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Non-convecting solar ponds

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A salt gradient is imposed on a black-bottomed pond about 1 m deep; this creates a density gradient (positive measured downwards) which suppresses convection when the pond is heated from the bottom by absorbed solar radiation. Between 15 and 25% of the incident radiation, depending upon pond cleanliness, reaches the bottom and can be decanted by stratified hydrodynamic flow of the bottom layer. Temperatures approaching the boiling point have been recorded. At 32° latitude and under Israel sunshine conditions, estimated annual thermal output from a pond of 1 km^2 is equivalent to 43000 t of fuel oil. A method of avoiding salt diffusion, which would slowly destroy the gradient, is described. Practical problems include suppression of surface mixing by wind and the possible effects of heating large areas of ground.

Basic philosophy and historical background

Solar collectors as known today are small devices usually a few square metres in area: for larger areas, many collectors may be connected together, but clearly this process cannot be used to harness solar energy by the square kilometre. Even the large 'power tower' concept covering very large areas is really an assembly of small units with integration and transport of the collected energy effected by radiation transfer rather than by circulating a thermic fluid.

A mass of water, i.e. a pond, lake or ocean, constitutes a large-area collector – and indeed the ocean has been considered as a source of energy by exploiting the differences in temperature at the surface and at great depth, a difference due to the absorption of solar radiation in the ocean. (O.T.E.C. – Ocean Temperature Energy Conversion – plants were studied and even built in the past, but the very low available temperature difference, ΔT, made them impractical. The U.S. Government has re-opened the subject and is conducting a number of programs, but the basic problem of low ΔT remains.)

Some attempts have been made in the past to use artificial black-bottomed ponds as solar collectors with the aim of obtaining greater temperature differences than occur in natural oceans. If the pond is not covered, evaporation (as well as convection and radiation to the sky) results in pond temperatures close to ambient. Attempts to reduce the evaporative loss by use of an oil layer or monomolecular layer have not been successful owing to the effect of wind removing the layer and, at best, have produced a temperature rise of only a few degrees. Covering such a pond with a transparent window of glass or plastic is a partial reversion to the classical flat plate collector approach with its problems of limited size, removal of dirt, etc.

With this background, the concept of the non-convecting pond (Tabor 1963, 1966)[†] where elevated temperatures at the bottom are possible because the water acts as its own insulator,

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[†] The first reported work on non-convecting solar ponds was initiated by the author in 1958 on the suggestion of Dr R. Bloch of the Dead Sea Works, and continued until 1966 when the work was discontinued owing to the low cost of fuel oil at that time. The project was re-activated, with the support of the Israeli Government, in 1975.

has been particularly attractive. It is to be noted that this concept attacks four of the major technical problems (apart from cost) pertaining to classical collector technology, i.e.

(i) low energy density, which requires large areas;
(ii) effect of intermittency, which requires storage;
(iii) negative influence of dirt collecting on windows and needing removal;
(iv) transport of energy to a central zone.

Thus a solar pond allows collection over large areas with negligible energy transport losses; there are no windows or mirror surfaces to be kept clean and there is built-in storage adequate to smooth out diurnal and weekly fluctuations of output; even seasonal storage is not ruled out.

A number of natural non-convecting solar ponds have been reported in the literature (Kalecsinksy 1902; Anderson 1958; Por 1970; Wilson & Wellman 1962), the density gradient being caused by various mechanisms, such as having a natural salt bottom which is then flooded with water so that natural diffusion gives rise to a salt concentration gradient, i.e. a density gradient that suppresses convection. The famous Medve Lake in Transvaniyl (Kalecsinksy 1902) showed temperatures up to 70 °C at a depth of 132 cm at the end of the summer; a lake in Oroville (Washington) (Anderson 1958) gave temperatures of 50 °C at a depth of 2 m during midsummer.

Experiments conducted in Israel in the mid-1950s with artificial ponds and magnesium chloride (i.e. the end-brines from salt production) gave maximum temperatures of over 90 °C (Tabor & Matz 1965): this was for rather small ponds; more recent experiments on a 1200 m^2 pond gave temperatures of 103 °C: the operators hurried to pump out energy to prevent the temperature rising still further!

STABILITY CRITERIA

When a mass of water of uniform density is heated from the bottom, the density of the heated portion decreases: buoyancy forces then cause this water to rise leading to the classical convection pattern. If, however, we start with a solution that, at a uniform temperature T, has a positive density gradient $\mathrm{d}\rho/\mathrm{d}z$, where z is depth measured positive going downwards, convection will only start – in the simple model – when the effect of local heating is to reduce the density gradient locally to zero or just negative.

Thus the density gradient due to salt concentration must be greater than the negative density gradient produced by the temperature gradient, i.e.

$$\frac{\mathrm{d}\rho}{\mathrm{d}z} = \frac{\partial s}{\partial z}\frac{\partial \rho}{\partial s} \geqslant -\frac{\partial \rho}{\partial T}\frac{\partial T}{\partial z}, \tag{1}$$

where s represents salt concentration (note that $\partial\rho/\partial T$ is a negative quantity) i.e. the required salt concentration gradient, at any point in the pond, should satisfy the equation

$$\frac{\partial s}{\mathrm{d}z} \geqslant -\frac{\partial \rho}{\partial T}\frac{\partial T}{\partial z}\bigg/\frac{\partial \rho}{\partial s}. \tag{2}$$

In actual fact, because of small perturbations that occur in all natural systems, the salt gradient required for maintaining stability is given by (Veronis 1965)

$$\frac{\partial s}{\partial z} \geqslant -\left[\frac{\nu+k_{\mathrm{T}}}{\nu+k_{\mathrm{s}}}\right]\frac{\partial \rho}{\partial T}\frac{\partial T}{\partial z}\bigg/\frac{\partial \rho}{\partial s}, \tag{3}$$

where ν is the viscosity, k_T the coefficient of temperature diffusivity, and k_s the coefficient of salt diffusivity. For weak solutions the quantity in the square bracket has a value of about 1.14, i.e. the criterion for stability is somewhat more stringent than given by the simple buoyancy model.

In any real pond with a non-convecting zone there will be a mixed zone at the top due to wind, and a mixed zone at the bottom due to energy extraction as described later. In actual fact, an NaCl pond (greater than 75 cm deep) must have a mixed zone at the bottom as the stability conditions (at the bottom) would call for salt concentrations greater than saturation. In connection with the mixed zone at the top, how to reduce the effect of wind effectively and economically is still subject to study.

Transmission of solar radiation

We first note that there is a reflexion loss at the surface. The usual Fresnel laws can be used, taking the refractive index of water as 1.33, and integrating for the angular position of the Sun during the day. Because a solar pond is horizontal, the loss is quite small in summer when the sun is nearly overhead, and its value increases in winter, especially for the higher latitudes. Thus the following table (Tabor & Weinberger 1979) shows the fraction τ of solar radiation that just penetrates the surface.

Table 1. Values of τ for direct radiation

latitude 1 deg.	summer solstice	equinox	winter solstice
0	0.97	0.97	0.97
10	0.97	0.97	0.96
20	0.97	0.97	0.95
30	0.97	0.96	0.93
40	0.97	0.96	0.89
50	0.96	0.94	0.78

This is for direct beam radiation. For diffuse radiation, using the approximation that the sky is of uniform brightness (which is not strictly true), then the value of τ for diffuse radiation is approximately 0.93.

Using some typical figures we arrive at table 2 when allowance is made for both direct and diffuse components of the incident radiation.

Table 2. Seasonal variations in radiation/(W m^{-2}) at various latitudes

latitude/deg	spring equinox	summer solstice	autumn equinox	winter solstice
0	307	264	302	281
10	301	296	297	235
20	283	319	279	183
30	252	331	248	129
40	213	333	211	74
50	166	321	163	30

We observe that the ratio of maximal to minimal daily mean irradiance is only 1.16 at the equator but increases to 10.7 at high latitudes. This large ratio at high latitudes severely influences the usefulness of solar ponds at these latitudes.

Having penetrated the surface, the insolation is then attenuated by absorption in the pond so that only a fraction reaches the bottom (figure 1). Natural ocean waters are remarkably clear: artificial solar ponds will tend to be less so. Thus dirt that falls onto the surface of a homogeneous lake will either float (and could be skimmed off) or sink to the bottom. In a density-gradient medium, such dirt may sink to a level corresponding to its own density and stay there. Also, the conditions in a solar pond may encourage the growth of thermophilic and halophilic algae (Cohen *et al.* 1977).

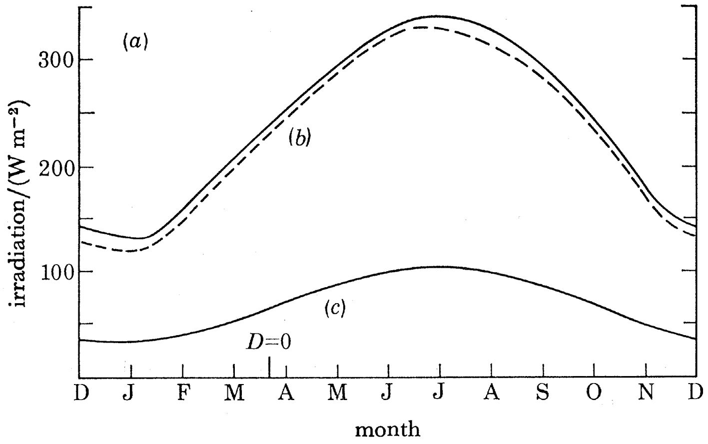

FIGURE 1. Seasonal variation of irradiation: (*a*) daily global incidence (32° latitude – Dead Sea); (*b*) mean daily irradiation just penetrating water surface; (*c*) mean daily irradiation reaching 1 m depth.

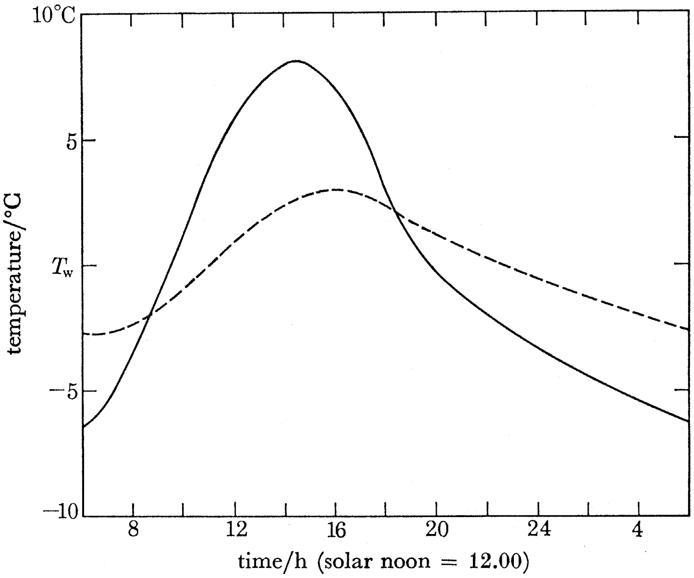

FIGURE 2. Hourly variation about the mean daily temperature, T_w; ——, with no convective zone at the bottom of the pond; – – –, with a 20 cm convective zone at the bottom of the pond.

Quite apart from any 'dirt', the water itself attenuates the radiation; in particular the infrared component is rapidly absorbed in the first few centimetres: as this component represents about half of the solar spectrum, the shallowest pond could not collect more than 50% at the bottom; practical values for ponds of the order of 1 m depth are 15–25%.

It is, however, interesting to note that the energy absorbed on the way down is not entirely without value, as it increases the effective insulation value of the water column above the extraction level. Indeed, as pointed out by Weinberger (1963), under the 'optimum' extraction conditions he chooses, the water behaves as a nearly perfect insulator, i.e. the temperature gradient just above the extraction layer is approximately zero.

CONSTRUCTING THE GRADIENT

The usual method is to add a number of layers of progressively lower concentration, starting from the bottom (though it is also possible to start with the weakest solution and inject heavier solutions underneath). The concentration 'steps' are rapidly smoothed out owing to the diffusion process aided by partial mixing resulting from kinetic energy exchange during the filling process.

HEAT EXTRACTION

Two methods have been proposed for the extraction of energy from a solar pond: the first is to place a heat exchanger in the bottom of the pond, as has been discussed by Hipsher & Boehm (1976). The method suffers from two disadvantages: the first is the large quantity of tubing needed for efficient heat transfer and the second is the difficulty in locating and repairing a damaged element of the heat exchanger on the bottom of the pond.

The second method is to selectively extract the bottom layer of heated brine through an exit port, remove the absorbed energy in an external heat exchanger and return the cooled brine to the pond by means of an entrance port. This method is intrinsic to the physical nature of hydrodynamic flow in the solar pond. In a liquid system possessing a stable density gradient, selective flow of the bottom layer can be maintained without requiring a mechanical separation barrier between the flowing and stable regions of the system (Elata & Levin 1962; Daniels & Merriom 1975). An example in Nature is the flow of seawater over long distances up the bed of the estuary of freshwater rivers.

Experimental studies of stratified flow for the conditions to be expected in a solar pond indicate that stable flow is established when the Froude number Fr is unity, i.e.

$$Fr = \frac{v}{d^2}\left[\frac{2\rho}{g\,\partial\rho/\partial z}\right]^{\frac{1}{2}} = 1, \tag{4}$$

where v is the flow per unit width of the pond and d is the thickness of the mixed flowing layer. Equation (4) is valid for Reynolds number vd/ν less than 1000. If U is the energy extracted per metre width, then

$$U = v\rho c d \Delta T/L, \tag{5}$$

where ΔT is the temperature drop (kelvins) in the heat exchanger, L the length (metres) of the pond, and c the specific heat of the brine.

Equation (4) then yields:

$$d^3 = \frac{LU}{\rho c \Delta T}\left[\frac{2\rho}{g\,\partial\rho/\partial z}\right]^{\frac{1}{2}}.$$

Consider a numerical example: $L = 1000$ m, $\rho c = 3.1\times10^6$ J/(m³ K), $\rho = 1.2\times10^3$ kg/m³, $U = 100$ W/m² (this is considerably larger than will generally occur), $\Delta T = 10$ K,

$\partial\rho/\partial z = 200$ kg m^4. Then $d = 0.12$ m and $v = 0.11$ m/s. The thickness d predicted has been confirmed within a factor of two in experimental ponds: it is seen that both d and v have practical values.

SALT DIFFUSION

A concentration gradient in a mass of water will not normally be maintained indefinitely even if the water is quiescent. This is because of the effects of diffusion. The process is, in fact, quite slow but because it is integrative and the areas involved are large, considerable quantities of salt will diffuse towards the surface. Thus a quantity of 60–80 g/m^2 day, as typical for an operating pond, may not sound much, but this is of the order of 20000 tonnes per year for a pond of 1 km^2! Thus steps have to be taken either to replace the salt that diffuses upwards, or to avoid the diffusion.

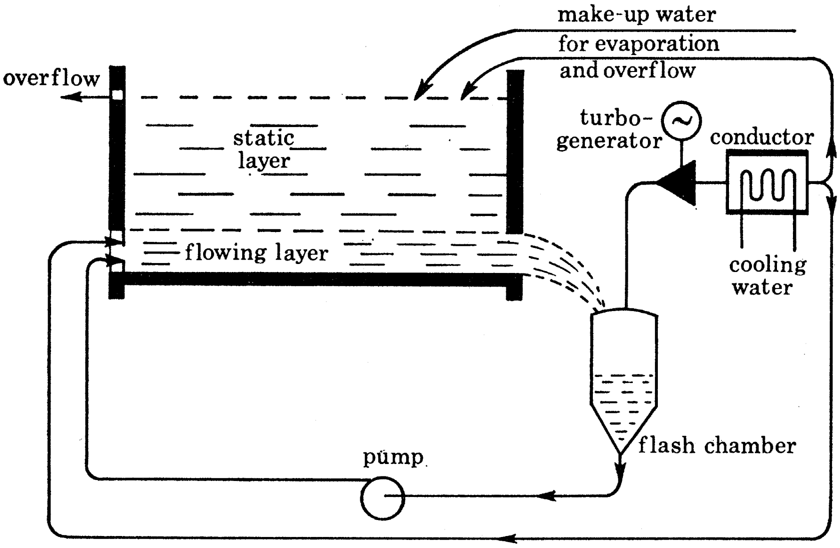

FIGURE 3. Schematic representation of the 'falling pond' method of extracting heat from the bottom of a pond.

We note that the salt concentration gradient in a solar pond is governed by the diffusion equation:

$$\partial\left(k_s\frac{\partial s}{\mathrm{d}z}\right)\Big/\partial z = \frac{\partial s}{\partial t}, \tag{6}$$

where k_s is a 'constant' being a weak function of concentration but strongly temperature dependent.

For steady state conditions, i.e. $\partial s/\partial t = 0$, integration gives the salt flux q as:

$$q = -k_s\frac{\partial s}{\mathrm{d}z}. \tag{7}$$

However, if the mass of fluid in the pond has a vertical velocity v (measured positive downwards), equation (6) has to be written

$$\partial\left(k_s\frac{\partial s}{\mathrm{d}z}\right)\Big/\partial z = v\frac{\partial s}{\partial z}+\frac{\partial s}{\partial t}, \tag{6a}$$

which, under steady state conditions, leads to:

$$q = vs - k_s \frac{\partial s}{\partial z}. \qquad (7a)$$

This equation leads to one method of avoiding the diffusion effect and is known as the 'falling pond' concept (Tabor 1966).

As we have seen, one method of extracting heat from the bottom of the pond is to decant the hot layer at the bottom from openings at one end of the pond. The heat content can be obtained by flashing this hot brine in a chamber at sub-atmospheric pressure, the vapour being used to operate a heat engine or to pass its heat on to a second fluid via a heat exchanger. The brine that is left contains all the salt but less water, so that if it is returned to the other end of the pond, we have returned all the salt but less water, i.e. the pond mass moves downwards. A calculation shows that this rate of fall would be many times the velocity of diffusion upwards so that, by a suitable bypass or dilution of solutions, it is possible to arrange for the velocity of fall v (equation (7*a*)) to equal the velocity of salt diffusion upwards, i.e. *the salt remains stationary in space*. In this way no salt need be added to the mass of the pond. (The situation at the surface is slightly different. Because of evaporation, the salt concentration will tend to increase: therefore the surface is washed with low-salinity water, e.g. seawater, and the overflow rate can be adjusted to maintain a desired constant salt concentration at the surface.) Figure 3 illustrates this 'falling pond' method.

SEASONAL VARIATION AND ENERGY STORAGE

A solar pond, being horizontal, shows a greater variation of output between summer and winter for all latitudes other than near the equator, than a conventional collector that can be tilted. Table 2 shows this effect for the energy *penetrating the surface*: the seasonal variation of the *output* (at constant temperature) from the bottom will be rather similar.

Calculations for a site at latitude of 32° showed a variation of about 4 : 1 between maximum and minimum yields for a fixed operating temperature, i.e. the minimum was about 0.4 times the annual average and the maximum about 1.6 times.

At the bottom of a pond one can expect to find a convecting zone. This zone is necessitated by all envisaged energy extraction processes. Even quite a thin zone will substantially even out diurnal variations. A typical calculation shows that, if there were no convecting zone at the bottom, a daily variation of ± 7 °C about the mean would be expected: with a 20 cm convecting zone, the diurnal variation falls to about $\pm 2\frac{1}{2}$ °C. Larger convective zones can be used to obtain considerable attentuation of the *annual* variation. Thus a simple model, ignoring energy stored in the ground, shows the annual variation $\pm\theta$ of temperature about the annual mean as

$$\pm\theta = \frac{3.16 \times 10^7 \bar{I}}{2\pi d \rho c} = 1.62\ \bar{I}/d,$$

where $\bar{I}$ is the mean energy level (assumed constant extraction rate during the year) and d is the thickness of the storage zone in metres. Thus for $\rho c \approx 3.1 \times 10^6$ J m^{-3} K^{-1}, $\bar{I} = 34$ W/m^2, $d = 10$ m, then $\theta \pm 5.5$ °C.

Efficiency of collection, energy yield and applications

Apart from the question of pond clarity, i.e. how much energy reaches the bottom, the efficiency is affected by many factors, such as the conductivity of the ground under the pond, the depth of the non-convecting layer and the temperature of extraction. The theory is covered in Weinberger's classical paper which indicates optimum depths: a shallow pond will transmit more energy to the bottom but offer a shorter insulating column whereas a deeper pond will bring less energy to the bottom but insulate it better. Thus, for a given clarity (and a given solar radiation régime) there is an optimum depth for each operating temperature. The optimum also depends upon whether the output is required simply as a source of calories for heating purposes or is required to operate a heat engine where the Carnot characteristics of the engine take part in the optimization process. Thus for the sample pond chosen by Weinberger, using the climate in the Dead Sea area and seawater no. 3, the optimum operating temperature is 87 °C with a pond depth of 1.25 m, and a collection efficiency of approximately 24 %. Actual experimental ponds showed somewhat lower efficiencies because a small pond would tend to have a lower clarity than the figure used for ocean water.

The annual yield from solar ponds can be significant in energy terms. If we take an annual efficiency of 20 % in region having an annual global radiation (on the horizontal) of the order of 7200 $\mathrm{MJ/m^2}$ (2000 $\mathrm{kWh(t)/m^2}$) then the annual yield from a pond of 1 $\mathrm{km^2}$ area would be 1800×10^6 MJ (400000 MWh(t)). This is the heat equivalent of burning 43000 t of fuel oil at 80 % combustion efficiency. As a source of power, if the pond outlet temperature were 87 °C, the sink temperature 30 °C, an ideal Carnot engine would have an efficiency of about 13.2 % – allowing a total drop of 10° in the heat exchangers – and a real machine might yield about 60 % of this, i.e. approximately of 32000 MWh(e), equivalent to a continuous power of 3.7 MW or an installed power of 6.4 MW operating 5000 h a year (58 % load factor).

Applications

The solar pond bears some resemblance to the classical flat-plate collector: its maximum temperature is limited to about 100 °C; a further limitation is that it is untiltable so that the system is not practical at high latitudes ($c > 45°$) and, except near the equator, there is a considerable variation between summer and winter outputs. Against these limitations are the advantages already referred to, i.e. large-area collection with very little plumbing; no windows to be kept clean; built-in storage that reduces diurnal variations of output to a small value and which can be increased to provide a considerable measure of seasonal storage. While efficiency will be a little lower than for 'traditional' collectors, the cost per unit area is an order of magnitude lower (i.e. U.S. $\$10/\mathrm{m^2}$ cf. $\$100/\mathrm{m^2}$) leading to the lowest cost energy of any solar device yet proposed.† The solar pond, in those areas where it is practical, can thus be used for any application of heat below 100 °C, such as water heating and the heating and cooling of buildings. (It is not believed that very small ponds are practical: thus this application would be for large buildings or groups of dwellings. One such pond of 6500 $\mathrm{m^2}$ area has been built to heat and cool a hotel now under construction in the Dead Sea area.)

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† With a target cost of $\$10/\mathrm{m^2}$ for the pond and 15 % annual charges, the cost of heat is equivalent to \$26/t fuel oil: current world fuel oil cost is about \$80/t at central delivery points and considerably higher at remote areas.

The calories being low in cost, the generation of electricity can be considered despite the poor Carnot efficiency. One 1500 m² pond constructed at the ORMAT Turbine plant in Yavne has been used to generate electricity, using a 6 kW organic-vapour, low-temperature, Rankine cycle turbine.† With a target cost of \$10/m² for the pond, the 'fuel component' for solar power is about 4½ ¢/kWh(e), which is a little higher than for large central power stations, but much lower than for most small isolated stations. Thus, even at the present state of technology, many applications for solar power can be envisaged for areas not connected to a central grid. (As indicated later there is one option open for competition even with central station power.) Desalination is another possibility, strengthened by the development in Israel of two multi-effect desalination processes that are designed to operate at well below 100 °C. One paper study (Tabor 1975) has been reported, showing how to match a solar pond to a desalination plant with an estimated yield of close to 13000 m³/day from a 1 km² pond.

Table 3 summarizes the estimated yields of heat, power and desalinated water for a 1 km² pond in a solar régime similar to that in Israel.

TABLE 3. ESTIMATED ANNUAL YIELD OF SOLAR POND. AREA 1 km²

(1)	insolation	2000 GWh(t)
(2)	pond heat yield	400 GWh(t)
	equivalent fuel oil	43000 t
(3)	power yield	33 GWh(e)
	source temperature	87 °C
	sink temperature	30 °C
	H-X drops	10° total
	Carnot effect	13.2 %
	turbine factor	0.6
	overall thermal energy	*ca.* 8 %
	equivalent cont. power (58 % load factor)	6.4 MW
(4)	desalinated water	4.7×10^6 m³ (12900 m³/day)

PROBLEMS OF SOLAR PONDS

The basic simplicity and apparent low cost of solar ponds poses the question as to why they are not already in widespread use. There are a number of difficulties and limitations which are now under intensive study and for which viable solutions seem in sight.

(1) *Surface mixing*. The wind tends to mix the upper layer, i.e. there is a convecting zone near the surface. This zone is part of the effective depth z as far as transmission of solar radiation to the bottom of the pond is concerned, but it does not contribute any insulating properties. It is clear, therefore, that the upper mixed layer should be kept as small as possible, preferably in the 5 cm range. Most naturally occurring solar ponds appear to be protected from prevailing winds by local geographical features.

A number of proposals have been made as to how to protect a pond from wind effects economically and effectively without simultaneously unduly attentuating the incident insolation. Thus Nielsen has experimented with floating plastic pipes. One solution *not* recommended is the use of a floating plastic sheet: where this was tried, wind-borne dirt and sand settled on the sheet which became opaque to light in a few days.

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† These turbines were developed in Israel in the 1950s and 1960s (Tabor & Bronicki 1961) for solar use but found no solar market. They were converted to operation by gas or kerosene and have been installed in some 40 countries and many millions of hours of operational experience have been accumulated (Bronicki 1978).

(2) *Geophysical and ecological factors*: loss from the bottom. We note a number of limitations in the siting of a solar pond: it should preferably be situated on relatively sterile land of no mineral importance and near salt or brackish water supplies which have little alternative value. The site should be relatively flat and easily worked to avoid major earth-moving operations.

The site should not overlie too closely an aquifer: if the underlying aquifer is of fresh water, then an accidental leakage of brine from the pond bottom could seriously pollute a valuable water resource. Even if the aquifer contains brackish water, it could pose serious thermal and structural problems for the pond. If the underground flow rate is sufficiently high, then heat will be removed from the pond, i.e. the underground insulation is no longer 'infinite' but limited in depth approximately to the aquifer surface.

The situation for a stationary aquifer can be even more serious. As the aquifer is heated to elevated temperatures, copious quantities of dissolved gases may be released from the aquifer solution. This appears to have occurred in an experimental pond constructed in Atlit, Israel, where the released CO_2 developed sufficient pressure to destroy the packed clay-bed structure of the pond bottom.

Other geophysical requirements are that the underlying earth structure be homogeneous and free of stresses, strains and fissures. If the structure is not homogeneous, then increases in temperature will cause differential thermal expansions which could result in earth movements.

The change of an existing water body – fresh or saline – into a solar pond could affect the food-chain of surrounding flora and fauna. Another problem in solar ponds is the possible growth of thermophilic and halophilic algae (Cohen *et al.* 1977) that can seriously reduce pond transparency.

The lining of the bottom of a solar pond to prevent leakage of solution into the ground – which leakage represents both a loss of heat and of salt inventory – is one of the most expensive items in the construction of a pond since the lining must be unaffected by u.v., by temperatures up to 100 °C or thereabouts and by (hot) concentrated salt solutions. In addition, it must be possible to make lasting watertight seals *in situ*.

SOLAR LAKES

An approach to solving the problems related to the bottom of the pond such as the cost of the lining and difficulties that may arise from elevating the temperature of a large area of ground, has been suggested by Assaf (1976). Here, one encloses an area of a natural lake of great depth and high natural salinity and feeds into the lake, at great depth, higher concentration solution (obtained from a nearby pond where the saline is concentrated by partial solar evaporation). As in the solar ponds discussed, the surface is also 'washed' to maintain a constant low density.

The result is a multi-layer system comprising a thin top mixed layer (due to wind); a non-convecting layer having a concentration gradient (and in which the temperature gradient is created); a thick mixed layer of high concentration and temperature from which heat is extracted (and which provides considerable storage capacity); and a bottom layer, going to the bottom of the lake, having a reverse† temperature gradient giving rise to a small loss of

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† This is equivalent to the 'natural' gradient that occurs in oceans: it is reverse only with respect to the artificial 'inversion' of the solar pond system.

heat from the bottom of the mixed zone (small because the bottom layer is very deep and non-convecting).

This system is now being studied; it has its own problems, one of which is that it can only be tried out on a large scale as the boundary effects are critical: furthermore, the places where it is applicable are limited.

CONCLUSION

The solar pond appears to be an attractive approach to harnessing solar energy on a large scale for thermal applications below 100 °C including power production using low-temperature turbines (the technology of which is already well established) for those areas where it is practical. A number of problems still remain and are the subject of intense R. & D. activity.

REFERENCES (Tabor)

Anderson, C. G. 1958 *Limnol. Oceanogr.* **3**, 259–269.
Assaf, G. 1976 *Sol. Energy* **18**, 294–299.
Bronicki, L. 1978 Reported at the First Israel International Solar Energy Conference, Haifa, September 1978.
Cohen, Y., Krumbein, W. & Shilo, M. 1977 *Limnol. Oceanogr.* **22**, 609–634.
Daniels, D. G. & Merriom, M. F. 1975 Fluid dynamics of selective withdrawal in solar ponds. *ISES Congress*, session 35, Los Angeles.
Elata, C. & Levin, O. 1962 Selective flow in a pond with density gradient. *Hydraulic Laboratory Report*, *Technion*. Haifa, Israel.
Hipsher, M. S. & Boehm, R. F. 1976 Heat transfer considerations of a non-convecting solar pond exchanger *Am. Soc. mech. Engrs* 76-WA/sol 4.
Kalecsinksy, A. V. 1902 *Annln Phys.* D **7**, 408–416.
Por, F. D. 1970 *Nature, Lond.* **218**, 860–861.
Tabor, H. 1963 *Sol. Energy* **7**, 189–194.
Tabor, H. 1966 *Sci. J.*, June 1966, 66–71.
Tabor, H. 1975 Proc. Desalination Conf., Eilat, March 1975. *Desalination* **17**, 289–302.
Tabor, H. & Bronicki, L. 1961 *UN Paper E/CONF* 35/5 54.
Tabor, H., & Matz, R. 1965 *Sol. Energy* **9**, 177–182.
Tabor, H. & Weinberger, H. Z. 1979 Non-convecting solar ponds. *Handbook on solar energy*. New York: McGraw-Hill. (In the press.)
Veronis, G. 1965 *J. mar. Res.* **23**, 1–17.
Weinberger, H. 1963 *Sol. Energy* **8**, 45–56.
Wilson, A. T. & Wellman, H. W. 1962 *Nature, Lond.* **196**, 1171–1173.