A Salt-Gradient Solar Pond

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ABSTRACT

This description of the development of a salt-gradient solar pond – its construction, operation, performance and applications – starts with a brief history of solar ponds. The working principle of the pond and the absorption of radiation in salt water have been described and the factors affecting the performance of the solar pond have been identified. The methods of construction, operation and maintenance of the salt-gradient solar pond have been dealt with in detail. Finally, the possible applications of the solar pond have been discussed.

INTRODUCTION

Solar energy is free, but the conventional flat-plate collectors, used for the collection of this energy, are quite expensive. Moreover, due to the intermittent supply of solar energy, the conventional system requires a separate storage device. In order to make solar energy economically viable, it is essential to develop a low-cost collection and storage system. There has been persistent effort to identify such a low-cost collection and storage system so that solar energy can be used profitably.

Several attempts have been made to collect solar energy in a large body of water, such as ponds and lakes. In such a homogeneous body of water convection currents were set up whenever temperature inversion occurred in the pond. The energy collected at the bottom of the pond was carried to the surface by convection effects and lost to the atmosphere due to evaporation. These early attempts failed as only a few degrees rise in temperature were obtained. In 1948, R. Block[1] suggested that the evaporation problem might be solved if convection effects were stopped. He conceived the idea of using salt-gradient ponds on the basis of heating observed in the Transylvanian lakes first studied by Kalecsinsky.[2] Hirchmann[3] found from a theoretical study that the presence of a density gradient, which prevents convection in the body of water when temperature inversion occurs, reduces the evaporation loss by about 65%. This led to the development of solar ponds.

A solar pond, as the name indicates, is a large body of water with an open top which is heated by the sun. In the literature, there are several solar collectors referred to as solar ponds. These are (a) salt-gradient solar ponds, (b) shallow solar ponds, and (c) saturated solar ponds.

In a salt-gradient solar pond the salinity increases with depth, the density of the salt solution being highest at the bottom and lowest at the top, as shown in Fig. 1. Convection currents, which normally develop due to the presence of hot liquid at the bottom and cold liquid at the top, do not occur because of the presence of this density gradient. The bottom of the pond is painted black to absorb all the radiation reaching the bottom. As a result of this heating, the temperature of the water increases. The absence of convection currents and the low thermal conductivity of stagnant water help to confine the heated liquid at the bottom. The typical depth of a salt-gradient solar pond is about 2 to 3 m.

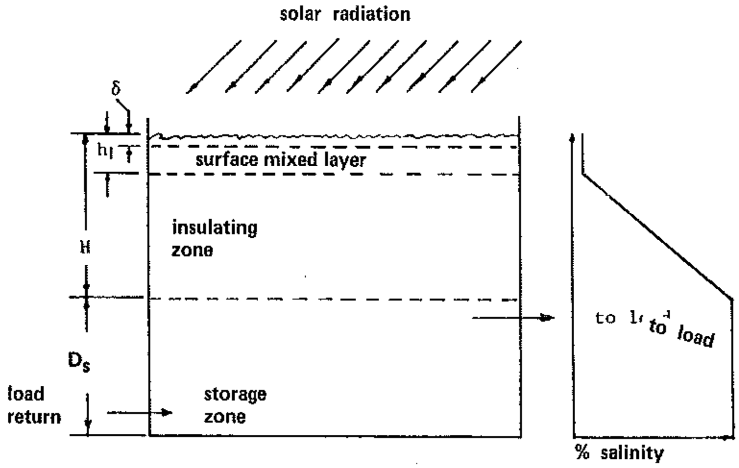

Fig. 1 Schematic diagram of a salt-gradient solar pond.

A shallow solar pond (SSP) is a thin layer of water, approximately 5 cm deep, contained in a plastic bag with a black bottom and a transparent top. A glazing at the top is provided with clear plastic, as shown in Fig. 2. A slab of heat insulating material is placed under the bag to prevent heat losses. A separate store is required for this type of pond. The theory and technology of this pond is similar to the conventional flat-plate collector and this being the case the subject will not be covered in this study. For further information on shallow solar ponds, the reader is referred to ref. 4.

In the salt-gradient solar pond, there is diffusion of salt from the bottom to the surface due to a density difference, and this requires the addition of salt to the bottom and the removal of salt from the surface to maintain the density gradient. A saturated solar pond has been proposed to overcome this situation.[5] This pond is filled with a saturated solution of salt, borax or potassium

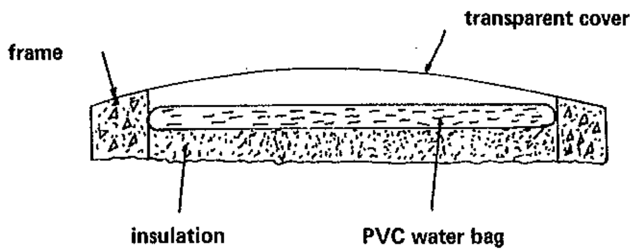

Fig. 2 A section of a shallow solar pond.

nitrate,[6] which shows a marked increase in solubility with temperature. This requires a certain amount of solid salts at the bottom to ensure saturation when the temperature there increases. When solar radiation heats up the bottom, more salt goes into the solution, thereby increasing the density – which prevents convection effects produced by thermal expansion. Saturated solar ponds have not attained the same level of maturity as salt-gradient solar ponds, and consequently require further study to evaluate their performance.

In this study, the development of salt-gradient solar ponds will be described in detail, with particular emphasis on construction, operation, maintenance, application and performance.

HISTORICAL BACKGROUND

The salt-gradient solar pond or lake which shows temperature inversion, i.e. an increase in temperature with depth, has been in existence for a long time, although the phenomena was only observed and recorded recently.

The first recorded study of a natural solar-heated salt-gradient solar pond was reported by Kalecsinsky,[2] who described the Medve Lake in Transylvania (42° 44′N, 28° 45′E). It was found from the analysis of the data on temperature and salinity that the temperature rose to 70°C at a depth of 1.32 m, and this was caused by solar heating in the absence of a convection current. Even at that time, Kalecsinsky proposed the use of an artificial solar pond for residential and industrial applications. Salt-gradient solar lakes have been reported by Anderson,[7] Wilson and Wellman,[8] and Por.[9] Following the publication of Kalecsinsky's research,[2] some investigations were made on natural solar heated lakes in Transylvania, but no attempt was made to construct a solar pond for practical applications.

In the year 1948, Rudy Block[6] again proposed solar ponds for the collection and storage of solar energy. Successful research on salt-gradient solar ponds began in 1959 when Tabor[10] built a 1 m deep experimental pond. The research on solar ponds in Israel continued until 1967, and resulted in useful contributions towards understanding the physics of solar ponds and the possible applications of these ponds.

At that time, it was found that solar ponds could not compete with fossil fuel,[1] and consequently very little work was done until recently. The majority of the early work was directed towards the operation of the pond to generate electricity. The oil crisis of 1973 created a revival of interest in solar ponds and a number of researchers have recently reported work directed towards different applications[11–15] such as space heating and cooling, industrial process heating, and desalination.

Solar ponds have been studied in India,[16] in the USSR[17] and in Chile.[18] In the USA, solar pond research began at the Ohio State University and led to the construction of 200 m² pond which has been in operation since 1975.[13] A solar pond was also built at the University of New Mexico in 1975.[19] Another solar pond was built at the Ohio Agricultural Research and Development Centre for greenhouse heating.[20] A pond having an area of 7500 m² was built at Ein Bogeg near the Dead Sea in 1979 and provides a peak power of 150 kW(e).[6] The operating temperature of the pond is in the region of 90°C. A 5MW(e) solar power plant at Beit Ha'Arava became operational in July 1984.[21] This pond, having an area of about 250 000 m², is the largest solar pond powerplant in the world. This pond attains a temperature of about 85°C at the storage zone. A 4000 m² experimental pond built by Tennessee Valley Authority has been operational since 1982.[22] This pond attained a temperature of about 70°C in about 8 months.

A 2000 m^2 solar pond at Cheetham Salt, Victoria[23] has been built to investigate the feasibility of using solar ponds to provide low temperature industrial process heating. The solar pond at Alice springs,[23] which has a surface area of 2000 m^2, is being studied to evaluate the possibility of using the pond to generate electric power with the help of a Rankine Cycle.

WORKING PRINCIPLES

A salt-gradient solar pond will normally have three layers, as described below:

1. a surface mixed layer caused by wind action and evaporation;
2. a mixed layer at the bottom to store the collected energy; and
3. an insulating layer between the two mixed layers where a convection current is prevented because there is a density gradient. The heat transfer through the insulating layer is due to conduction only, and for stagnant salt water the thermal conductivity is low.

When solar radiation falls on the surface of the pond, there is a region of thickness, δ, where rapid attenuation occurs, as shown in Fig. 1. The rapid attenuation at the surface is mainly due to the presence of an infrared component of the radiation which is absorbed within a few centimetres from the surface. The remaining radiation is transmitted through the salt water and suffers an exponential decay[24-26] until it reaches the bottom of the pond. Most of the radiation reaching the bottom will be absorbed there. Some amount of radiation may be reflected if the absorptance of the bottom liner is not unity. The radiation absorbed in the storage zone and at the bottom of the pond will cause the temperature of the fluid in the storage zone to rise. For a large pond, heat losses from the side walls are negligible. The soil under the pond acts as a thermal stabilizer,[27] receiving heat when the pond is at a higher temperature and delivering heat when the soil is at a higher temperature. This, in fact, reduces the fluctuation of temperatures of the storage zone as a result of load variation. A large pond requires about 2 to 3 years to attain a quasi-steady state. The energy can be extracted from the storage zone by passing it through heat exchangers.

SOLAR RADIATION ABSORPTION

The solar radiation landing on a horizontal plane at the surface of the earth is dependent upon the time of day, the day of the year, atmospheric conditions and the latitude. At sea level, radiation with a wavelength of 0.29-4 μm is the most significant. Five percent of the radiation reaching the sea level is ultraviolet, 50-55% visible, and the remainder is infrared. The radiation reaching a horizontal surface will have direct and diffuse components. A fraction of the total radiation reaching the surface of the pond will be reflected and the remainder will penetrate into the liquid. It should be mentioned here that water is the least reflecting substance[28] covering the surface of the earth. Fig. 3 shows the reflectance of the water surface as a function of zenith angle.

The absorption of solar radiation in water depends on the wavelength, as shown in Table 1. Table 2 shows the radiation transmitted through pure water layers of different thicknesses. Calculations have been made of the attenuation of solar radiation in water by considering it to be divided into spectral bands with known attenuation coefficients.[12,29,30] For example, Rabl & Nielsen[12] used four bands, and more recently Hull[30] obtained similar results using 40 bands. In an actual pond, the penetration of solar radiation will also depend upon the quality and clarity of the

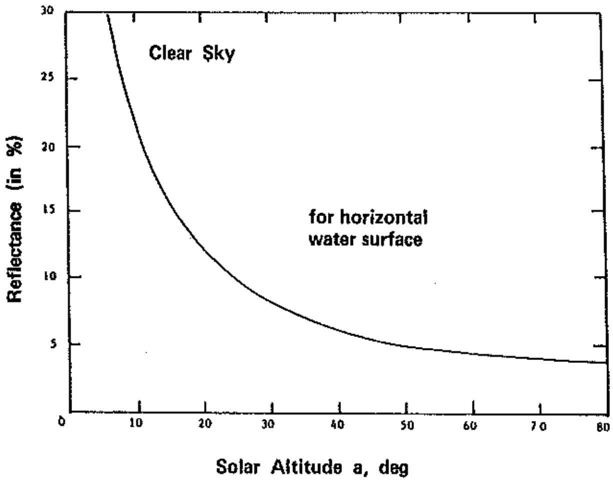

Fig. 3 Reflectance of solar radiation on a horizontal water surface as a function of solar altitude (Raphael[51]).

Table 1
Absorption coefficient of pure water (Dake & Harleman[26])

Wavelength μm	$\mu(m^{-1})$	Wavelength μm	$\mu(m^{-1})$
0.32	0.58	0.62	0.178
0.34	0.38	0.65	0.210
0.36	0.28	0.70	0.84
0.38	0.148	0.75	2.72
0.40	0.072	0.80	2.40
0.42	0.041	0.85	4.12
0.44	0.023	0.90	6.55
0.46	0.015	0.95	28.80
0.48	0.015	1.00	39.70
0.50	0.016	1.05	17.70
0.52	0.019	1.10	20.30
0.54	0.024	1.20	123.20
0.56	0.030	1.30	150.00
0.58	0.055	1.40	1600.00
0.60	0.125		

Table 2
Transmittance of solar radiation in pure water (Defant[37])

Wavelength μm	Layer Thickness								
	0.00	0.01 mm	0.10 mm	1.00 mm	1.00 cm	10.0 cm	1.00 m	10.0 m	100 m
0.2-0.6	23.7	23.7	23.7	23.7	23.7	23.6	22.9	17.2	1.4
0.6-0.9	36.0	36.0	36.0	35.9	35.3	35.3	12.9	0.9	
0.9-1.2	17.9	17.9	17.8	17.2	12.3	0.8			
1.2-1.5	8.7	8.6	8.2	6.3	1.7				
1.5-1.8	8.0	7.8	6.4	2.7					
1.8-2.1	2.5	2.3	1.1						
2.1-2.4	2.5	2.4	1.9	0.1					
2.4-2.7	0.7	0.6	0.2						
2.7-3.0	0.04	0.02							
Total	100.0	99.4	95.2	85.9	73.0	54.9	35.8	18.1	1.4

water, as shown in Fig. 4. It is indicated that reflection and absorption near the surface is followed by an approximately exponential decay. For a solar pond, an exponential approximation of the following form may provide an adequate representation of the essential features of absorption:[24]

$$I_h = I_s (1 - F) \exp(-\mu Z).$$

The fraction, F, of the net radiation incident on the surface of the pond is absorbed within a small depth, δ, at the surface of the pond. This fraction F appears to have an average value of 0.4 and has been found to be independent of time.[31]

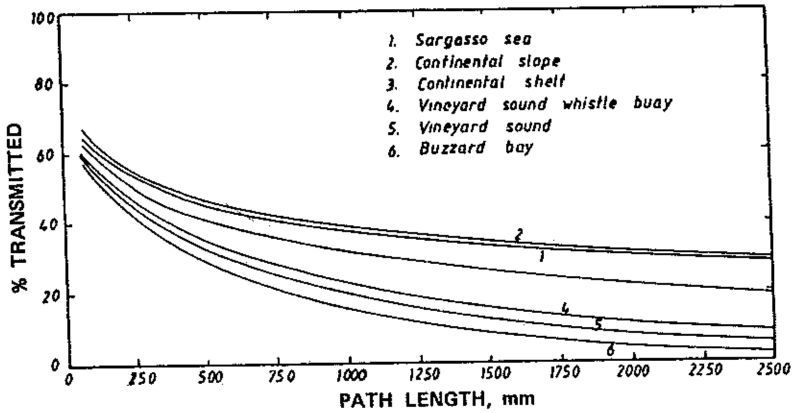

Fig. 4 Transmittance of solar radiation in salt water (Weinberger[29]).

FACTORS AFFECTING POND PERFORMANCE

The following factors affect the temperature of the storage zone:

a) The location of the pond.

b) The physical parameters, such as –

   i) the thickness of the surface mixed layer,

   ii) the depth of the storage zone,

   iii) the thickness of the insulating layer, and

   iv) the overall dimensions of the pond.

c) The absorptance of the bottom liner.

d) The transparency of the pond.

e) The extraction of heat.

a) The location of the pond

The storage temperature of the pond is greatly affected by the soil conditions and groundwater movement. These effects were studied by Duyar and Bober,[32] Akbarzadeh and Ahmedi,[27] and Haelader.[33] The effects of groundwater movement on the performance of the pond were studied by Hawlader and Brinkworth[25] by using difference values of heat loss coefficient for the ground. It can be seen from Fig. 5 that a higher value of the ground loss coefficient resulted in a

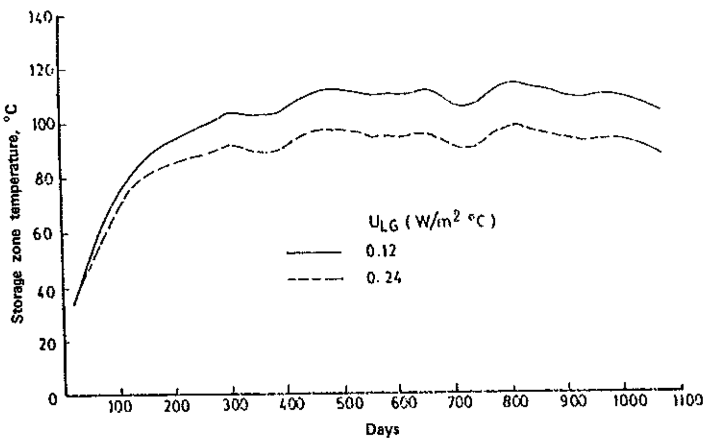

Fig. 5 Effect of ground loss coefficient on the storage zone temperature (Hawlader[33]).

lower temperature of the storage zone of the pond. The increase in ground loss coefficient, U_{LG}, from 0.12 W/m² °C to 0.24 W/m² °C, reduced the temperature of the storage zone by about 16°C.

b) The physical parameters

The increase in thickness of the surface mixed layer, caused by wind action and evaporation, reduces the effective insulation effect, causing more heat losses from the surface. It has been found from a simulation study that the temperature of the storage zone reached a maximum value of 93°C and 77°C for depths of surface mixed layer of 0.3 and 0.5 m respectively, as shown in Fig. 6. Figures 7 and 8 show the effects of thicknesses of the insulating layer and storage zone. The influences of the surface mixed layer, the storage zone and the insulating layer have also been studied by Kooi,[34] Akberzadeh and Ahmeli,[35] and Atkinson and Harleman.[36]

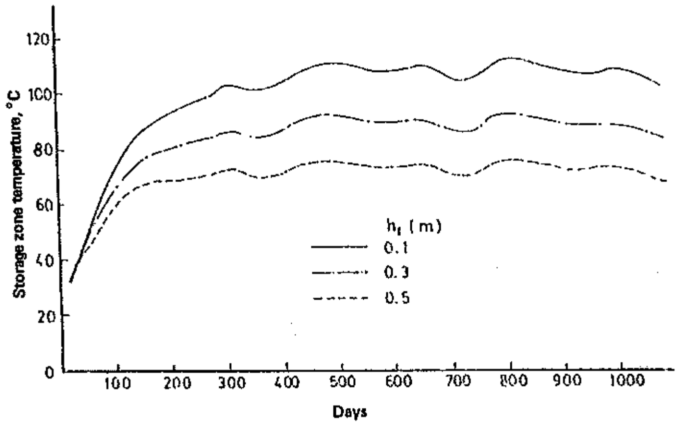

Fig. 6 Effect of surface mixed layer thickness on the temperature of storage zone (Hawlader[33]).

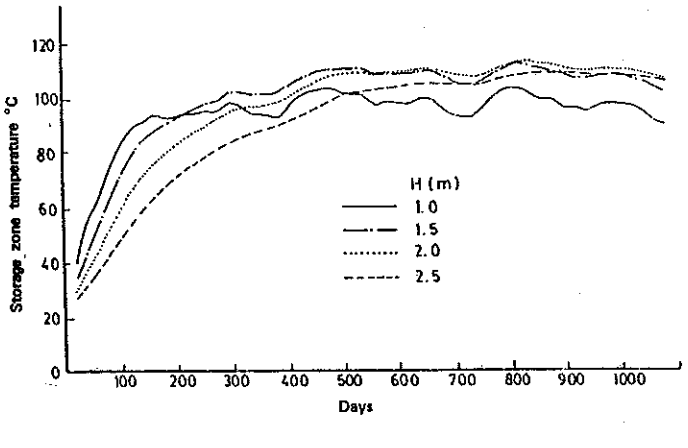

Fig. 7 Effect of insulation layer thickness on the performance of solar pond (Hawlader[33]).

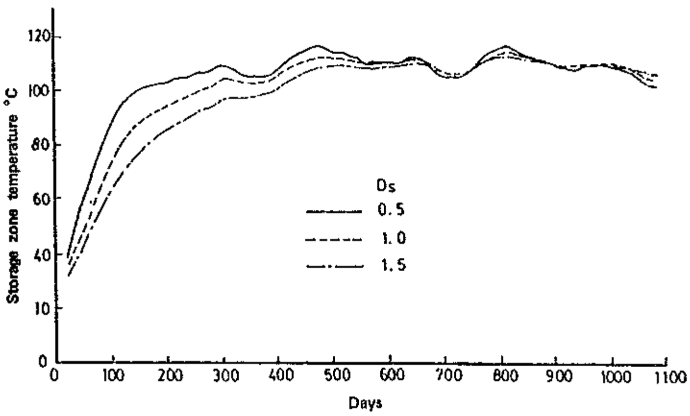

Fig. 8 The effect of storage zone thickness on its temperature (Hawlader[33]).

c) The absorptance of the bottom liner

The absorptance of the bottom liner of the pond affects the temperature of the storage zone. If the absorptance of the bottom liner is less than unity, some amount of radiation will be reflected from the bottom. For a deep pond, the reflection loss may not be appreciable, but for a shallow pond these losses will be quite significant.

d) The transparency of the pond

The transparency of the pond affects the performance to a great extent, as shown in Fig. 9. In this figure, the transparency has been expressed in terms of the extinction coefficient. With an increase in the magnitude of the extinction coefficient, the amount of radiation available at the storage zone decreases. Hence, there is a considerable reduction in the operating temperature of the storage zone.

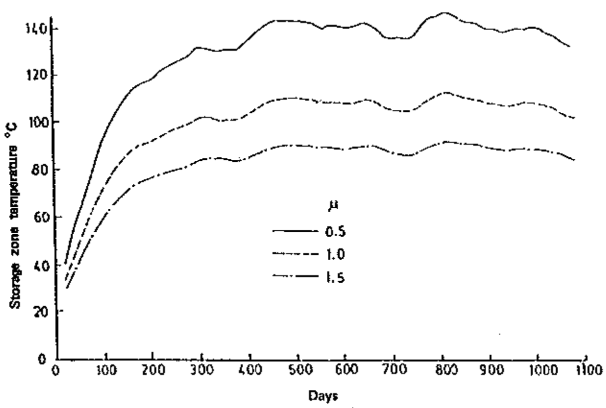

Fig. 9 The effect of extinction coefficients on the temperature of storage zone (Hawlader[33]).

e) The extraction of heat

The withdrawal of heat from the storage zone affects its temperature. Figure 10 shows that the equilibrium temperature of the storage zone decreases with an increase in load. It can also be seen from the figure that the variations of the temperature under quasi-steady state conditions were the same, irrespective of whether the load was applied after 90 days or 300 days of initial heating.

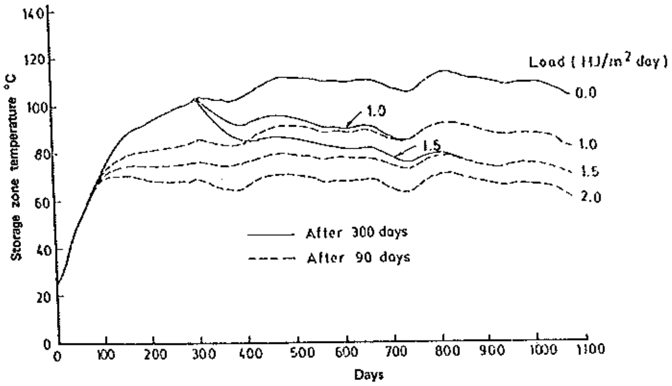

Fig. 10 The effect of load on storage temperature (Hawlader[33]).

CONSTRUCTION AND OPERATION OF SOLAR PONDS

Selection of site

In the selection of a site for a solar pond, the following points should be considered.

1. The pond should be located at a site where a source of salt or brine is available.
2. The site of the pond should be fairly flat to reduce earth removal.
3. The pond should not be located near an underground aquifer as it may cause structural problems.
4. There should not be any groundwater movement under the pond. The groundwater movement will increase heat losses and reduce the temperature of the storage zone.
5. The soil under the pond should be free from stresses, since an increase in temperature may cause differential thermal expansion, resulting in earth movement.
6. There should be adequate all-year exposure to solar radiation and no shade.

Construction of the pond

A solar pond may be constructed either by –

1) digging out a volume of earth, or
2) flattening the site and erecting a perimeter wall.

The second method reduces the amount of earth removal required for a larger pond. In order to get rid of the perimeter wall, some ponds are built with a sloping wall. For small ponds, this will increase the cost of liners and reduce the effective surface area available for the collection of solar energy. A sloping wall will have a negligible effect on a large pond.

Lining of the pond

It is essential to have some kind of lining to stop leakage of hot salt water from the pond. The lining used should fulfill the following criteria:

a) It must be able to stand the maximum temperature attainable in the pond.

b) It must not suffer any corrosion effects due to continuous immersion in strong salt solutions.

c) It should be resistant to UV degradation.

d) It should be fairly easy to join the linings at the site.

e) It must possess sufficient mechanical strength to support the load.

A pond at Ohio State University used 0.88 mm thick nylon-reinforced black chlorinated polyethylene.[13] Short et al.[20] used a polyester-reinforced alloy-vinyl pond liner for the pond at the Ohio Agricultural Research and Development Centre. This liner was found superior in strength, dimensional stability, and low porosity for a temperature range of about 0-80°C. Good fabrication is important since pond leaks may occur at seams or poorly designed corner areas. A pond in Australia[38] used RIVASEAL, a kind of terylene cloth impregnated with fibre-glass and coated on either side with bitumen. A gas torch was used to weld the strips together. When the pond was dismantled after two years of operation, the liners were found to be intact.

Selection of salts

The salt selected for the building up of the salinity gradient in a solar pond must have the following characteristics:

i) it must be available in abundance;

ii) it must be cheap;

iii) it must have a high solubility value so as to allow high solution densities; and

iv) the solubility should not vary appreciably with temperature.

Figure 11 shows the solubility of a few likely candidate salts for salt-gradient solar ponds. The maximum concentration required at the bottom of the pond is determined by the stability criteria. Magnesium chloride and sodium chloride are the two salts most commonly used in salt-gradient solar ponds. Magnesium chloride is found to be more useful than sodium chloride since the former has a higher solubility than the latter, giving the higher densities required at temperatures greater than 100°C. At the maximum density of $MgCl_2$, a solution at nearly saturated conditions is about 1330 kg/m^3, and that of sodium chloride is 1220 kg/m^3. This implies that the maximum temperature attainable in a NaCl pond is lower than that in a $MgCl_2$ pond. If the solubility of the salt changes appreciably with temperature, it may give rise to the following problems:

1. A fluctuation in temperature could result in a salt deposit on the base of the pond, thereby increasing reflection losses due to the formation of a white coating.

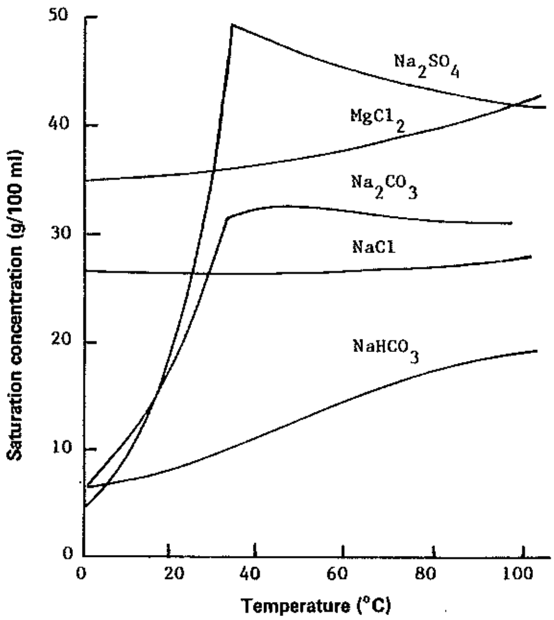

Fig. 11 Candidate salts for solar ponds (Charter[23]).

2. A salt deposit on heat exchangers may cause poor heat transfer.

Determination of salt concentration gradient

When heated from below, convection currents will be set up in a homogeneous body of liquid at a Rayleigh number of about 2000. In a solar pond, the vertical convection effect is prevented by means of a salinity gradient of increasing concentration with depth. The stability of solar ponds has been extensively studied by Weinberger,[29] Nielsen and Rabl,[39] Leshuk et al.,[40] and Elwell et al.[41] It was found that the static stability against the vertical convection required only that the density of the fluid should increase as the depth of the fluid increases, i.e. –

$$\Delta T < \frac{\epsilon}{\beta} \Delta S, \tag{1}$$

where ΔT = temperature difference between two points

ΔS = change in salt concentration between the same points

$\epsilon = \frac{1}{\rho} \frac{\partial \rho}{\partial S}\Big|_T$

$\beta = -\frac{1}{\rho} \frac{\partial \rho}{\partial T}\Big|_S$

ρ = density

S = salinity

T = temperature.

More stringent dynamic stability criteria must be met to prevent an oscillating motion which increases with time. For this case, the salinity and temperature gradient must satisfy the following condition:[41]

$$\Delta T < \frac{P_r + \phi}{P_r + 1} \frac{\epsilon}{\beta} \Delta S, \tag{2}$$

where P_r = Prandtl number

ϕ = ratio of salt diffusivity to thermal diffusivity.

In the above equation, the magnitude of the factor $(P_r + \phi)/(P_r + 1)$ is less than unity, and hence the oscillatory disturbance mode reduces the maximum temperature difference that a given salinity gradient can stably support, and the stability limit of the pond is calculated on the basis of the above equation.

Depth of the pond

The total depth of the pond consists of the sum of the depth of the surface mixed layer, the insulating layer and the storage zone. It is essential to maintain the depth of the surface mixed layer to a minimum. An increase in the depth of the surface mixed layer reduces the effective insulation effects, and hence the maximum temperature attainable in the storage zone is reduced. The depth of the insulating layer depends considerably on the local meteorological conditions. An increase in the depth of the insulating layer causes a reduction in the available radiation at the storage zone but increases the insulation effect, thereby reducing the heat transfer from the storage zone to the surface. Thus an optimum value exists for a particular condition of the salt solution. The depth of the storage zone depends on the type of application and the temperature requirements for such applications. It also depends on the nature of the storage facilities (e.g. storage over a long period or interseasonal storage). For a small depth of storage layer the temperature fluctuations will be higher as compared to a deep storage zone.

Filling the pond

There are several methods available for filling the pond which give a density gradient. A description of each of these methods is given below:

a) **Layer by layer method**

In this method, layers of salt solution, each of about 5-10 cm thick, of different concentrations are delivered to the pond one above another, starting with the highest concentration at the bottom. The salt water may be delivered to the pond using floats with radial holes which allow flow in the radial direction and thus prevent vertical mixing. Figure 12 shows a typical density gradient in a 0.5 m laboratory pond where filling was performed by adding one layer above another, starting with the densest layer at the bottom. Usually the ponds are filled from the bottom upwards, introducing the bottom layer (containing the highest concentration of salts) first. A solar pond[38] may also be filled by starting with the lightest layer at the bottom. Successive denser layers are pumped below the lighter layer, thereby lifting the lighter layer.

In this case, if the heating is started immediately after filling, convection may become esta-

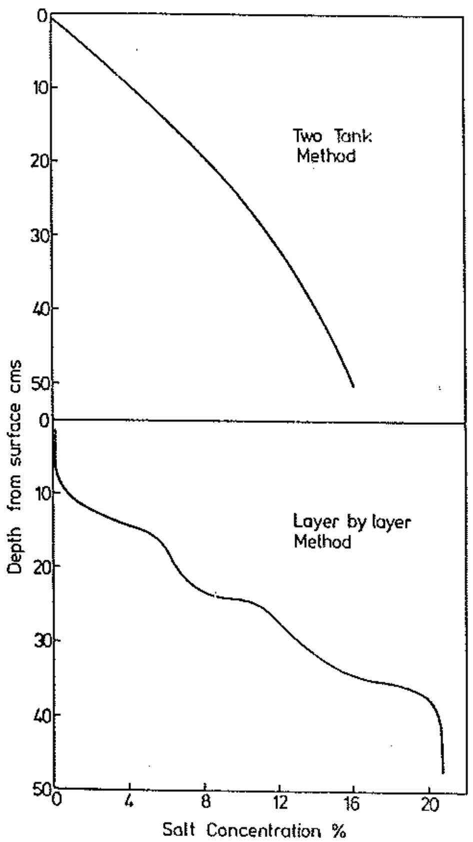

Fig. 12 Typical density gradient in solar ponds.

blished. The thermal diffusivity of salt water is about 100 times greater than the salt diffusivity. Thus it is possible that the destabilizing temperature gradient might diffuse more rapidly than the stabilised salt gradient and convection currents may persist. This can be avoided by allowing a time lag between filling and the start of heating in order to permit a continuous gradient to form due to the diffusion of salt.

b) **Two-tank method**

A continuous density gradient may be built into the pond by using two tanks to provide fluid during filling. One tank would provide plain water at a constant head while the other, with a variable head, would supply saturated salt water, and both the tanks would discharge into a common feed system. The level of water in the water tank is maintained constant, thereby delivering a constant flow rate of water to the feed solution, whereas the level of the salt solution in the salt water tank is allowed to fall, and consequently delivers decreasing amounts of salt solution. The density of the resulting solution decreases as the filling continues, giving a continuous gradient, as shown in Fig. 12. This method is normally suitable for a small experimental pond.

c) **Layer formation method**

In this method, the pond is initially filled to a certain depth with a saturated solution of salt. Different amounts of fresh water are pumped into the solution at different depths, using a diffuser – the exact amount of water required at different depths being dependent upon the density of the salt solution required for a particular density gradient as determined by the stability criteria. In this method, there will initially be some mixing in each of the different layers due to the presence of fresh water and salt solution. An equilibrium density is attained within a short time. Like method (a), heating immediately after filling should be avoided to prevent a convection current between the layers, which may destroy the concentration gradient.

Extraction of heat

Heat can be extracted from the storage zone of the solar pond by –

a) laying an array of pipes through which heat exchange fluid is pumped;

b) passing the fluid from top of the storage zone through an external heat exchanger and returning it to the bottom of the pond.

In the first method, the heat transfer mechanism is mainly controlled by natural convection phenomena, and a large surface area is required for a particular amount of heat transfer as compared to method (b). Hipsher and Boem[42] studied method (a) analytically to show the effect of tube spacing, heat extraction rate and pond depth. Nielsen[13] used a heat exchanger consisting of about 36 m of 2.54 cm copper tube located at a height of 0.5 m above the base of the 2.5 m deep prototype solar pond, which had an area of about 200 m^2. He observed a satisfactory operation of the system with a sodium chloride salt solution which he used to obtain the density gradient in the pond. However, it has been found that a solution of commercial $MgCl_2$ has some corrosion effects on copper because of the presence of magnesium sulphate.

In the second method, the salt water is circulated through the external heat exchanger using appropriate diffusers to prevent erosion of the gradient zone due to excessive velocity of the fluid. This method has been tried by Jain[16] and Zangrando and Bryant.[19] This method may be suitable for commercial and industrial process heat.

The 7600 m^2 and 250 000 m^2 ponds at, respectively, Ein Bogeg and Beit Ha 'Arava, use an external heat exchanger to withdraw energy from the pond.

MAINTENANCE OF THE POND

It is essential to ensure proper maintenance of the salt gradient to prevent convection currents. Due to the density difference between the surface and the bottom of the pond, there will be a diffusion of salts from the bottom to the surface, and this will cause a change in the density gradient. This requires the addition of salts to the storage zone and the removal of salts from the surface.

The transparency of the pond is also an important factor, since it determines the amount of radiation reaching the storage zone of the pond. Factors affecting the transparency of the pond will be described separately.

Diffusion of salts

The rate of transfer of salt due to the density difference in a solar pond is determined by Fick's Law:

$$\dot{m}_s = -\alpha_s \frac{\partial S}{\partial h} . \tag{3}$$

The salt diffusion coefficient, α_s, is a function of temperature and salt concentration. For sodium chloride this varies from 1.296×10^{-4} m^2/day to 4.54×10^{-4} m^2/day for a temperature variation of 25°C to 90°C respectively.[41] For $MgCl_2$, this varies between 9.6768×10^{-5} and 1.49×10^{-4} m^2/day for a range of temperature of 20°C to 40°C.

Assuming an average coefficient of salt ($NaCl_2$) diffusion of 2.9×10^{-4} m^2/day for a pond having an insulation layer thickness of 1 m, it will be found that the rate of salt transfer, due to a density difference of 200 kg/m^3 between the top and bottom of the pond, will be 1.75 kg salt/m^2 per month. A 100 000 m^2 pond will require about 175 000 kg/month to be added at the bottom of the pond to maintain a constant density gradient. As a result of this diffusion of salts towards the surface and also due to evaporation from the surface, the density of water at the surface will increase and create an unstable situation at the surface. This requires occasional washing of the surface with fresh water. The rainwater helps in the washing process.

An alternative suggestion for a means of maintaining the salt concentration and stability is the concept of a 'falling pond'.[43] In this method, the concentrated brine remaining after heat extraction by flash evaporation is returned to the bottom of the pond. Fresh water (condensate) is added to the surface simultaneously. The level of the pond water falls gradually due to heat extraction, while the addition of fresh water ensures the correct level, and the diffusion of salt upward maintains the desired concentration gradient. A schematic representation of the method is shown in Fig. 13. Mathematically, this can be represented by the following equation:[4]

$$Q = \omega S - \alpha_s \frac{\partial S}{\partial h} , \tag{4}$$

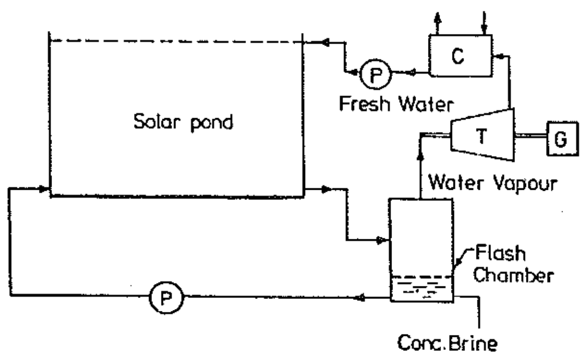

Fig. 13 Conceptual arrangement of a 'Falling Pond' technique.

where ω = bulk movement of the fluid

α_s = salt diffusion coefficient

h = depth of the pond.

The 'falling pond' concept has not yet been evaluated in practice and further investigation is required, particularly with regard to the specification of appropriate control functions.

Transparency of the pond

In order to operate the pond effectively, it is essential to keep the pond clear. The dust particles floating on the surface of the pond may be removed either through the process of surface washing or by mechanical means. Particles that settle at the bottom do not create any serious problem although they may reduce the absorptance of the pond base. The bottom of the solar pond does not need to be perfectly black, and in practice it is always covered with debris which destroys the original colour.[19] A light-coloured liner on the walls may be beneficial since it will absorb little radiation and minimize the risk of localised convection effects which may destroy the salt gradient. Particles that remain suspended in the liquid may create problems because they reduce the transparency of the liquid, but these can be removed by periodic horizontal sweeping of the pond with vertical filters. Nielsen[44] found that biological growth in the pond can be prevented by the addition of copper sulphate with a trace of hydrochloric acid. About 3 ppm of $CuSO_4$ is required in this process and a slight acidity ($pH < 6$ or 7) is sufficient to keep copper in solution.

APPLICATIONS AND ECONOMICS OF SOLAR PONDS

The applications of solar ponds, like any other conventional collection and storage system of solar energy, depends on the available temperature. This in turn depends on the location of the pond and the local meteorological conditions. Solar ponds may be used for the following low temperature applications:

a) heating and cooling of buildings,

b) power generation,

c) desalination,

d) salt production,

e) low temperature industrial process heating,

f) greenhouse heating, and

g) grain drying.

a) Heating and cooling of buildings

The building heating system does not require a very high temperature source to maintain a comfortable temperature (approximately 21°C) in rooms. The heating load is mainly required in winter when the level of insolation is fairly low. It is thus necessary to design the pond for inter-seasonal use by providing a deep storage zone. The performance of the pond can also be improved by providing reflectors. Rabl and Nielsen[12] studied the possibility of using solar ponds for

Table 3
Performance of solar pond under different climatic conditions (Rabl and Nielsen[12])

Location	Latitude	Air Temp (°C)		Insolation (W/m²)		No. of degree-days Per year (°C days)	Size of pond			Performance of pond	
		$\overline{T}_a$	$\overline{T}_{ao}$	$\overline{H}$	$\overline{H}_o$		A (m²)	d_i (m)	d_c (m)	$\overline{T}$ (°C)	$\overline{T}_o$** (°C)
Alburquerque	35° 03 'N	13.4	12.2	254.2	112.0	2416	60	0.6	2.6	76.0	36.2
Boston	42° 22 'N	10.8	12.2	152.9	93.3	3130	140	1.6	1.8	62.6	28.6
St. Cloud	42° 35 'N	5.6	16.9	171.2	106.7	4933	180	1.8	2.2	68.3	27.4
Seattle	47° 36 'N	10.6	7.5	147.0	109.7	2858	130	1.6	1.8	67.6	28.6
Fairbanks*	64° 49 'N	−3.6	19.7	115.7	115.7	7933	240	1.6	3.4	70.1*	31.8*
Columbus	40° 00 'N	12.2	12.2	157.7	110.4	3145	140	1.4	1.6	76.3	32.6

* with mirror to double insolation
** with ground interaction

$H(t) = \overline{H} + \overline{H}_o \cos wt$
$T(t) = \overline{T} + \overline{T}_o \cos (wt - \phi_1)$

Total depth of pond
$d = d_i + d_c$
d_i = depth of insulation layer
d_c = thickness of convection layer

space heating applications and found that even at Fairbanks, Alaska [64° 49'N], a reasonably high temperature is attainable in the pond by using a mirror, as shown in Table 3.

In order to evaluate the cost of thermal energy obtained from such ponds, Nielsen[45] carried out an estimate with a 50 m diameter pond. The total depth was 4 m with a 2.2 m storage zone containing 22% sodium chloride by weight. The pond had a floating surface grid for wave control. The estimated construction cost, including earth moving, walls, liner, salt, surface grid and heat exchangers, for this pond was about US\$47.5/m^2. The cost of thermal energy obtained from the pond was estimated at 2.0 ¢/kWh. This higher cost was partly due to interseasonal usage, and would be different for different countries, depending on the cost of material and labour.

Bryant and Colbeck,[14] Hawlader and Brinkworth,[25] and Hawlader[46] also investigated the possibility of using a solar pond for space heating in the U.K. It was found that a modest load could be served and produce useful temperatures even in the unpromising climate. An auxiliary heater is essential to provide additional energy in order to maintain the desired temperature.

Solar cooling in conjunction with an absorption refrigeration cycle requires temperature of the order of 80 to 90°C. The COP of the absorption machine is strongly dependent upon the temperature at which energy is supplied to the machine. It is thus essential to supply energy at a reasonably constant temperature. Hawlader[47] considered the possibility of using solar ponds for space cooling. The study showed that tropical climate solar ponds can supply a moderate load at the desired temperature.

The total cost of this system now includes the cost of a cooling machine in addition to the cost of the pond. When the mean daily output of the pond matches the cooling load, the total cost of the pond can be obtained from the following expression:[48]

$$AC_P + \frac{DC_m}{R} = D\left[\frac{C_P}{P\,COP} + \frac{C_m}{R}\right],$$

where A = surface area of the pond

C_p = cost per unit area

D = mean cooling load

P = mean power output from the pond

C_m = cost of cooling machine per 'nominal' rated ton of cooling,

R = derating factor

COP = coefficient of performance,

and the total area of the pond is given by:

$$A = \frac{D}{P\,COP}.$$

b) Power generation

As already mentioned, the performance of the solar pond and its applications depend on its location and on local meteorological conditions. In some areas, the solar pond attains very high temperatures, nearly 100°C. It is possible to convert this energy into electricity by using a working fluid (ammonia or freon) which operates in a closed cycle. This requires two heat exchangers, one for the boiler and the other for the condenser, as shown in Fig. 14.

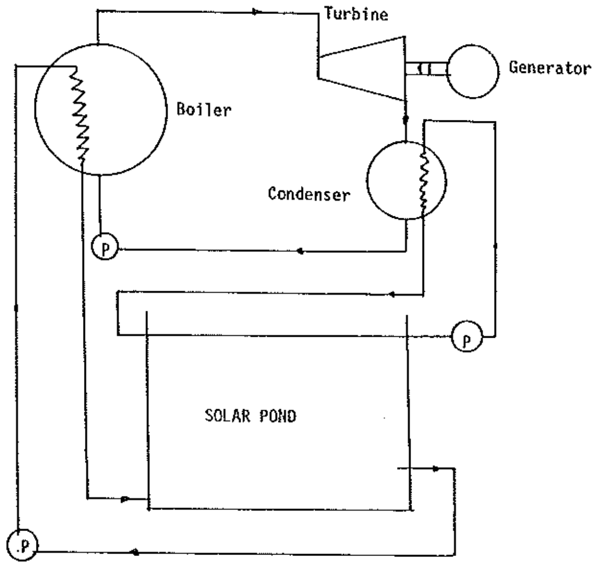

Fig. 14 Schematic diagram of a solar pond power plant.

Most of the work on solar ponds for power generation was carried out in Israel. A 7000 m^2 pond at Ein Bokek can generate a peak power of 150 kW. Tabor[6] estimated the cost of energy produced from such a pond in Israel. The cost of thermal energy was found to be 0.44¢/kWh(t) whereas the cost of electricity was found to be about 8¢/kWh for a thermodynamic conversion efficiency of 8%. A 250 000 m^2 pond has been in operation at Beit Ha'Arava, Israel.[21] This plant produces 5 MW of electricity.

c) Desalination

Multi-stage flash distillation plants have been used for desalination for areas where no fresh water supply is available, but brakish or sea water is available. This process requires the water to be heated to a predetermined temperature, which is about 70°C. Solar ponds offer a good potential source of heat for this low temperature water. Tabor[49] conducted a study to determine the availability of solar pond energy for this application. It was shown that the costs of water produced using a solar pond as the heat source are lower than the costs of using conventional fuel.

d) Salt production

Solar ponds can be used for salt production. The quality of salt produced from a solar pond appears to be better compared to the open pan type. This method increases the yield by twice that of an open pan evaporation plant. Salt production using solar ponds has been extensively studied by Matz et al.[50]

e) Industrial process heat

Many industrial processes, particularly in the food and paper industries, require low temperature thermal energy. Solar ponds may be used to supply this low temperature energy. For processes requiring thermal energy at temperatures higher than 100°C, solar ponds can also be used for preheating the water or air. Solar ponds are particularly suitable for process industries located outside the city area where land is available for the construction of the pond.

f) Greenhouse heating

Short et al.[20] have reported the use of a solar pond for greenhouse heating. This pond had an area of about 150 m^2. The total depth of the pond was 3 m, with a 1.5 m storage zone. A shell and tube heat exchanger was used for the extraction of heat from the pond. The heating system was designed so that the energy was extracted from the pond as long as the temperature in the storage zone remained above 40°C. A heat pump was used to deliver heat when the temperature of the storage zone dropped below 40°C. The temperature of the water delivered to the greenhouse was fixed at 40°C. When the solar system was not operating, a gas heater was used to supply the required energy.

g) Grain drying

Crop drying, under controlled conditions, is another low temperature application of solar ponds. This can be achieved by circulating warm air through a barn which contains the drying crop. If a high temperature is required, the solar pond can be used for preheating the air.

Table 4 gives the comparative costs of a few systems using solar ponds for the supply of low temperature thermal energy.

Table 4.
Cost comparison of solar ponds for different applications
(Nielsen[45])

Applications	Pond Size and cost	Average Output	Thermal Energy Cost
Winter space heating, Ohio, 40°N	50 m dia $47.5/m^2$	54 kW 27.5 W/m^2	2.0 ¢/kWh
Laundry, water pre-heating, Ohio, 40°N	100 m dia $18.33/m^2	291 kW 37 W/m^2	0.57¢/kWh
Water heating for hotel, Hawaii, 20°N	100 m dia $12.00/m^2	526 kW 67 W/m^2	0.20¢/kWh
Process heat (60°C), Texas, 26°N	500 m X 200 m $5.30/m^2	50 MW 50 W/m^2	0.12 ¢/kWh

REFERENCES

1. Styris D.L., R. Zaworski, and O.K. Harling (1975), *The non-convecting solar pond – an overview of technological status and possible pond application,* A report by the Pacific Northwest Laboratory of the Battelle Memorial Institute, Report No. BNWL 1891, Richland.
2. Kalecsinsky, A.V. (1902), Ueber die ungarischen waimen un heissen Kochsalzseen als natuerlich Waermeaccumulatoren, *Ann. Physik, IV,* Vol. 7, p. 408.
3. Hirschmann, J. (1962), *Suppression of natural convection in open ponds by a concentration gradient,* Report on UN Conf. on New Sources of Energy, New York, p. 478.
4. Dickinson, W.C., Clark, and A. Iantuono (1976), Shallow solar pond for industrial process heat: The ERDA-SOHIO PROJECT, *Solar Thermal and Ocean Thermal: Sharing the Sun,* Vol. 5., p. 117, *Proc. AS/ISES and the Solar Energy Soc. Canada Inc.,* Winnipeg, Aug 15-20, 1976.
5. Kooi, C.F. (1981), Salt gradient solar pond with reflective bottom: application to the saturated pond, *Solar Energy,* Vol. 26, No. 2, pp. 113-120.
6. Tabor, H. (1981), Solar ponds, *Solar Energy,* Vol. 27, No. 3, pp. 181-194.
7. Anderson, C.G. (1958), Limnology of shallow saline meromectic lake, *Limnology and Oceanog.,* Vol. 3, pp. 259-269.
8. Wilson, A.T. and H.W. Wellmann (1962), Lake Vanda, an Antarctic Lake, *Nature,* Vol. 196, pp. 1171-1173.
9. Por, F.D. (1970), Solar lakes on the shores of the Red Sea, *Nature,* Vol. 218, pp. 860-861.
10. Tabor, H. (1959), Solar collector developments, *Solar Energy,* Vol. 3, No. 3, pp. 8-10.
11. Styris, D.L., O.K. Harling, R.J. Zaworski, and J. Leshuk (1976), The non-convecting solar pond applied to building and process heating, *Solar Energy,* Vol. 18, pp. 245-252.
12. Rabl, A. and C.E. Nielsen (1975), Solar pond for space heating, *Chemtec,* pp. 608-616.
13. Nielsen, C.E. (1976), Experience with a prototype solar pond for space heating, Solar thermal and Ocean thermal, Sharing the sun, Vol. 5, pp. 169-182, *Proc. Conf. AS/ISES and Solar Energy SOC of Canada Inc.,* Winnipeg, Aug. 15-20, 1976.
14. Bryant, H.C. and I. Colbeck (1977), A solar pond for London?, *Solar Energy,* Vol. 19, No. 3, pp. 321-322.
15. Beckman, W.A. (1977), Problems of solar cooling system, *Sun World,* No. 6, pp. 2-6.
16. Jain, G.C. (1973), Heating of solar ponds, *Conf. Proc. Solar Energy Congress,* Paris, July 1973.
17. Usmanov, Y.U., G.Y. Umarov, and R.A. Zakhidov (1969), Salt ponds as accumulators of solar energy, *Geliotekhnika,* Vol. 5, p. 49.
18. Hirschmann, J.R. (1970), Salt flats as solar heat collectors for industrial purposes, *Solar Energy,* Vol. 13, pp. 83-97.
19. Zangrando, F. and H.C. Bryant (1978), Heat extraction from a salt gradient solar pond, *Solar Age,* 1978.
20. Short, T.H., C.B. Phillip, and W.L. Roller, The operation of a solar pond to greenhouse heat-

ing system, *Proc. 4th Ann Workshop on Solar Energy for Heating Greenhouse.*

21. Beit Ha'Arava solar pond power plant inaugurated (1984), *Sunworld,* Vol. 8, No. 1, pp. 18-19.

22. Chinery, G.T. and G.R. Siegel (1983), Design, construction, and cost of TVA'a 4000 m^2 (1-acre) non-convecting salt-gradient solar pond, *Proc. ASME 5th Technical Conf.,* April 18-21, 1983, Orlando, Florida.

23. Charters, W.M. S. (1983), Solar ponds in Australia, *Sunworld,* Vol. 7, No. 1, pp. 10-13.

24. Hawlader, M.N.A. (1980), The influence of the extinction coefficient on the effectiveness of solar ponds, *Solar Energy,* Vol. 25, pp. 461-464.

25. Hawlader, M.N.A. and B.J. Brinkworth (1980), An analysis of the non-convection solar ponds, *Solar Energy,* Vol. 27, No. 3, pp. 195-204.

26. Dake, J.M.K. and D.R.F. Harleman (1969), Thermal stratification in lakes: analytical and laboratory studies, *Water Resources Res.,* Vol. 5, p. 484.

27. Akbarzadeh, A. and G. Ahmedi (1978), Yield of ground storage of heat in solar ponds, *Proc. ISES Conf. Sun, Mankind's Future Source of Energy,* pp. 1165-1170, New Delhi, 1978.

28. Eagleson. P.S. (1970), *Dynamic Hydrology,* McGraw-Hill, New York.

29. Weinberger, H. (1964), The physics of solar pond, *Solar Energy,* Vol. 8, pp. 45-56.

30. Hull, J.R. (1980), Computer simulation of solar pond thermal behaviour, *Solar Energy,* Vol. 25, pp. 33-40.

31. Holman, J.P. (1976), *Heat Transfer,* McGraw-Hill, New York.

32. Duyar, A. and W. Borber (1984), The bottom loss of a solar pond in the presence of moving ground water, *Journal of Solar Energy Engineering,* Vol. 106, pp. 335-340.

33. Hawlader, M.N.A. (1982), The use of solar ponds for air conditioning, *Proc. Conf. on Utilization of Solar Energy for Refrigeration and Air Conditioning,* Int. Institute of Refrigeration, March 14-19, 1982.

34. Kooi, C.F. (1979), The steady state salt gradient solar ponds, *Solar Energy,* Vol. 23, pp. 37-45.

35. Akberzadeh, A. and G. Ahmadi (1977), Computer simulation of the performance of a solar pond in southern part of Iran, *Solar Energy,* Vol. 24, p. 321.

36. Atkinson J.F., and D.R.F. Harleman (1983), A wind-mixed layer model for solar ponds, *Solar Energy,* Vol. 31, No. 3, pp. 243-262.

37. Defant, A. (1961), *Physical Oceanography,* Pergamon Press, Oxford.

38. Davey, T.R.A. (1968), *The Aspendale solar pond,* Rep. R15, CSIRO, Australia.

39. Nielsen, C.E. and A. Rabl (1976), *Salt requirements and stability of solar ponds,* Department of Physics, Ohio State University, Columbus.

40. Leshuk, J.P., R.J. Zaworski, D.L. Styris, and O.K. Harling (1978), Solar pond stability experiment, *Solar Energy,* Vol. 21, No. 3.

41. Elwell, D.L., T.H. Short, and P.C. Badger (1977), Stability Criteria for Solar (Thermal-Saline) ponds, *Proc. Conf. 1977 Ann. Meeting of the AS/ISES,* Orlando, June 6-10, 1977.

42. Hipsher, M.S. and R.F. Boehm (1976), *Heat Transfer Consideration of a Non-Convecting*

Solar Pond Heat Exchanger, ASME Paper No. 76-WA, Vol. 4.

43. Tabor, H. and R. Matz (1965), Solar pond project, *Solar Energy,* Vol. 9, No. 4, pp. 177-192.
44. Nielsen, C.E. (1977), *Solar Pond/Update 1977.* Dept. of Physics, Ohio State University, Columbus.
45. Nielsen, C.E. (1979), Non-convecting salt gradient solar ponds, *Solar Energy Handbook* (Ed. Dickenson and Cheremishoff), Marcel Decker, New York.
46. Hawlader, M.N.A. (1984), Performance characteristics of solar ponds operating at different latitudes, *Applied Energy,* Vol. 17, pp. 97-115.
47. Hawlader, M.N.A. (1981), Solar ponds for space cooling, *Proc. Conf. 3rd Convention of Engineering Institutions of South East Asian Nations, Singapore,* 15-18 April, pp. 311-333.
48. Tabor. H. and Z. Weinberger (1980), Non-convecting solar pond, *Solar Energy Handbook* (Ed. Kreider), McGraw-Hill, New York.
49. Tabor, H. (1975), Solar Pond on heat source for low temperature multi-effect distillation plants, *Desalination,* Vol. 17, p. 289.
50. Matz, R., E.M. Feist, and M.R. Bloch (1965), The production of salt by means of a solar pond, *Chemical Engineering,* April 1965, pp. CE81-87.
51. Raphael, J.M. (1962), Prediction of temperature in rivers and reservoirs, *Proc. ASCE J. Power Division,* No. PO2, Paper 3200, pp. 157-181, July 1962.