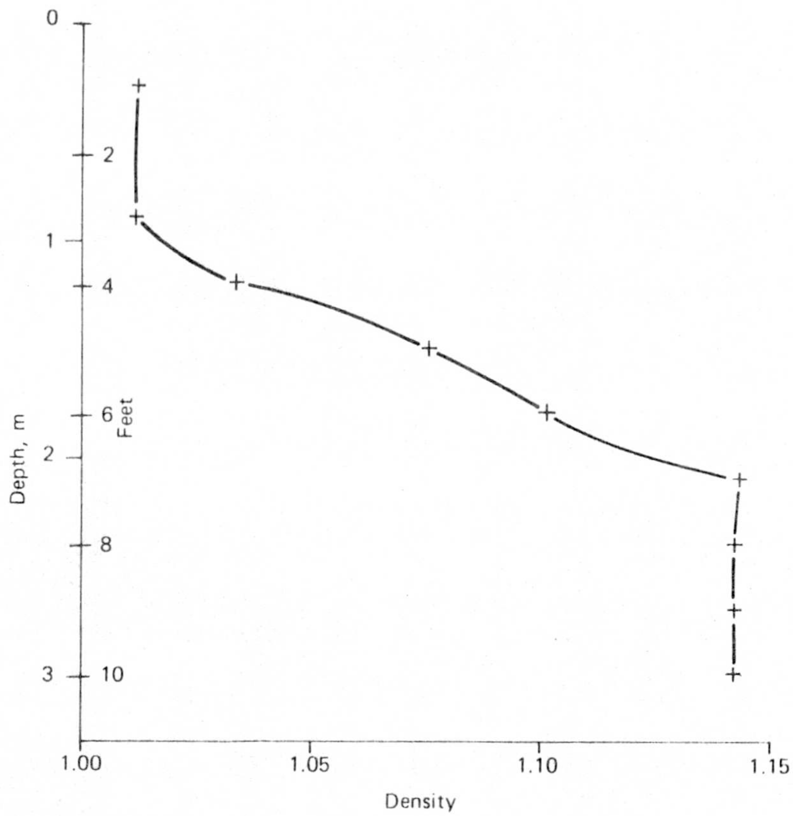

Fig. 7. Density-depth profile in pond.

Pond Construction Improvements

Although several unforseen operational difficulties have arisen with this pond, with proper preventive measures their occurrence can be reduced or their results mitigated, as discussed below.

The preparation of a firm foundation for the pond is essential. The use of rough fill followed immediately by excavation without compacting should be avoided. Also, the slope of the walls should be increased from 1:1 to preferably 3:1 in order to prevent the sagging and shifting of the side walls and bottom which have occurred in this pond. This ground movement has resulted in stresses being placed on the liner.

The use of a thick sand layer under the liner may not be advisable. During installation of the liner, the sand was disturbed, especially along the side-walls, and formed depressions under the liner. These depressions have caused additional stresses on the liner. If the sand were not used, then the sharp rocks would have to be removed or covered with clay in order to prevent punctures to the liner.

The 3% excess liner material which was initially installed to allow for shifting of the ground is not sufficient. Nearly twice as much excess material should be installed.

A Quality Assurance Program with in-plant inspections is needed at each step during the fabrication of the plastic liner. This is especially important if a sequence of fabricators prepare the liner. Also, an inspection of all seams must be made after the liner installation is completed.

A method for determining possible leakage from the pond should be installed. A simple system may be to lay drainage tile under the pond which can be monitored for salt water content.

Because of the highly corrosive character of the hot, concentrated brine solution, the long-term integrity of the metal heat exchanger is unknown and it may require periodic repair. We plan to install a heat exchanger outside of the pond, where the repairs can be made more easily. The hot brine water from the pond will be delivered to the heat exchanger with suitable plastic piping.

The pond system at Miamisburg has been up-graded following many of these suggestions and is being returned to its full operational performance during the summer of 1980.

Thermal Performance

The pond reached operational temperatures in June 1979, see Fig. 8; therefore, 144 GJ of heat was extracted during the summer months of 1979. With one-half of the heat exchanger in use, the average heat extraction rate from the pond was 23.06 kW, or 340 W/m^2 of heat exchanger surface.

The thermal performance of the pond has been evaluated for the one-dimensional model given by Eq. 10 based on monthly increments of heat use, solar insolation and ambient air temperature. Temperature of the water and ground beneath the pond were determined from the appropriate thermocycles, Fig. 9. In order to experimentally evaluate the solar radiation absorbed in the solar pond, the optical transmission of the pond water was determined. A water-tight commercial pyranometer which had a slow temperature response was lowered slowly into the pond and was constantly compared with a similar instrument which remained above the surface so that variations in the cloud cover were not recorded. The response of this instrument was not reliable; consequently, an experimental pyranometer (Etter, 1980) was developed with low thermal capacity which responded quickly to the changing ambient temperature.

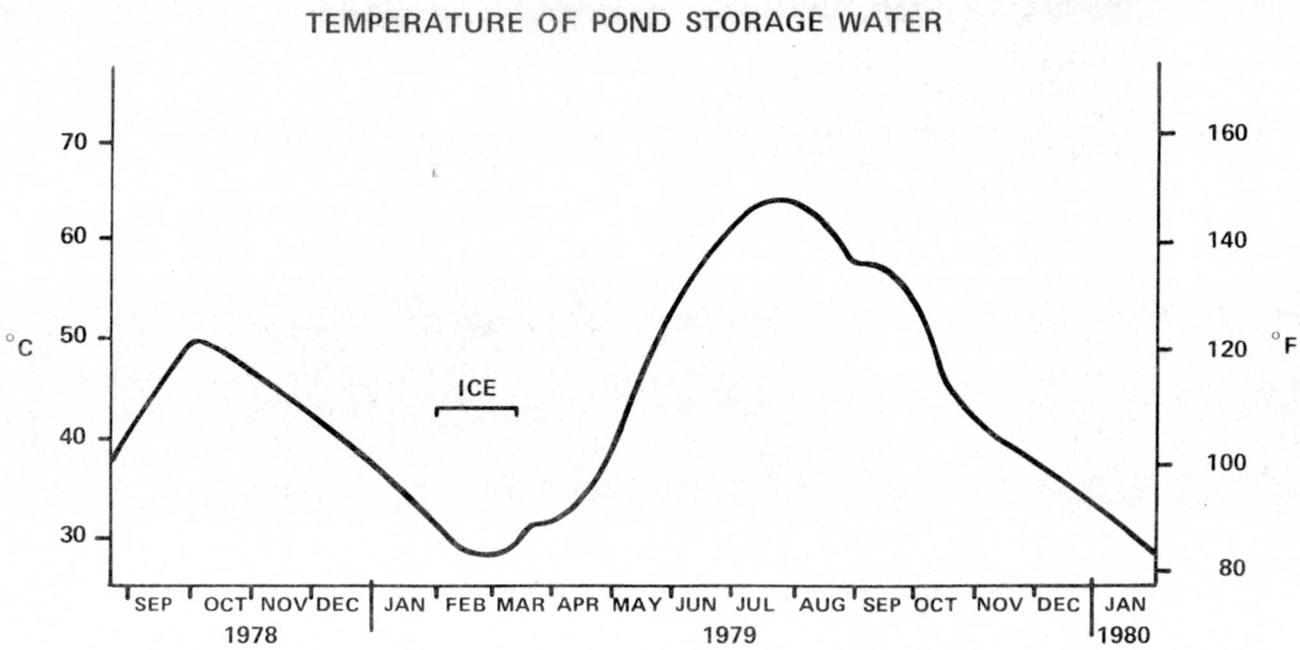

Fig. 8. Seasonal variation of temperature of pond storage water.

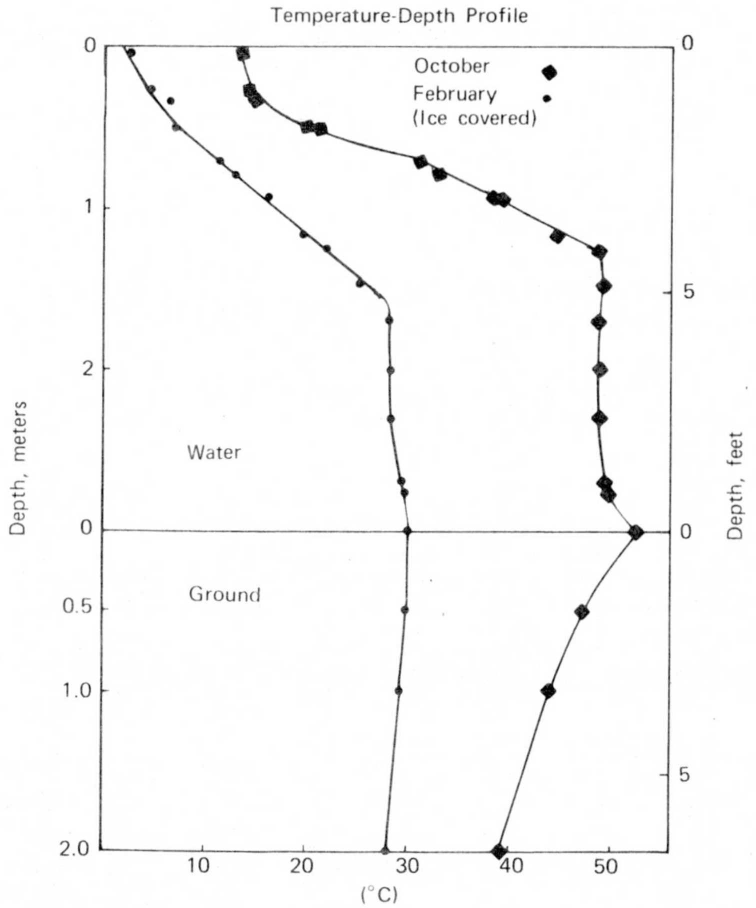

Fig. 9. Temperature-depth profile in the pond and ground below the pond for two different seasons.

Preliminary data from the experimental pyranometer are compared, Fig 3, with the value for water. The experimental measurements indicate lower transmission into the pond than that calculated for water, except near the surface where the measurements are difficult. Lower transmission into the pond water is to be expected because of insoluble particles being blown into the open pond and the dissolution of dyes such as the intentionally added copper sulfate and the leaching of pigments from tree leaves, for instance.

Based upon the relationships for solar energy heating of the pond together with the assumed relationships for thermal losses, a predicted performance for the pond was made, Table 3, for each month of the year. This prediction assumed average values of solar insolation and air temperature for our location. The optical transmission of the pond was assumed to follow the value for transmission into treated pond water. Also, the heat loss into the ground was calculated based upon the ambient ground temperature; however, the ground under the pond will attain a higher average temperature so that this heat loss term will not be as large as calculated. The heat requirements for each month were used, except that no heat was withdrawn when the pond temperature was below 30°C.

TABLE 3 Predicted Heat Extraction From the Solar Pond

Month	Monthly Insolation (GJ)	Transmission[a]	Absorbed in Pond[a] (GJ)	Monthly Losses (GJ)		Heat Used (GJ)	Temperature LCZ (°C)
				Top	Bottom		
Jan	295	0.090[b]	27[b]	136	31	0	27.0
Feb	418	0.090[b]	38[b]	97	14	0	21.3
Mar	580	0.323	187	45	9	0	31.6
Apr	613	0.327	200	65	32	0	39.6
May	1147	0.328	376	73	38	317	35.6
Jun	1148	0.329	378	42	27	317	35.1
Jul	1030	0.328	338	35	24	0	56.6
Aug	896	0.327	293	105	44	116	58.9
Sep	822	0.319	262	112	41	95	60.0
Oct	485	0.313	152	152	82	11	52.8
Nov	228	0.306	70	137	67	90	35.5
Dec	230	0.297	68	106	32	69	24.8

[a] Calculated from $\left[\frac{h'(x)}{x_2-x_1}\right]$ corrected for reflection and refraction.

[b] Approximate values when covered with ice.

These results predict that heat extraction during the summer months can be 845 GJ (800 million BTU) for heating the swimming pool. Heat extraction of up to 170 GJ (160 million BTU) from the solar pond can be used, to heat the adjacent bathhouse from October through December, without the use of a heatpump. The total heat use predicted for the solar pond indicates that approximately 13% of the annual incident solar radiation is utilized.

If the heat utilized from the solar pond were more evenly distributed during the year, the efficiency of the pond is predicted (Nielsen, 1980b) to be nearly 20%, which would produce 1372 GJ (1300 million BTU) of useful heat. This prediction assumes ideal optical transmission of the water, no ice formation during the winter, the formation of optimum salt and temperature gradients and no edge losses.

Cost Evaluation

As noted in Table 2, the cost of the pond installation in 1977 was $70,000. This does not include costs required to connect the pond heat produced to the end-use heating system. Such costs would be specific to each site and end-use.

The installation, like other solar heating systms, has a high capital cost, but low operational costs; consequently, the cost of the installation must be amortized fairly against the energy produced during the depreciation period. For the installation of a capital improvement by a municipal government, no tax rebates or other incentives are applicable; therefore, the annual cost C_S of the solar pond is simply, (Dickinson and Brown, 1979),

$$C_S = I(OM + CRF) \tag{11}$$

where I = the initial cost ($70,000)
OM = annual operation and maintenance costs (as a fraction of the initial cost)
and CRF = the capital recovery factor (i.e., the annual payment required to pay back the principal and interest for the capital investment)

The municipal bond rate is approximately 7% on long-term loans and the life-time of the installation (depreciation period) has been conservatively set at 15 yr; therefore, CRF = 0.1098.

The OM costs were estimated from the cost of the chemicals needed. For instance, $100/yr of chemicals were used for algae control; also, 2%/yr of salt (20 ton x $30/ton = $600) diffuses to the surface and is not recovered; therefore, the total cost of chemicals is approximately $700/yr. In the absence of any quantitative information a similar cost, $700/yr, was assigned for manpower. The total cost of OM is, therefore, $1400/yr (0.02 of the initial cost). The actual maintenance costs, which are believed to be small, are presently being evaluated.

The annual cost, C_S, in current year dollars is $9,086. The system is estimated to produce 1015GJ (962 million Btu) of heat per year; therefore, the cost of this energy is approximately $8.95/GJ ($9.45/million Btu). This cost compares favorably with the present cost of heating with fossil fuels; e.g., $6.75/GJ ($7.15/million Btu) for natural gas and $9.50/GJ ($10.00/million Btu) for fuel oil at this site.

Additionally, the installation does benefit significantly by the fact that once the investment has been made the value of the dollars decrease during the depreciation period due to the general inflation rate. The present value (PV) of the installation at its time of completion (in zero-year dollars) was determined by the relationship,

$$PV = I \frac{1}{DP} \sum_{t-1}^{t=DP} 1 \Big/ (1+g)^t \tag{12}$$

When the following values were assigned to these terms:

I = initial cost ($70,000), DP = depreciation period (15 yr), g = inflation rate (10%/yr), the value of PV is $35,000.

The levelized annual cost, C_S, is, therefore,

$$C_S = \frac{PV}{DP} + OM = \frac{\$35000}{15\ yr} + \$1400/yr = \$3730/yr. \tag{13}$$

The cost of the energy produced during this period is, therefore, only $3.70/GJ ($3.90/million Btu) and can be compared directly with the present cost of heating with fossil fuels. Clearly, the solar pond has the potential for producing low cost, low temperature heat over its life-time.

FUTURE PROJECTS

Solar ponds can be used to supply low-temperature heat for the following purposes: industrial process heat, electrical power generation, heating and cooling of buildings, agricultural uses the production of alcohol and water desalination. Currently, the generation of electrical power is receiving considerable attention, particularly for areas of the world which have high insolation and no installed electrical power grid. Ormat Turbines Co. of Israel has pioneered in the development of Rankine cycle turbogenerators for this use. The turbine utilizes a low-boiling organic fluid in which the boiler is supplied with hot (80-90°C) brine from the LCZ of a solar pond. The condenser can be cooled with water, at approximately 30°C, from the surface of the pond or supplemented with a cooling tower.

For electrical power production the surface area of the pond must be very large, up to 1 km^2 for 5 MW electrical generation. Such large ponds require extensive land area at low cost, minimal cost for salt and a low cost substitute for the plastic liner. Such sites exist at terminal inland lakes, such as the Dead Sea, in Israel, and the Great Salt Lake and Salton Sea in the U.S.A. Projects at each of these sites are currently being proposed in which the installation costs are in the range of $\$5/m^2$.

At Ein Bokek on the Dead Sea, the world's largest pond, 7500 m^2, was completed in 1978 and has reached temperatures of 88°C (Assaf, 1979). Initially, a 25 kWe turbine was operated at the pond. In December 1979 a 150 kWe turbine began generation on an intermittent basis. Based upon this success, other ponds are planned in the Dead Sea area (Sargent and Neeper, 1980). A pond scheduled for 1981 completion will be 0.25 km x 1 km and produce 5 MWe on an intermittent basis. This size should be economically competitive with existing electricity costs in Israel, 7¢/kWH for baseload and 15¢/kWH for peak load generation. By 1982 a pond 1 km^2 in area is scheduled for construction which will produce 5 MWe on a continuous basis. The designers believe that this size pond should be a basic module size and plan to build up to 2000 MWe capacity if the first module is successful (Bronicki, 1980).

A feasibility study for electrical power generation at the California Salton Sea is currently in progress by a consortium of U.S., California and Israel sponsors. (French, 1980) If this study gives optimistic results, the next stage would be a detailed design study. The operational concept, Fig. 10, visualizes the construction of dikes along the shoreline to enclose 130 km^2 (50 sq mi) of the total 920 km^2 (360 sq mi) of the lake. Sea water at 40,000 ppm will wash across the surface of the solar pond and enter an evaporation pond. In the evaporation pond, the brine will be concentrated and reinjected into the bottom of the solar pond to maintain the solar pond gradient. In time, excess salt will accumulate in the evaporating pond so that the concentration of the entire lake will approach 30,000 ppm in 12 yr, an improved condition for fishlife in the lake. If all 50 sq mi of diked area is converted into solar ponds, a power generation potential of 600 MWe will result. The optimum module size is expected to be in the range of 30-50 MWe.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the cooperation of R. S. Bryant, Parks and Recreation Director, City of Miamisburg, who has permitted us to install instrumentation at the pond; valuable consultation with Dr. C. E. Nielsen, Ohio State University; data collection and evaluation by M. J. Harris; and engineering support during construction by R. P. Bowser, B. E. Pack, and W. E. Kesling. The evaluation study is sponsored by the U. S. Department of Energy, Office of Solar Applications for Buildings.

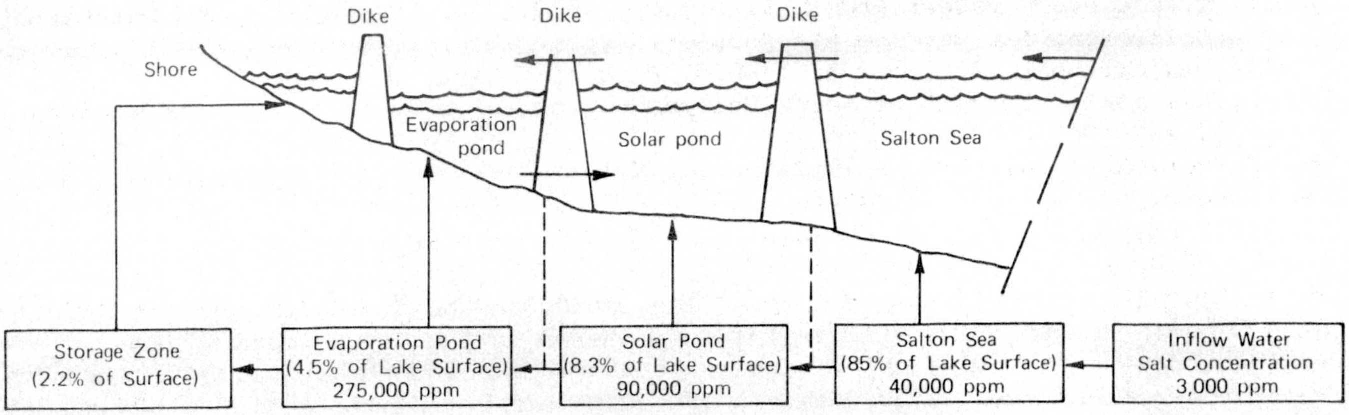

Fig. 10. Salton Sea solar pond concept.

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THE 1980 INTERNATIONAL SYMPOSIUM ON SOLAR ENERGY UTILIZATION

MLM-2770(OP)

AUGUST 10-24, 1980

AT

THE UNIVERSITY OF WESTERN ONTARIO
LONDON, ONTARIO, CANADA

SALT-GRADIENT SOLAR PONDS: DESIGN, CONSTRUCTION AND POWER PRODUCTION

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ABSTRACT

Salt-gradient solar ponds are combined solar energy collectors and thermal storage systems. The ponds are made non-convective by the formation of a density-gradient composed of salt solutions whose concentrations increase with depth. The depth of the various layers of the pond determine the efficiency and thermal storage capacity of the system. The construction of the largest such pond in the U.S., 2000 m^2, was completed in 1978 for approximately $\$35/m^2$. The pond is estimated to produce 1015 GJ/yr of low-temperature heat at a cost of \$8.95/GJ, when the installation costs are amortized over 15 yr. Construction changes are suggested to improve the reliability of the system. Electrical power generation by the use of Rankine cycle turbogenerators connected to solar ponds has been demonstrated in Israel. Feasibility studies are in progress to propose electricity production of up to 2,000 MW for projects near the Dead Sea in Israel, and 600 MW in a proposed project at the California Salton Sea.

KEYWORDS

Solar ponds; salt-gradient; solar collector efficiency; thermal storage; construction; cost evaluation; performance; electrical power production; Dead Sea; Salton Sea.

INTRODUCTION

The solar ponds considered here are bodies of water of sufficient depth that they are combined solar energy collectors and thermal storage systems. Such solar ponds must be made non-convective, otherwise the water temperature closely follows the ambient air temperature. The ponds are made non-convective, in this instance, by the dissolution of salts whose concentration and density increase with depth.

Natural salt-gradient solar ponds have been located in several areas of the world. The utilization of artificial solar ponds as a renewable energy source was described

*Mound Facility is operated by Monsanto Research Corporation for the U. S. Department of Energy under Contract No. DE-AC04-76-DP00053.

by H. Tabor (1963) in Israel. An adequate physical model of the solar pond was given by Weinberger (1964). Experimental work in Israel ceased for a period but has been recently revived with the construction of a 7500 m^2 pond near the Dead Sea. The hot water from this source has been used to power a Rankine cycle turboelectric generator.

Studies of solar ponds for the heating of buildings were introduced by Rabl and Nielsen (1975) in the U.S.A. approximately ten years ago. Dr. Nielsen (1980a) constructed several research ponds at the Ohio State University. Another research pond has been in operation at the University of New Mexico (Zangrando and Bryant, 1978). The utilization of such a pond for agricultural purposes is being demonstrated at the Ohio Agricultural Research Center (Short, Badger and Roller, 1979). The largest pond in the U.S., 2000 m^2, was constructed by the City of Miamisburg, Ohio, in 1978 for use in a recreational complex (Bryant, Bowser and Wittenberg, 1979).

This article will briefly review the physics of these ponds; describe the construction and initial operation of the Miamisburg pond; and indicate some of the large-scale projects being proposed for such ponds.

PHYSICS OF SOLAR PONDS

Hydrodynamic stability. The concept of such ponds relies upon the formation of non-convective layers; solar radiation, which is transmitted through these layers, heats the water near the bottom of the pond but this hot water cannot rise to the surface. As a result, the solar energy is stored in the form of hot water near the bottom of the pond. In order to establish the non-convective layers, salt solutions of various concentrations are formed so that the density of the water increases with depth (Fig. 1). Stability in such a pond is obtained, therefore, when the density gradient (of the salt solutions) exceeds the thermal expansion of the hot water. This is expressed by the relationship (Weinberger, 1964).

$$\frac{d\rho}{dx} = \frac{d\rho}{ds}\frac{ds}{dx} + \frac{d\rho}{dT}\frac{dT}{dx} \geq 0 \qquad (1)$$

where ρ = density
x = depth (m)
s = salt concentration
T = temperature (K)

Because $(d\rho/dT)$ is negative for most common salt solutions, it is desirable to have (ds/dx) as large as possible. One method of achieving a large concentration change with depth is to select a salt whose solubility increases rapidly with temperature and, then, operate near the solubility limit. A review of candidate salts, Fig. 2, (Edesess, Benson, Henderson and Jayadev, 1979) indicates that over limited temperature ranges, sodium sulfate and sodium carbonate would be likely candidates for use in "saturated salt-gradient ponds;" however, only limited experiments have been performed with such salts. Nearly all ponds constructed thus far have used sodium chloride, because it is relatively cheap and widely distributed throughout the world; however, the ponds in Israel which use water from the Dead Sea are predominantly magnesium chloride brines.

Returning to Eq. 1, one finds that for sodium chloride solutions (which will be considered in the remainder of this paper), the density gradient can support a temperature differential of 100°C when the concentration increases approximately 5 wt % from the top to the bottom. A pond constructed on this stability criterion is shown, however, to be unstable to oscillatory motions which are induced by the diurnal heating of the pond or severe wave action at the surface. A pond must be stable, therefore, both hydrodynamically and diffusionally, to the double-diffusive actions