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SHALLOW SOLAR POND: STATE-OF-THE-ART

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Abstract—This review article deals with the various aspects of shallow solar ponds (SSP) suitable for domestic purposes and for supplying industrial process heat. The introduction gives a general idea of the status of the SSP technology among various solar energy applications. This part also surveys designs and performance of both water bag type and large scale SSP, already experimentally studied by other workers. The analysis of thermal process of SSP takes the input energy, the mechanism of thermal absorption and various losses in the system, into consideration. The methods for the improvement of the system performance suggests the materials that can be used and designs that can be incorporated in the various components of SSP. Here, a detailed study of the module, the glazing, the glazing supports and the insulation is done. The auxiliary systems viz, the mode of water transfer and water storage, play an important part in the optimum performance of the SSP systems. The "modes of operation" gives an account of the three different ways of circulating the liquid through the system—batch heating, closed cycle continuous flow heating, and open cycle continuous cycle flow heating. The theoretical analysis of the thermal performance of the SSP is done by making use of the Hottel–Willier–Bliss model for the flat plate collectors. A computation based on this model is employed in evaluating the values of monthly average daily collections efficiency with respect to the ambient temperatures for various initial water temperatures. The results obtained from the experiments conducted by Lawrence Livermore Laboratory, gives an idea of the system performance. The review also looks into the effects of various parameters, such as, the mass flow rate of the liquid, the total mass of water required per day, water depth, radiation intensity, average day-time ambient temperature, number of glazings, total heat loss coefficient, etc. The different modes of flow of the liquid are compared. An incorporation of the reflector in the SSP by various workers proved to provide a marked improvement in the system performance. The aspects such as, the cost effectiveness, maintenance and reliability of the SSP are briefly dealt with. It was felt that the review would be incomplete without a mention of the limitations and potential applications of the SSP. Based on these studies on SSP, done by various workers, the conclusion was that the performance of the system can be improved by the proper choice of the material, and by optimizing the design and the modes of operation.

Shallow solar pond   Industrial process heat   Hottel–Whillier–Bliss model

INTRODUCTION

The shallow solar pond (SSP) is a solar energy collector that is intended to supply large amounts of heat to industrial applications at a cost that is competitive with fossil fuel. Its use for the conversion of solar energy into low grade thermal energy has been a subject of intensive investigation for a number of years, especially by the Solar Energy Group at Lawrence Livermore Laboratory (LLL) [1–6].

Though the term shallow solar pond resembles the non-convective salt gradient solar pond, its concept has very much been derived from that of the solar still. The name implies that the depth of water in SSP is very small, typically only a few centimetres, which is like a conventional solar still consisting of a blackened tray holding some water in it. The stills take advantage of evaporation of salt water by solar heat, but in a SSP that shallow level of water is covered by means of a plastic film in such a way that the film comes in contact with the top surface of the water and thus prevents the cooling effect due to evaporation. It is capable of heating a large quantity of water to appreciable temperature, and because of its simplicity in working, it holds out promise for one of the cheapest known methods for harnessing solar energy.

Tracing back the history of shallow solar ponds, we can see that Willsie and Boyle [1–3] were the first to use this novel idea for producing shaft power in the very beginning of the twentieth century. They tried to maximize the efficiency and minimize the cost by using various small systems. The resurgence of the on-going idea of using shallow solar pond for power production put forward by D'Amelio [1–3] is basically the modernization of the technicalities worked out by the pioneer workers like Willsie, Boyle and Shuman.

A shallow solar pond is essentially a large water bag or pillow placed within an enclosure with a clear upper glazing. A schematic diagram of a SSP is shown in Fig. 1. Water is placed within the bag, which is generally constructed from a clear upper plastic film and a black lower plastic film. The depth of the water within the bag is normally in the range of

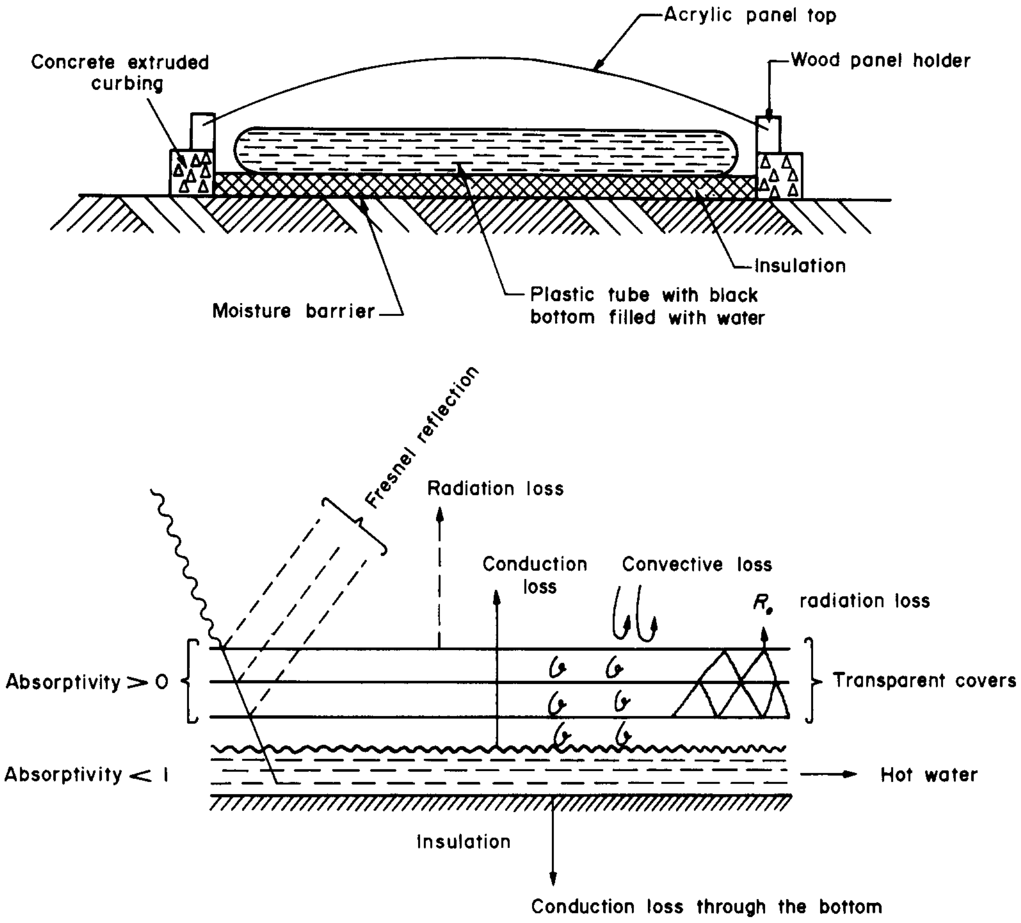

Fig. 1. Schematic diagram of shallow solar pond. (a) Thermal process in shallow solar pond.

4–15 cm. The solar energy collection efficiency is directly proportional to water depth, whereas the grade of thermal energy collected (i.e. the water temperature) is inversely proportional to water depth. Solar energy is converted to thermal energy by heating the water during the day. The water is withdrawn from the SSP before sunset (or more precisely when the collection efficiency approaches zero) for utilization or storage.

The idea of using such a simple device, viz a water pillow, for solar energy collection is not new. The Japanese have been using numerous variations of this idea to heat water for domestic usage since the 1930's. In fact, 39 patents were issued for solar water heaters in Japan in the 1930's and another 20 were issued in the 1940's, the majority of these being for the water pillow type [7].

Harris *et al.* [8] tested a solar water heater which was similar in design to that of the LLL group. The major difference being that their water pillow was constructured from a black butyl rubber tube.

Gopffarth *et al.* [9] tested a plastic solar water heater, in which the water pillow was formed by heat sealing one black layer and one clear layer of polyethylene. They also investigated the use of tedlar as an upper glazing for the enclosure. The utilization of plastic materials as upper glazings in solar collectors has been reported in the literature numerous times, e.g. by Whillier [10] and Grimmer and Moore [11].

Kudish and Wolf [12, 13] have done the testing on a compact SSP designed for camping and military use. Their prototype design consisted of a water pillow placed within an insulated container. The container cover was insulated on the outside to maintain the water temperature for overnight storage and fitted with a mirrored surface (aluminized mylar) on the inside to function as a reflector, when open and in operation during the day.

Sodha *et al.* [14] have done the analytical study of the system consisting of a metallic rectangular tank with black bottom and sides and a transparent cover at the top. It is concluded that one dimensional analysis is adequate for prediction of the performance of the shallow solar pond water heater. The daily efficiency would increase if water would be continually withdrawn for consumption, thereby reducing the average pond water temperature and the resultant rate of heat loss.

These systems have been rejected in the past because low fuel costs and materials problems have made it uneconomical. Recently, however, rapidly rising fuel costs and improvements in inexpensive plastic have made the SSP look more promising.

Typical peak temperatures for a shallow-solar-pond range from 60°C in the summer down to 40°C in the winter. Higher temperatures can be achieved (100°C has been obtained) but only at a substantial sacrifice of efficiency. With a nominal 7.5–10.0 cm operating depth, the annual efficiency of the shallow-solar-pond system is about 50%.

For large scale systems, a team of active workers at the Lawrence Livermore Laboratory is participating in the conceptual, analytical and practical development of shallow-solar-pond systems. There were three attempts to use shallow-solar-pond technology to provide useful energy to a large scale user. One was the ERDA-Sohio (1974) project at Lawrence Livermore Laboratory to provide hot feed water to a uranium leaching operation. This system provided about 50% of the 10^5 GJ (10^5 MBtu) annual requirement of process heat at 60°C, with a consequent annual saving of about 12,000 lbs of fuel oil. The solar heater area under this project was about 6 acres. The second one was Teledyne-Brown Engng:Sweet Sue Kitchens (1978), which was meant for providing hot feed water to the plant boiler at the Sweet Sue Kitchens Inc., a chicken packing plant in Athens, Alabama; but this project failed due to a number of serious design problems and high cost. The solar heated area under this project was 1600 m^2. The third one was Fort Benning, Georgia, which was supposed to supply hot water to a few barrack complexes and to the post laundry. This system consisted of 10,000 m^2 of shallow solar pond area supplying 800,000 l/day of hot water. This project is running smoothly, and moreover, the system economics are more favourable.

THE THERMAL PROCESS IN A SHALLOW SOLAR POND

The input in a shallow solar pond collector is solar insolation. The solar radiation on a surface normal to the sun's rays just outside the earth's atmosphere is about 1353 W/m^2. This is the so-called solar constant. Of this, approximately 7% of the energy is in the ultraviolet spectrum, 47% is in the visible spectrum and 46% is in the infrared spectrum.

In a SSP, the sun's rays are absorbed by the black bottom of the pond. As a result, the shallow water level in the pond get heated. The total solar energy absorbed by the whole system cannot be used as useful energy. This is because of several loss factors and a number of other mechanisms which reduce the total input of solar radiation. For instance, the absorbtivity of the absorbing surface of the collector is never unity. The transparent sheet over the SSP also does not allow all the radiation to go inside. It scatters and absorbs a part of it. There are also thermal losses due to conduction, convection and radiation. Conduction loss is reduced by using a suitable insulation material. In order to reduce the thermal loss by convection and radiation, one or two transparent sheets are used over the pond. This may give rise to Fresnel reflection at the interface of the transparent material. The more would be the transparent covers, the more would be the selective absorption in these covers. The Fresnel reflection depends on the refractive index of the material used. Again, it is necessary to consider the durability of collector materials. The principal component of the solar radiation which causes degradation of the materials is the ultraviolet component of the solar spectrum. So, it is an important task to select the proper material for glazing cover over the shallow solar pond, which would in turn decide the thermal performance of the collector as well as its cost. The thermal process in a shallow solar pond is represented in Fig. 1(a). It is to be noted that a shallow solar pond is very much like a flat plate collector and is also suitable for collection of diffuse radiation. From the above discussion, we once again note that, like all other solar thermal collectors, the efficiency of a shallow solar pond is never the optical efficiency η_o, but the net collection efficiency (η_c) is the difference between the optical efficiency (η_o) and the net loss efficiency (η_l)

$$\eta_c = \eta_o - \eta_l.$$

In a shallow solar pond, the working fluid is water and its physical properties play the most important role in dealing with the whole system. So, before going to the detail of the system discussion, let us simply refresh our memory about the fundamental thermal properties of water.

Thermal conductivity, $K = 1.43 \times 10^{-3}$ cal/cm/s°C
Density $= 1.0$ gm/cm^3
Specific heat $C_p = 1.0$ cal/gm°C
Diffusivity $= 1.43 \times 10^{-3}$ cm^2/s
Viscosity $= 0.01 \dfrac{\text{dyne-s}}{\text{cm}^2}$.

DESIGN OF THE LLL SHALLOW SOLAR POND SYSTEM

Here the costs of a shallow solar pond (SSP) are minimized by the use of large area modules and polymeric materials to replace the metal and glass used in conventional flatplate collectors. The absorber plate is replaced by a layer of water, either flowing or static, contained in a plastic bag with a black bottom and transparent top. A top glazing constructed from a semi-rigid sheet of corrugated clear plastic is arched over the water bag.

Figure 2 shows an artist's concept of the project to approximate scale. Water is pumped from wells and put into cold storage. At or before sunrise the water is pumped into the ponds to collect energy before flow-

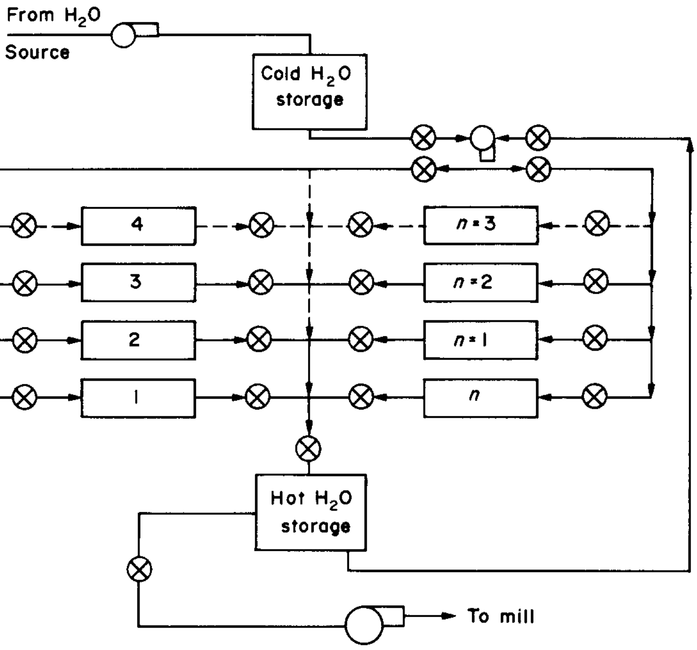

Fig. 2. Water flow schematic of the Sohio project.

ing into hot storage. The pond water can be recirculated if necessary or desired as shown in the flow diagram.

Module design description

Water bag. The water bag is made of two layers of plastic film, usually ultraviolet (u.v.)—stabilized film, sealed along the edges. The bottom layer is 0.5 mm thick and black in colour to absorb solar radiation while the top layer is 0.3 mm thick and colourless. Containment of the water in a closed plastic bag serves to eliminate heat losses by evaporation. The water bag is shielded from dust and wind as well as from most u.v. radiations by the top glazing and is expected to have an effective lifetime of 5 or more years.

Table 1 gives the detailed description about the materials which are used for water bags.

About 95% of solar radiation normally incident on the top surface of the water bag (nominally filled to a depth of about 10 cm) will pass into the water. About half of this radiation lies in the near infrared ($\lambda > 0.7\,\mu$m) and is absorbed in the top few centimeters of the water. Of the remaining radiation, about 95% will be absorbed by the black bottom surface. Thus, the overall absorptivity of the filled water bag for normal incident radiation is about 92%.

Table 1. Materials which are used for making water bags

Materials	Temperature range	Merits	Demerits
Polyvinyl chloride (PVC)	up to 65°C	Well suited for industrial use	Cannot be used for direct heating of portable water or for higher temperature water
Chlorosulfanated polyethylene (CSPE)	up to 100°C	Can be used for higher temperatures, and portable applications, highly resistant to U.V. radiations, longer life	Costly, available only in black colour (if the entire bag is made up of black CSPE material then the black top surface will absorb all the incoming radiation and create a hot stable layer near the top surface. This hot layer causes higher losses and reduces the pond's daily efficiency by 10 to 20% when compared to a clear top, black bottom bag)
Polybutylene	up to 100°C	Very cheap, can be used for high temperature and portable applications (polybutylene is used for foods to be cooked in their wrappers), available in clear and black colour	Sensitive to u.v. radiations and will probably need replacement every 4 to 5 years

Natural convection mixing of the heated water occurs so that the entire volume gets heated uniformly. If the top layer of the water bag is of black colour, all absorption will take place there, and poor mixing will result in a higher temperature of the top layer with a consequent greater upward heat loss. It has been shown that the collection efficiency for an all-black water bag is typically lower by 5–10%.

Glazing. Glazing covers over a thermal collector suppresses upward radiative and convective heat losses. The radiative heat loss is minimized by glazing by the greenhouse effect where the low frequency heat waves are unable to come out of the transparent cover. The suppression of convective heat loss is, however, a bit more complicated phenomenon where optimization of conduction vs convection comes in, which determines the separation between the top glazing and the middle one. Again, the Fresnel loss vs thermal loss decides the number of glazings to be used over a thermal collector. The top glazing suppresses upward convective and radiative heat losses as does a single glazing on a conventional flat plate collector. A major difference between these two designs is the distance between the top of the water bag or plate and the middle of the top glazing. The large distance (~ 30 cm) for the SSP should result in no greater upward convection heat loss than occurs with the conventional flat plate collector with a shorter plate to glazing distance (~ 2 cm). Experimental work [15, 16] shows that, for Rayleigh numbers from 10^4 to about 10^8 the convective heat transfer coefficient, hc, is proportional to $L^{-0.12}$ to $L^{-0.15}$, where L is the distance between plates. For the range of temperature of interest here, and for an L of 30 cm, the corresponding Rayleigh number is between 10^7 and 10^8. Therefore, the convective heat transfer between the SSP water bag and top glazing should be somewhat lower than for a conventional collector with a Rayleigh number from 10^4 to 10^5.

Various greenhouse panel materials have been tried for this glazing, including clear fibreglass and clear acrylic paneling. The present choice is a corrugated Filon supreme greenhouse panel manufactured by the Vistron Corporation, which is a 1.5 Kg/m^2 weatherized fibreglass with a u.v. absorbing Tedlar bonded top surface. It has an 83% transmissivity for normal sunlight, averaged over the corrugations, and a short-wave cut-off at 0.38 μm (10% transmission point).

Bottom insulation. Care of thermal loss must be taken into account with the base material of a SSP system, otherwise it would act as a "thermal pump". The whole day's collection of heat would disappear in the night through the uninsulated bottom. If an SSP is to be built directly on the ground, rather than on a rooftop, bottom heat losses can amount to about 20% of the daily collected heat, assuming that the ground is completely dry. However, for the usual conditions of dampness, the bottom heat losses will be considerably higher and therefore, a slab of heat insulating material under the water bag is desirable.

Polyurethane foam was initially used as an insulator, but in dry pond conditions a large temperature gradient occurs across the foam slab with resulting severe and irreversible buckling of the material. A 3.8 cm ($1\frac{1}{2}$ in) slab of foamed glass is presently being used. This material is water impermeable and protects the water bag from rodent and insect damage. The heat loss through the foamed glass is calculated to be about 6% of daily collected heat.

Glazing support structure. Vertical elevation for the glazing panels as well as a solid attachment base is provided by concrete curbing. Crossbow supports are attached on both sides of the module at 1.2 m intervals. A steel bending tie-down system over the bows uses standard packaging and crating techniques and provides a tie-down (against aerodynamic lift) of the panels. The edge of the glazing is clamped down against a continuous neoprene rubber strip glued to the curbings and is held with galvanized sheet steel angle and hold-down clips.

Auxiliary systems

Water transfer. The exact specifications of the water system depend on the size of the SSP system to be installed and its location. There are however, some general guidelines that are common to all systems. For SSP systems that are operated in a batch mode, one manifold can serve to fill and to drain line parallel rows of ponds. This header should be sized and sloped so that the ponds can be filled and drained in 2 h or less.

The ponds can be operated in a flow-through mode to suit a particular application, however, this mode requires separate inlet and outlet piping systems, which will add significantly to the cost. There is little difference in the daily efficiency of SSP's operated in either mode.

Water storage. Two water reservoirs are required. A cold water reservoir is needed because most existing water systems cannot provide a sufficient flow to fill the ponds in 2 h or less. An insulated hot water reservoir is required because few users can absorb the entire pond output in 2 h. Hot water storage should equal the capacity of the ponds. Larger storage systems will permit some carryover during cloudy days but their cost generally exceeds their worth.

Mode of operation. Three modes of operation are possible with the SSP; batch heating, closed cycle continuous flow heating, and open cycle continuous flow heating.

In batch mode heating, ponds are filled to depth L in early morning with water at temperature T_i. In the afternoon, when the water temperature reaches its maximum value, the ponds are emptied into an insulated storage reservoir.

For closed cycle continuous-flow heating, water is continuously circulated at a constant rate between ponds and the storage reservoir, in which heat may or may not be continuously removed by an appropriate heat exchanger. In the afternoon, when useful heat

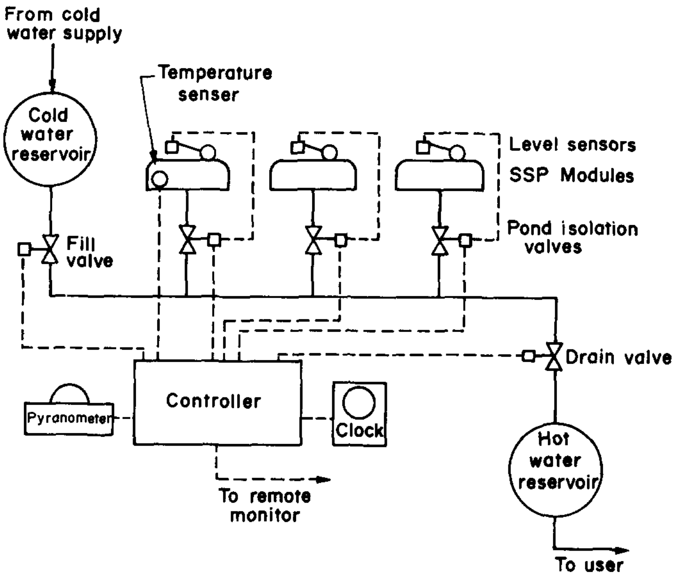

Fig. 3. Shallow solar pond control and flow diagram for batch operation.

added in ponds reaches zero, all water is emptied into the reservoir.

With open cycle continuous-flow heating, water at initial temperature T_i is flowed continuously at a constant rate through the ponds and then either to storage or to some end use. As in the closed cycle mode, water is drained from ponds when useful heat added in transit through ponds becomes zero. Figures 3 and 4 show the block diagram of batch and flow modes of operation.

Theory of SSP performance

A good computational model must contain all the important parameters that influence SSP performance as a collector of solar energy including solar radiation input, ambient temperature and wind speed, all heat loss mechanisms, depth and flow rate of water, and initial water temperature. If actual performance measurements are found to be in good agreement with model predictions, the model becomes a valuable tool for predicting SSP performance with varying values of input parameters.

Day *et al.* [1, 6] have developed the mathematical relationship for calculating the useful heat collected by the pond on the basis of the original Hottel–Whillier–Bliss model. With the help of computer models for all the three modes of SSP operations, its thermal performance is studied extensively.

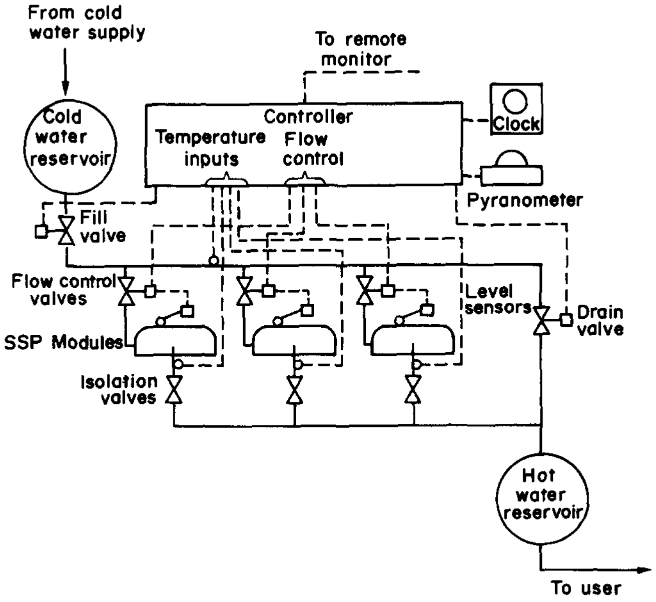

Fig. 4. Shallow solar pond control and flow diagram for flow through operation.

THE HOTTEL-WHILLIER-BLISS MODEL

This model has proven to be highly successful in predicting the performance of flat plate collectors. The two important parameters in the HWB model are the transmittance absorptance product, $\overline{\tau\alpha}$ (average taken over diffuse and direct radiation) and the overall heat loss coefficient, U, that accounts for conductive heat loss downward as well as for convective and radiative loss upward.

The HWB equation for the instantaneous rate of heat collection per unit SSP area is

$$q = [(\overline{\tau\alpha})I - U(T - T_a)] \tag{1}$$

where I is the total solar flux incident on the top glazing (assumed to be horizontal), T is the water temperature and T_a is the ambient air temperature. The heat loss coefficient, U, is a weak function of wind-speed as well as of water, ambient, ground, and sky temperatures. However, U can be assumed to remain constant over each month of the year and to change slightly from month to month. Typical calculated values of U for an SSP with single glazing vary from 6.2 W/m^2 K in winter to 7.4 W/m^2 K in summer.

The instantaneous (or hourly) collection efficiency is defined as

$$\eta_i = \frac{q}{I} = (\overline{\tau\alpha}) - U\frac{(T - T_a)}{I} = (\overline{\tau\alpha}) - U \cdot \frac{\Delta T}{I}. \tag{2}$$

It is also useful to define a daily collection efficiency

$$\eta_d = \frac{\int q \cdot \mathrm{d}t}{\int I \cdot \mathrm{d}t} = \frac{Q}{H} \tag{3}$$

a monthly average daily collection efficiency

$$\bar{\eta}_d = \frac{\sum^{30} Q}{\sum^{30} H} = \frac{\bar{Q}}{\bar{H}} \tag{4}$$

and, similarly, an annual average collection efficiency, $\bar{\eta}_a$.

In the above equations, Q represents the total daily collected heat per unit SSP area, H represents the total daily solar insolation (integrated from sunrise to sunset), and $\bar{Q}$ and $\bar{H}$ represent the monthly average daily values of Q and H. If

$$q = \frac{mC_p}{A} \cdot \frac{\mathrm{d}T}{\mathrm{d}t} \tag{5}$$

where A is the area, m is the mass, C_p is the specific heat and t is the time, then the differential equation in T is

$$\frac{\mathrm{d}T}{\mathrm{d}t} + \frac{AUT}{mC_p} = \frac{AS(t) + AUT_a}{mC_p} \tag{6}$$

where $S(t) = I(t) \cdot \overline{\tau\alpha}$.

Assuming T_a is constant at some average value over the period of interest, the solution of this equation for T_f at time t_f, given an initial water temperature of T_i at $t = 0$ is

$$T_f = [T_a + (T_i - T_a)\exp(-AUt_f/mC_p)] + \frac{A}{mC_p}\int_0^{t_f} S(t)\exp(-AU(t_f - t)/mC_p)\,\mathrm{d}t. \tag{7}$$

The heat collected by a unit surface area of water between time $t = 0$ and $t = t_f$ is then

$$Q(t_f) = \frac{mC_p}{A}[T_f - T_i] \tag{8}$$

and

$$Q(t_f) = \frac{mC_p}{A}[(T_a - T_i)(1 - \exp(-AUt_f/mC_p)] + \int_0^{t_f} S(t)\exp(-AU(t_f - t)/mC_p)\,\mathrm{d}t.$$

A parameter of interest is the depth of water in each pond. The dimensions of the pond are incorporated in the constant $\frac{mC_p}{A}$. Therefore, if

$$\frac{mC_p}{A} = C_p\rho d$$

$$Q(t_f) = C_p\rho d[(T_a - T_i)(1 - \exp(Ut_f/C_p\rho d)] + \int_0^{t_f} S(t)\exp(-U(t_f - t)/C_p\rho d \cdot \mathrm{d}t \left[\frac{BtU}{ft^2}\right]. \tag{9}$$

Each of the two terms on the right hand side of equation (9) has a simple physical significance. The first term represents the loss of heat originally contained in the water. Assuming $S(t) = 0$, if $T_i > T_a$ the water temperature will approach T_a exponentially with the time constant $C_p \cdot \rho d/U$. For large T_f this first term becomes $C_p \cdot \rho d(T_a - T_i)$. If $T_i < T_a$, then $U = 0$. The convection heat current downward from the top cover is small, and since the effective sky temperature is commonly 10°–15°C below T_a, the radiation heat transfer should be small. For ease of calculation in this case, the heat loss term is set equal to zero.

The second term in equation (9) represents the heat collection. Solar heat is collected at a rate $S(t)$ and the collected heat decays away with the time constant $C_p \cdot \rho d/U$. The fraction $1\text{-}\exp(-Ut_f/C_p \cdot \rho d)$ of the heat collected at $t = 0$ is lost out of the top and bottom of the SSP by time t_f, whereas all the heat collected at $t = t_f$ is retained in the water.

Computer program. Equation (9) provides the basis for calculating the total heat collected daily by the

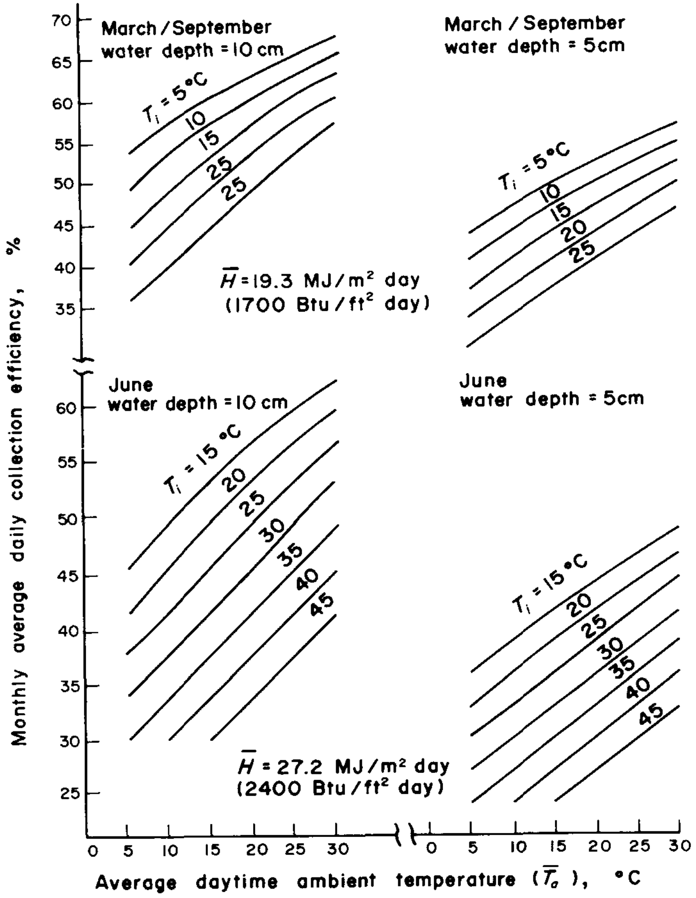

Fig. 5. Curves relating monthly average daily collection efficiency to average day time ambient temperature, $\bar{T}_a$, minium SSP water temperature, T_i, and collection efficiencies for March/September (top) and June (bottom) are very insensitive to reasonable variations in $\bar{H}$.

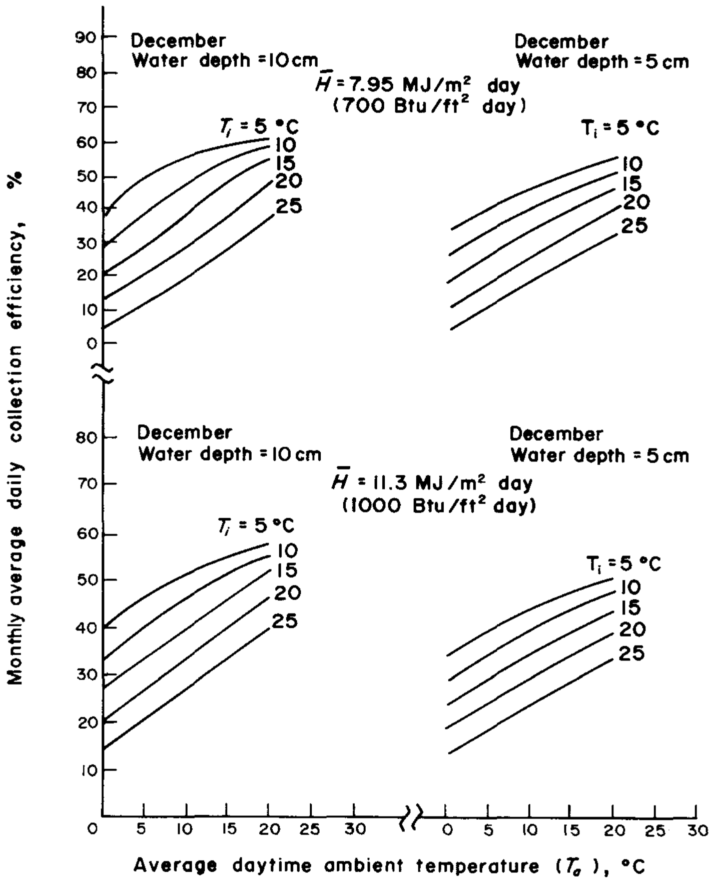

Fig. 6. Curves relating monthly average daily collection efficiency to average daytime ambient temperature, T_a, minimum SSP water temperature, T_i, and monthly average daily total insolation, $\bar{H}$. Collection efficiencies for December are influenced by variations in $\bar{H}$ and should be obtained by interpolation between the LLL (top) curves and the Sohio curves (bottom).

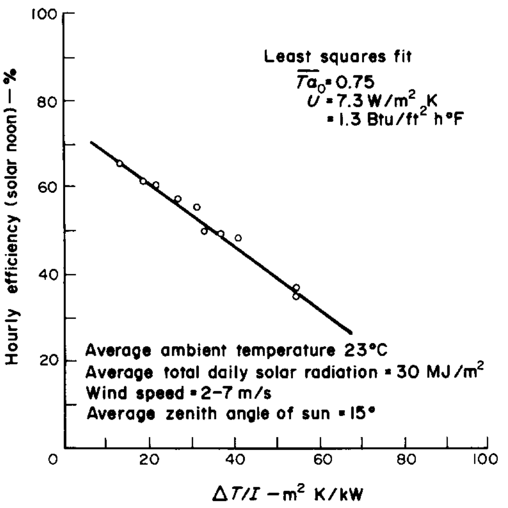

Fig. 7. Plot of hourly SSP efficiency at solar noon as a function of $\Delta T/I$, where ΔT is the average difference between water and ambient temperatures and I is the total incident radiation between 11.30 am and 12.30 pm. Data were taken over a 10-day period in July 1975.

shallow solar pond. A computer program has been written [17] which is applicable to each of the three modes of SSP operation; batch heating, closed cycle continuous-flow heating, and open cycle continuous flow heating.

Figures 5 and 6 present calculated values of (monthly average daily collection efficiency) vs average daytime ambient temperature for several values of T_i, the initial water temperature. On the left half of each figure, the curves are plotted for an SSP water depth of 10 cm and on the right half, for a depth of 5 cm. Although the final daily water temperature is higher for the 5 cm depth relative to the 10 cm depth, for the same value of T_a and T_i, the collector efficiency is significantly reduced for the shallower depth.

Data for the equinoctial months of March and September and for the summer solstice month of June are presented in Fig. 5 by the upper and lower sets of curves for two values of $\overline{H}$. The values of $\overline{\eta}_d$ are quite insensitive to reasonable variations of $\overline{H}$.

Curves for the winter solstice month of December for two different values of $\overline{H}$ are presented in Fig. 6 for two values of $\overline{H}$ typical for Livermore and New Mexico site.

Experimental results for LLL SSP's

Several SSP's of standard 3.5 m width but only one-fourth the standard length (15 m) have been built and tested at LLL(18). Different designs and materials were investigated to develop the design illustrated in Fig. 2. However, the thermal performance of all the SSP's is found to be essentially identical.

Measurements of η_i (equation 2) were made over the noon hour during several days in July 1975. A spread of $\Delta T/I$ values was achieved by varying the water depth each day over the range of 2–12 cm and the results of these measurements are shown in Fig. 7. The slope of the least squares fitted line through the data points gives $U = 7.3\ \mathrm{W/m^2\,K}$, in good agreement with the computed value of $7.1\ \mathrm{W/m^2\,K}$. Maximum water temperature and daily collection efficiency vs SSP water depth are plotted in Fig. 8. To heat a given volume of water to a specific required

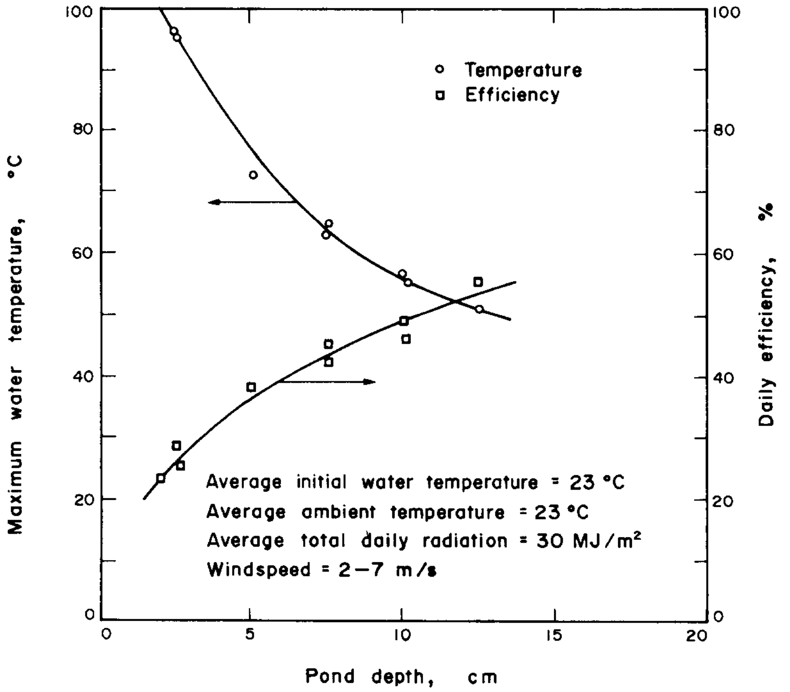

Fig. 8. Plot of maximum daily SSP water temperature and corresponding daily collection efficiency as a function of SSP water depth from data obtained in July 1975.

temperature, less fossil fuel is required if the entire volume is preheated in the SSP's and boosted to the final temperature by fossil fuel.

Figure 9 presents the data of Fig. 8 in terms of the percentage contributions to daily solar input. Thermal losses consist primarily of convective and radiative losses from the top glazing and conductive losses into the ground. Optical losses include reflective and absorptive losses from the top and middle plastic layers and reflective losses from the bottom black layer. In addition there is a "Utilization loss" (solar radiation falling on the SSP between the time the water reaches maximum temperature and sunset). This loss becomes negligible when the water is 10 cm deep or greater because the maximum temperature is reached only 2–3 h before sunset when both $\overline{\tau\alpha}$ and I are small.

Figure 9 illustrates summer conditions for an SSP with good bottom insulation. In winter, the percent optical loss is somewhat higher (near 40%) and the percent collected heat is somewhat lower, even though the percent thermal loss is about the same as in summer.

Measurements of daily collected heat were made on two of the LLL SSP's over continuous periods of 10–15 days in March, July, September and December in 1975. A summary of the data is presented in Table 2, and for comparison, the predicted values of average daily heat, $\overline{Q}_{\text{cal}}$, for the measured $\overline{T}_{\text{min}}$ are also included. The agreement between experimental and predicted values of Q is generally within 15%.

Effect of parameter variation

The parameters and variables of interest are (1) mass flow rate in ponds; (2) total mass of water required per day; (3) variation in water depth; (4) batch or continuous flow and area; (5) total heat loss coefficient; (6) radiation intensity; (7) average daytime ambient air temperature and (8) number of glazing over modules. The extensive study on all these parameters was done by Day *et al.* [6]. The effect on a fiducial system of varying parameters and fixing variables can be investigated. The fiducial system is specified by the following set of parameter values: L = module length = 200 ft., W = module width = 11.5 ft; $N = 112$; $d = 0.167$ ft. (2 in.); $\dot{m} = 2.5 \times 10^4$ pbs/h (50 gpm per module); $M = 6.01 \times 10^6$ lbs (720,000 gal); 1 glazing; $\tau_0 = 2.146$ h; and $\Delta = 0.959$ h.

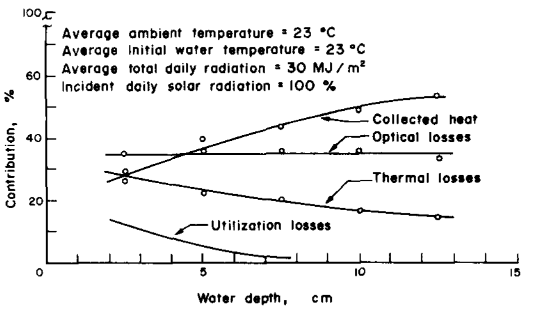

Fig. 9. Distribution of the total incident daily solar radiation among collected heat, optical losses, thermal losses, and utilization losses as a function of SSP water depth from data obtained in July 1975.

Beginning at about sunrise ($t = 0$), water is pumped at flow rate $\dot{m}$, into each of the 112 pond modules. When the water depth is 2 in. (at $t = \Delta$), water from the exit end of the modules flows into an underground hot water reservoir. At time $t = \tau_0$ the total daily mass M has entered the modules and the valve from the cold water source is closed for the remainder of the day. Water is circulated at the same constant flow rate between reservoir and modules until it is emptied into the reservoir for night storage.

The daily collection efficiency calculated for the SSP is 32.9% in December, 59.7% in June, with an annual average efficiency of 53.4%. Curve 1 of Figs 10 and 11 shows the average final daily temperature of water and average percentage of solar heat for each month of the year for the SSP system.

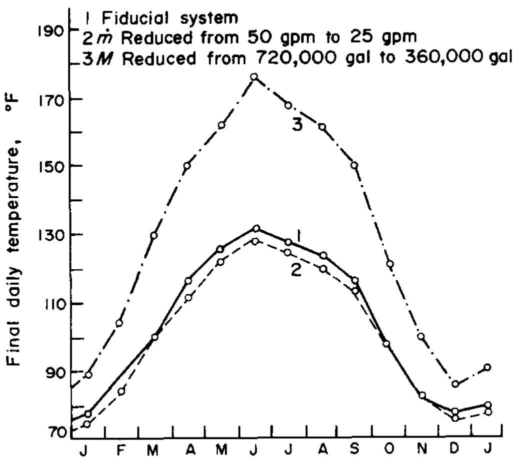

Fig. 10. Final daily water temperature of the ERDA Sohio project.

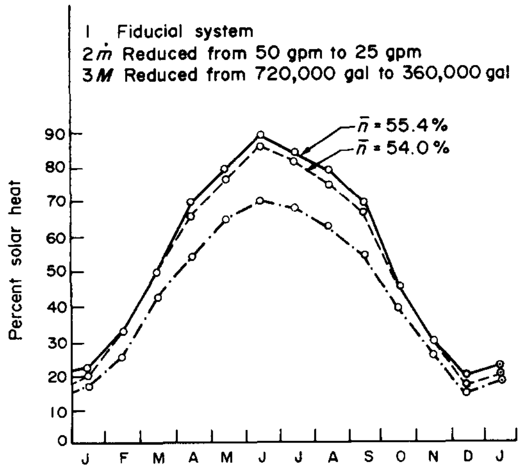

Fig. 11. Percent solar heat of the ERDA-Sohio project.

Variation of mass flow rate $\dot{m}$. From curve 2 of Figs 10 and 11, it is concluded that the mass flow rate $\dot{m}$ has a negligible effect on annual percentage of solar heat. However, a reduction in flow rate much below 25 gpm would probably not be desirable because of the long filling and emptying times.

Variation of total mass, M. If the total mass, M, of the water is halved, the average final daily temperature of water becomes considerably higher which is clear from curve 3 of Figs 10 and 11. However, because of higher water temperature reached, the heat loss increases, and the annual average percentage of solar heat is reduced from 55.4 to 45.5%. This represents a decrease in performance of almost 20% from the fiducial system.

Variation of water depth, d, *in modules*. If the water depth is changed from 2 to 1 in., the cycle time τ_0 does not change, but the module fill time decreases by a factor of two. The effect of this change is negligible. The percentage solar heat is slightly decreased in winter and increased in summer but the annual average percentage of solar heat is the same.

Batch vs continuous flow mode of operation. The annual average percentage heat vs the number of modules is shown in Fig. 12 for water masses $M/2$ and M. There is not a linear increase of annual average percentage heat with number of modules. The depth of water varies inversely with the number of modules, and the water gets hotter for smaller d, and so the losses increase (collection efficiency decreases). Also, for 168 and 224 modules in the summer months, there is more heat collected than is needed by the plant.

The annual average percentage heat collected for 112 modules in the batch mode is essentially the same as for the fiducial system that operated in the continuous flow mode. There appears to be no advantage in continuously flowing the water through the ponds. In fact, the daily heat lost in the reservoir and in the reservoir itself have not been accounted for in the continuous flow mode. It can be concluded that batch heating is preferable.

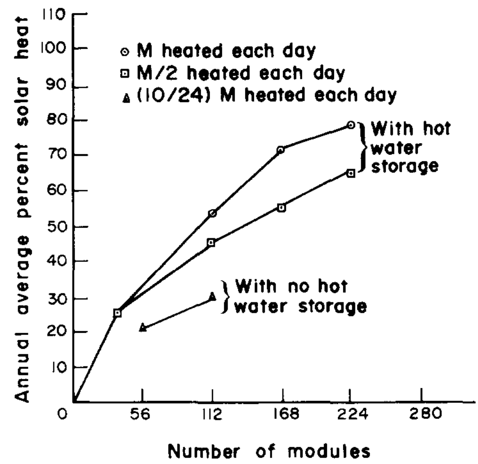

Fig. 12. Annual average percentage of solar heat versus the number of modules.

Variation of heat loss coefficient, U. The heat loss coefficients used in calculating daily collected solar heat were obtained for glass from a computer subroutine [17] for both one and two top glazings. It is expected that the solar transmissivity of glass and plastic material is about the same.

The calculated values of U include a bottom heat loss contribution equal to 10% of the top heat loss. This should be about the correct ratio of there is one plastic glazing over the pond and 2 in. of insulation underneath. If we increase the value of U for the fiducial system by 10%, the percentage decrease in collected heat is less than 2% in the summer months and average about 5% in the winter months. The annual average percentage solar heat is decreased from 55.4% for the fiducial system to 54.1%.

COMPACT SHALLOW SOLAR POND SYSTEM

LLL SSP system is a large scale installation system. It is also possible to consider the use of SSP's for portable purposes in camping and military sites.

Table 2. Summary of experimental and calculated performance data for LLL SSP's. In all cases, water depth was approximately 10 cm and all values refer to averages taken over the period of measurement (multiply by 88.1 to convert mJ/m^2 to Btu/ft^2)

Pond type	Bottom insulation[a]	Measurement period	$\bar{T}_{min}$[b] C	$\bar{T}_{max}$[c] C	$\bar{T}_a$[d] C	$\bar{H}$[e]	$\bar{Q}$[f]	$\bar{Q}_{cal}$[g]	$\bar{\eta}$[h]
Three layer	Yes	14/3–31/3	18.1	41.1	11.6	17.5	9.65	8.34	0.55
Acrylic panel	Yes	1/7–13/7	24.3	55.8	22.8	29.2	13.2	15.1	0.45
Acrylic panel	Yes	22/9–29/9	24.3	46.2	24.2	19.6	9.18	10.4	0.47
Acrylic panel	Yes	18/12–29/12	11.4	20.5	9.6	8.72	3.82	3.83	0.44

[a]—Five cm polyurethane foam slabs.
[b]—Pond water temperature at sunrise.
[c]—Maximum pond water temperature.
[d]—Daytime average ambient air temperature.
[e]—Total daily solar insolation on horizontal surface.
[f]—Measured daily heat collected by pond.
[g]—Calculated daily heat collected by pond.
[h]—Daily collection efficiency.

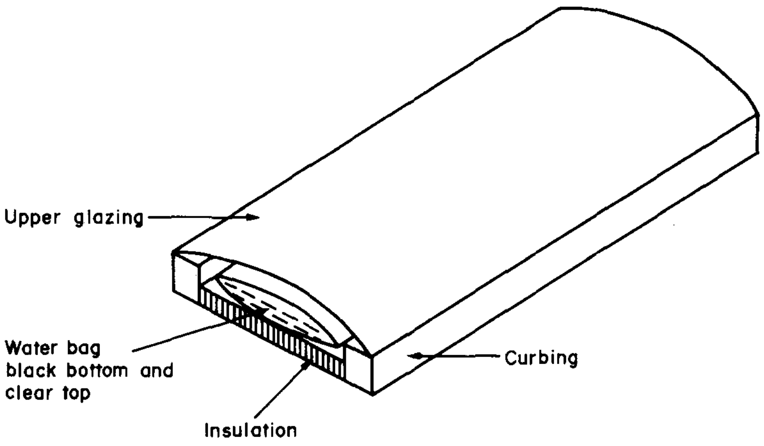

Fig. 13. Overall diagram of a SSP.

Kudish and Wolf [12, 13] have constructed and tested a large number of compact SSP's by varying the different parameters. Kudish made two types of studies on compact SSP's.

Small portable SSP

In the first case (Fig. 13), he constructed four small modules of portable shallow solar ponds of 2 × 1.3 m dimension, which were differing in the use of materials used for upper transparent film of the water bag, glazing material and glazing angle. He characterized the daily performance by three factors, viz, the maximum daily water temperature achieved, the total daily energy collected and the daily efficiency. Table 3 gives the description of materials used for four different SSP modules, while Table 4 gives the monthly average daily performance of the SSP modules.

From this study it was concluded that the SSP module having the upper glazing of Qualex shows better performance than the SSP module having Tedlar as the upper glazing material. Moreover, it is also important to note that the construction of the upper glazing using Qualex is much easier than from Tedlar. Qualex is produced in the form of rigid but flexible panels, whereas Tedlar is a thin film and requires closely-spaced supports. These supports also reduce the quantity of solar energy impinging on the pond surface due to their shading of the pond.

The effect of upper glazing angle was analysed by comparing the performance of SSP(2) and (5), which were both covered with a Tedlar upper glazing. From this study it was concluded that the upper glazing angle in the range of 20–30° has no significant influence on SSP performance.

The effect of pond PVC upper film was not accurately determined, since the modules which were to provide this data failed.

There appears to be no significant difference between Tedlar and Qualex with regard to their $(\tau\alpha)_e$ values. The monthly and overall average $(\tau\alpha)_e$ values for SSP(5) and (7) were very similar. It was observed that the SSP's [viz (7) and (8)] covered with Qualex are having lower U values than for the Tedlar covered SSP's.

Use of reflector in a compact shallow solar pond [12]

In the second type of study he constructed a prototype unit which consisted of a clear PVC pond placed within an insulated wooden container equipped with a hinged cover. The upper glazing was a 0.1 mm Tedlar film. The container cover served a dual purpose.

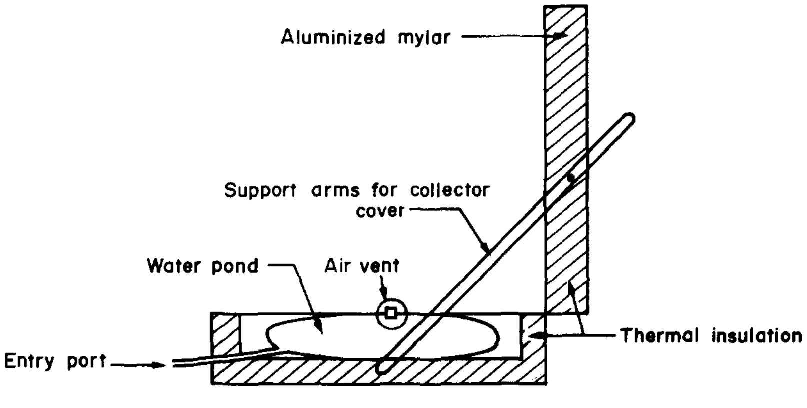

Fig. 14. Schematic diagram of compact SSP.

Table 3. Shallow solar pond test modules (13)

SSP No.	PVC films Transparent upper (mm)	Black lower (mm)	Glazing	Glazing angle
2	S150 (0.18)*	H65 (0.40)	Tedlar	21°
5	L06 (0.30)	H65 (0.40)	Tedlar	30°
7	S150 (0.18)	H65 (0.40)	Qualex (6 mm)	21°
8	L06 (0.30)	H65 (0.40)	Qualex (4 mm)	21°

* Film thickness.

During the day it performed as a solar reflector by means of an aluminium mylar film affixed to the inner side (Fig. 14), and it was thermally insulated so as to enable the overnight storage of the heated water.

This compact SSP was tested during the period extending from June until mid-September 1976. He tested the collector with the reflector angle alternating between 90°, 105° and 180° (i.e. without a reflector). During the period of testing, he found that the average daily efficiency was 0.38 for a reflector angle of 180°, 0.42 for an angle of 90° and 0.47 for an angle of 105°.

This cover also served as a wind shield.

FEASIBILITY CRITERIA OF A SOLAR ENERGY SYSTEM

There are four major criteria that will be used by a company to evaluate solar energy as a feasible alternative energy source.

(1) *Capital cost.* A solar heating facility will be capital intensive. The facility must cover a larger area of land or a factory rooftop. The capital cost of the collectors, piping, storage, controls and site preparation will be high compared to the cost of conventional oil fired boilers.

(2) *Reliability.* Because of the daily and seasonal

Table 4. Monthly average daily performance of SSP modules

Months	SSP No.	L (cm)	T_{max} (°C)	T (°C)	Q (KJ/m^2)	η
August (21d)	2	10	60.9	24.9	10,419	43.3
	5		64.2	27.4	11,377	47.2
	7		69.1	28.4	11,298	49.3
September (17d)	2	10	54.2	21.6	8,946	47.0
	5		54.3	22.0	9,020	45.9
	7		57.7	22.8	9,275	49.0
October (16d)	2	10	46.7	17.5	7,138	46.5
	5		47.4	18.3	7,461	48.1
	7		49.7	18.0	7,344	47.6
November (8d)	2	10	34.5	13.8	5,479	46.9
	5		34.8	14.2	5,620	46.3
	7		37.7	14.4	5,714	46.9
November (6d)	2	6	35.6	20.0	5,079	36.8
	5		38.1	21.8	5,450	39.4
	7		39.3	21.3	5,329	38.9
December (8d)	5	6	33.6	16.8	4,209	38.1
	7		36.1	16.7	4,172	37.7
	8		34.2	16.4	4,100	37.0
January (27d)	5	6	34.9	21.1	4,848	41.3
	7		35.2	18.9	4,372	36.5
	8		34.4	19.0	4,360	36.4
February	5(27d)	6	44.3	26.2	6,082	42.8
	7(28d)		44.3	22.8	5,291	36.9
	8(28d)		43.3	23.0	5,362	36.8
March(21d)	5	6	54.2	28.9	7,245	41.8
	7		54.1	26.0	6,550	37.0
	8		53.8	27.0	6,699	37.8
April(29d)	5	6	60.7	31.5	7,833	
	7		60.2	27.5	7,124	
	8		60.3	28.8	7,195	
May(14d)	5	6	69.1	38.1	12,410	
	7		67.7	32.7	10,532	
	8		68.1	34.7	11,869	
May(6d)	5	10	62.4	28.7	12,021	
	7	6	68.2	33.1	13,849	
	8	8	68.8	35.9	14,952	

variability of solar radiation, solar heat is best considered as a supplementary energy source that can furnish approximately 50 to 75% of the annual requirement for process or space heat. Heat storage can be effectively used to smooth out daily solar variability but it is seldom cost effective to provide sufficient collector area and storage capacity to cover periods of several days of bad weather. In some cases, it will be most cost effective to provide no storage and use solar heat when available and rely on fossil fuel heat at other times.

(3) *Operation and maintenance cost.* Reasonable operation and maintenance costs are acceptable for an industrial or commercial solar heat facility. However, the operation and maintenance costs for individual home solar collector systems must be kept at a minimum and with cost comparable to those for a conventional heating system. Otherwise the resulting nuisance would make solar systems unattractive to the average homeowner.

(4) *Unit cost of solar heat.* One does not get a fair measure of the relative merits of solar systems without an economic evaluation. The cost of a unit of solar heat vs the cost of a unit of fossil fuel heat must account for the required rate-of-return on investment, the estimated operational and maintenance costs and depreciation. In other words, a standard life-cycle cost analysis must be performed for the combined solar/fossil fuel system. An economic analysis of an SSP system has been reported by Clark and Dickinson [3]. The SSP system is in operation at the Sohio mill. The total cost of the system includes site preparation for the pond, reservoirs for cold and hot water, piping, pumps and controls, etc. An assumption of 15% rate of return on the total investment and zero salvage value after 15 y has shown that, to compete with fuel oil at $15/bbl, the installed SSP system would have to come down to about $\$40/m^2$ instead of $\$75/m^2$ which was the actual cost incurred in the Sohio mill SSP system. However, optimistic design data is available which promises lower cost per unit area of the SSP system. In view of the increasing importance of SSP systems for various purposes, a detailed economic analysis with local available data is to be made.

Limitations of SSP system

No system is perfect. In evaluating the potential applications of an SSP, one is to keep in mind the large area which would be needed by the SSP system for supplying useful hot water. Estimates show that an area of one acre is needed to install an SSP system for collecting about 25 GJ of heat. In an urban or an industrialized area, it is difficult to find such a large site. However, roof tops of an industry can be a suitable choice for installing an SSP system as a source of its required process heat.

The second consideration is economic viability. To date, an SSP system cannot demand its economic superiority over traditional energy sources. This is, however, a common feature of most solar energy systems. It would be a repetition of the same argument that, in future days, these solar energy systems will automatically offer economic viability when the fuel prices will be more and more high.

The SSP system is expected to be among the first group of systems which would reach this goal in the near future. It is necessary to mention here that the SSP system has already been judged to be in an economical advantageous position in some locations of the U.S.A. [4].

Potential applications of shallow solar ponds

Shallow solar ponds find applications in innumerable processes requiring hot water. A few of these applications are listed below:

(1) Providing hot water for space heating purposes.
(2) Providing industrial process heat.
(3) Supplying pre-heated water to industrial boilers.
(4) Generating electric power from hot water of SSP.
(5) Providing service hot water.
(6) Supplying hot water for washing clothes in laundry.
(7) For washing bottles in dairies and in different industries.

A realistic appraisal of the energy situation shows that solar process heat has a potential impact on the gross energy input (GEI) of any industrialized nation. Solar process heat is simply process heat obtained by the collection and transmission of solar energy. A number of solar thermal power collectors have already been tested and analyzed as a means of solar process heat. Shallow solar ponds have been found to be an economical viable solar thermal converter for this purpose—preheating of water by solar energy through shallow solar ponds for use in industrial boilers can reduce drastically the fuel consumption. Food processing industries, mining, chemical industries require a large amount of low grade heated water for various purposes. Similarly, dairies require moderately heated water for bottle washing and laundries for clothes washing. Shallow solar ponds can effectively supply heated water at the required temperature in sufficient amount and thus can save a good amount of valuable conventional energy.

The service hot water which is needed for daily domestic purposes can well be derived from SSP's. The capital investment for an SSP is really minimal, and an individual can afford that amount. However, the storage system costs a little more, but it ensures the supply of water throughout the day and night. A shallow solar pond can easily be installed on the roof top of domestic buildings, schools, hospitals, commercial buildings, etc. for collecting solar heat for space heating and service hot water.

The heated water from an SSP can also be used to run a turbine for power production. Low boiling point fluids, like Freon II, can easily be used for this purpose by using solar heated water at about 80°C. However, the efficiency of the total system from solar energy to generated electrical energy is very much less and still not economically viable.

CONCLUSIONS

Size

The proposed system must be large enough to keep fixed costs from becoming an excessive part of the project cost.

Simplicity

Because the system must be kept as simple as possible to keep costs under control, the plumbing and storage must be designed to do the minimum job necessary and not include a lot of extra "nice but not vital" features that always seem to appear. This is especially true of heat exchangers, which are expensive and require additional plumbing to service them.

Other than these two points the following conclusions are drawn from the present survey:

(1) the daily heat collected is insensitive to flow rate for a daily fixed mass of water required.

(2) Changes in heat loss coefficients of ±10% make only small changes (±2%) in heat collected during the summer months, and somewhat larger changes (±5%) during the winter months.

(3) Adding a second cover glazing is not cost effective on large scale systems.

(4) Hot water storage is cost effective.

(5) Qualex should be preferred over Tedlar for use as an upper glazing. It exhibits superior performance characteristics and is much easier to construct.

(6) A change in the upper glazing angle in the range of 20–30° has no significant influence on the SSP performance.

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