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Lawrence Livermore Laboratory

LLL-SOHIO SOLAR PROCESS HEAT PROJECT
REPORT NO. 3
LLL SOLAR ENERGY GROUP

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LLL-SOHIO SOLAR PROCESS HEAT PROJECT

REPORT NO. 3

ABSTRACT

In a venture sponsored by the U.S. Energy Research and Development Administration and the Sohio Petroleum Company, the Lawrence Livermore Laboratory has built and operated a shallow solar pond prototype facility in New Mexico. The facility consists of three 11.5 ft × 200 ft shallow solar ponds, cold and hot water storage reservoirs, and instrumentation to measure the performance of the ponds as solar thermal collectors. The total facility cost Sohio slightly under \$7 per square foot of collector. Unit area costs for the completed system (72 pond modules) are estimated to be about half of the prototype costs.

In this report, we describe the basic theory of shallow solar ponds and compare the performance of the New Mexico ponds to similar ponds operating at LLL during 1975. Agreement of calculated and experimental values of daily collected heat is better than 10%. The annual average collection efficiency for the ponds is close to 50%, corresponding to an annual collection of between 0.25 and 0.30 MBtu/ft² collector. We found that the annual collected heat would be reduced by only about 10% if the ponds were operated 9 months of the year (from February 15 to November 15).

INTRODUCTION

This is the third progress report on the LLL-Sohio solar process heat project.¹ Under a no-funds-exchanged contract between the Sohio Petroleum Company and ERDA, the Lawrence Livermore Laboratory is designing a shallow solar pond (SSP) facility for the new Sohio uranium mining and milling complex now nearing completion near Grants, New Mexico.

The on-site Sohio solar project is being conducted in two phases: the prototype and final-system phase. The former includes designing, constructing, operating, and testing three full-size SSP modules (each 11.5 ft × 200 ft).

Each module has unique design features. The prototype facility has been completed and performance measurements have been made over the past 9 months.*

STATUS OF THE NEW MEXICO SOHIO PROTOTYPE FACILITY

In Report No. 2,¹ Fig. 2 shows the system layout for the 1-acre prototype facility. At the time that report was written (May, 1975), we had just completed preparing the site and we had started to build Ponds A and B. Both ponds are made of three layers of polyvinylchloride (PVC) (see Fig. 3 of Report No. 2). Pond A has a layer of good bottom insulation and Pond B rests on a sand bed. In August we completed a third SSP, Pond C, with a 2 layer PVC water bag and corrugated acrylic top glazing.

Since September the entire prototype facility, including hot and cold water reservoirs, has been fully operational. (We will present performance data later in this report.) Figure 1 is a photograph of the Sohio prototype facility taken last August when Pond C was nearing completion. We summarize below the major things we have learned in the construction and operation of the facility.

Costs

A careful record was maintained of the incurred costs of the prototype system (Table 1).

Table 1. Incurred costs of prototype facility.^a

Item	Pond A ^b	Pond C
Pond material	\$1.75	\$2.29
Pond construction labor	1.15	0.70
Auxiliary system (piping, etc.)	1.96	1.96
Site preparation	1.76	1.76
Electrical	<u>0.20</u>	<u>0.20</u>
Total	\$6.82	\$6.91

^aAll costs are reduced to dollars per square foot of SSP collector.

^bPond B costs \$0.40/ft² less than Pond A since it does not have insulation below the pond.

* Shallow solar ponds have also been built and tested at LLL. We have measured the performance of these SSPs over the past year.

Fig. 1. Sohio prototype facility.

We estimated in Report No. 2 that prototype unit costs would be about twice the final system unit costs. This estimate still appears to be valid. We are presently projecting costs for the full-sized system of between \$3.50 and \$4.00/ft². Our economic analyses — based on a 15% rate of return to Sohio on its investment — indicate that at a system cost of \$3.50/ft², the solar facility will provide energy competitive with fuel oil at the current delivered price to Sohio of about \$15/bbl.

Cold Water Reservoir (28,000-gal capacity)

The cold water reservoir for the prototype system consists of a 3:1 sloping wall, bare earth, open reservoir, lined with 30-mil black Hypalon.* A number of disadvantages have become apparent with this design. To keep sand and other debris from accumulating in the reservoir, we had to install a filtering system. Cold night time ambient temperatures in the late fall and winter result in significant cooling of the water that is pumped into the reservoir from the wells during the night. Hence, in these periods the SSPs often do little more than reheat the water during the day to a temperature not much different than that of the well water. Floating a cover on a reservoir of this design does not appear economical.

Based on our experience, we now recommend an above-ground steel tank as a cold water reservoir. It may be advisable to insulate the tank if the well water temperature is significantly higher than the ambient temperature in the winter months.

Hot Water Reservoir (28,000-gal capacity)

The hot water reservoir consists of a 9-ft-wide, 80-ft-long, 5-ft-deep trench at the discharge end of the SSPs. A wood cover, insulated with 2-in. polyurethane foam slabs, covers the top. The reservoir has 2 in. of polyurethane foam sprayed on the walls and bottom to reduce heat losses. A black Hypalon liner is installed over the foam surface.

This design works for the prototype system but would not for a full-sized facility. The trench would have to be at least twice as deep, thereby necessitating the use of some structural material to prevent the walls from

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

caving in. The shape of the hot water reservoir for the full-sized facility should minimize the surface-to-volume ratio.

Piping System

All piping at the inlet manifold end is above-ground and had to be wrapped with heating tape and insulated. This is costly and labor consuming. A better arrangement would have been to bury all the lines and only have the pipes to the inlet of the bags above-grade. The piping for the prototypes is not representative of the full system because the capacity of manifolds is different. Probably PVC pipes will not be used for line sizes larger than 6 in. since the field assembly of large PVC pipes is expensive. Welded steel pipes are preferable. Another point that became evident in construction of the prototype system is that we can save significant time and money by prefabricating the manifolds into sections before installing them in the field.

Pond Construction

We have ruled out the use of polyurethane foam for the bottom insulation based on our experience with its use under Ponds A and C. It does the job, but one has to be very careful to avoid a dry pond condition that can produce a large temperature gradient across the foam and result in severe buckling of the material. Currently, we favor glass foam as a bottom insulating material.

Site Preparation

Selecting a site for the SSPs is critical to the performance of the system. Our experience indicates that adequate soil stabilization is essential to the system and that we cannot generate a grading plan from a topographical map alone. Sufficient soil data are needed to assess whether the ground under the pond beds is stable and has a good foundation. Also, earth-moving equipment must be available to ensure minimum site preparation costs and avoid unnecessary hand work. At present we are considering a sandstone region as a site for the full system. Such a site would eliminate the need to contend with the expanding clays that we dealt with for the prototype system.

Ponds

Our experience with the two types of SSPs clearly indicates that Pond C's acrylic panel design is better. Figure 2 is an isometric sketch of a short

Fig. 2. Short length of SSP (acrylic panel design).

length of this pond. The concrete curbs help to protect the plastic water bag from the weather as well as from other adverse conditions (sharp objects, small animals, etc.). There is no question, after building the two types of SSPs at the site, that separating the top glazing from the water bag is a better approach to take. First of all, it is easier to install, service, and remove a two-layer bag. Moreover, the top glazing, by protecting the PVC water bag from wind, dust, and most of the uv light, may well extend the effective life of the bag to 5 years or more.

We presently favor a semi-rigid top glazing, based on our experience with the prototype SSPs; however we have not made a final choice of material. Pond C currently has a 1/16-in. corrugated acrylic top that is holding up well. However, it is expensive: \$0.50/ft². We are installing a half-dozen sheets of Filon "Supreme," Tedlar-coated fiberglass panels, which cost \$0.34/ft², for evaluation.* The manufacturer's data sheets indicate that the expected life of this material should be 5 years or more, which is considerably less than that of the acrylic sheets, but it is expected to be more cost-effective. The tie-down system for the top glazing appears satisfactory and simply needs some refinement to make the installation costs lower and the assembly easier.

Winter Operation

Even though the performance of the ponds through the winter is estimated to increase annual heat collection by no more than 10% (see Performance Data section), we are currently operating the prototype facility periodically throughout the winter to obtain experience under extreme cold weather conditions. Information is needed on the cold weather performance to determine whether a 9-month operating season is more desirable than continuous use. There are things that can be done to keep the SSPs in use throughout the winter, but whether or not this is cost-effective is questionable. Our experimental work this winter will help us make a decision in this area.

BASIC THEORY OF SSP PERFORMANCE

A reasonably accurate computational model of a shallow solar pond should contain all the important parameters that affect SSP performance: solar

* Both the acrylic and the Filon Supreme have a measured short-wave cut-off at about 3800 Å (10% transmission point). Hence, the PVC water bag is almost completely shielded from ultraviolet light.

radiation input, ambient air temperature and wind speed, heat loss mechanisms, and initial water temperatures. If the performance predictions of the model are found to be in good agreement with experimental performance measurements, then the model becomes a valuable tool in predicting SSP performance under varying values of the above input parameters.

We have developed a computational model of the SSP based on the Hottel-Whillier-Bliss (HWB) model of a flat plate collector.² The two important parameters in the HWB model are the transmittance-absorptance product, $\overline{\tau\alpha}$ (average taken over diffuse and direct solar radiation), and the overall heat loss coefficient, U , which accounts for conductive heat loss downward and convective and radiative heat loss upward. The HWB equation for the instantaneous rate of heat collection per unit area of SSP is

$$q = \overline{\tau\alpha}I - U(T - T_a), \quad (1)$$

where I is the total solar flux incident on the horizontal top of the SSP, T is the water temperature, and T_a the ambient air temperature.³ The heat loss coefficient is a weak function of windspeed, and water, ambient, ground, and sky temperatures. However, to a good approximation, we assume the coefficient is constant over each month of the year and changes slightly from month to month.*

The instantaneous (or hourly) efficiency is then defined as

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

*It might be thought that because of the large space between the top surface of the water bag and the middle of the top glazing (about 12 in.) that the upward convection heat loss (and hence also U) would be greater than for a conventional flat plate collector (1 to 2 in. between absorber plate and glazing). However, experimental work by Goldstein and Chu shows that for Rayleigh numbers from 6×10^5 to about 10^8 the convective heat transfer coefficient, h_c , is proportional to $L^{-0.12}$, where L is the distance between plates.⁴ Buchberg et al. confirm this, finding that for Rayleigh numbers from about 10^4 up to 10^7 , h_c is proportional to $L^{-0.15}$.⁵

For our range of temperatures and spacings, the Rayleigh number is between 10^7 and 10^8 . Therefore, the convective heat transfer between water bag and top glazing should actually be somewhat lower for a shallow solar pond than for a collector with 1 to 2 in. of spacing, and characterized by a Rayleigh number in the range of 10^4 to 10^5 .

If η_i is plotted vs $\Delta T/I$ for the same hour of each day (say from 11:30 a.m. to 12:30 p.m.) for several days, a straight line should result with y intercept $\overline{\tau\alpha}$ and slope $(-U)$.

Measurements of η_i were made over several days in July, 1975 for one of our LLL experimental SSPs. Since the sun was almost overhead (zenith angle $\approx 14^\circ$), we determined the normal value, $\overline{\tau\alpha}_0$. The value of q in Eq. (2) is the heat collected per unit area over the 1-hour period, which is given by

$$q = \rho C \ell (T_f - T_i), \quad (3)$$

where ρ , C , and ℓ are density, heat capacity, and depth of water respectively, and T_i and T_f are the water temperatures at the beginning and end of the 1-hour period.

Figure 3 shows the results of these measurements. We achieved a spread of values of $\Delta T/I$ by varying the water depth each day over the range of 25 to 125 mm. The value of $U = 7.3 \text{ W/m}^2 \cdot ^\circ\text{K}$ ($1.3 \text{ Btu/ft}^2 \cdot \text{hr} \cdot ^\circ\text{F}$) — obtained from Fig. 3 — is in excellent agreement with the computed value of $1.26 \text{ Btu/ft}^2 \cdot \text{hr} \cdot ^\circ\text{F}$ (see Ref. 3 and Fig. 3). The Fig. 3 intercept value of $\overline{\tau\alpha}_0 = 0.75$ is lower than would be expected for the ideal case. Clean PVC has a transmissivity of about 0.89. Assuming a value of 0.95 for the absorptivity of the water bag with the black PVC bottom layer, then $\overline{\tau\alpha}_0 = 0.85$. [Measurements were made on clear days when the noontime diffuse component was only about 15% of the total and, hence, would not appreciably affect values of $\overline{\tau\alpha}_0$.] Later in this report we describe a measurement on the effect of dust on the PVC glazings of the Sohio ponds in which the rather heavy layer of dust was found to decrease collected heat by about 13%. This corresponds to an increased optical loss of about 20%. The LLL pond (on which the above described measurements took place in July, 1975) had a dust covering that did not appear as heavy as the one at Sohio. Therefore, we can assume that there was perhaps as much as a 10% optical loss due to dust. This would reduce the calculated $\overline{\tau\alpha}_0$ to 0.77.

It is also useful to define the daily collection efficiency of an SSP as

$$\eta = \frac{\int q dt}{\int I dt} = \frac{Q}{H}, \quad (4)$$

where the numerator is given by Eq. (3) (T_i and T_f are replaced by $T_{\min}$ and $T_{\max}$, the minimum and maximum daily water temperatures, respectively) and the denominator is the integrated total solar radiation from sunrise to sunset.

Fig. 3. 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 a.m. and 12:30 p.m. The data were taken on an LLL SSP over a 10-day period in July, 1975.

A question that is often asked is: "How hot will the water get in an SSP in 1 day?" This will depend on several parameters: initial water temperature, average ambient air temperature, solar radiation, and water depth. By filling an SSP to a very shallow depth (say 2.5 cm), it is possible to obtain water near the boiling point. However, the daily collection efficiency will be quite low. On the other hand, by increasing the depth of the water (say 10 cm), the maximum water temperature achieved will not be as high but the total amount of solar heat collected will be considerably higher.

This is illustrated by the data plotted in Fig. 4, where both maximum water temperature and daily collection efficiency are plotted vs SSP water depth. The conclusion is that increased solar energy is collected by increasing the water depth. A useful corollary is: If a given volume of water is to be heated to a certain required temperature, more solar energy will be collected (and less fossil fuel required) if the entire volume of water is preheated in the SSPs (and boosted to final temperature by fossil fuel) rather than heating only a portion of the water volume in the SSPs to the final required temperature and using fossil fuel to heat the remainder. A second corollary is: If a given volume of water is to be heated, a doubling of the total SSP area does not result in a doubling of heat collected. This is because the water depth is decreased by half and hence the daily collection efficiency is reduced.

The principal energy losses from an SSP can be characterized as thermal and optical. Thermal losses primarily consist of convective and radiative losses from the top surface of the SSP and conductive losses into the ground. Optical losses include reflective and absorptive losses from the top and middle glazings and reflective losses from the bottom black-absorbing layer. In addition, for very shallow depths when maximum temperature is reached only an hour or two after solar noon, there will be a "utilization loss" (solar radiation falling on the pond between the time when the water reaches maximum temperature and sunset). This loss becomes negligible when the water is 10 cm deep or greater since the maximum temperature is reached only 2 to 3 hours before sunset.

In Fig. 5 the same data as presented in Fig. 4 are given in terms of the percentage contributions to daily solar input. Utilization and thermal loss values as well as collected heat values are calculated from experimental data. When these are subtracted from the daily solar radiation, the remaining amount

Fig. 4. Plot of maximum daily SSP water temperature and corresponding daily collection efficiency as a function of SSP water depth. The data were taken on an LLL SSP in July, 1975.

Fig. 5. Distribution of the total incident daily solar radiation among collected heat, optical losses, thermal losses, and utilization losses (explained in text) as a function of SSP water depth. The data were obtained on an LLL SSP in July, 1975.

is attributed to optical losses. Notice that the optical losses are more than a factor of two higher than thermal losses for a water depth of 10 cm. These curves apply to summer conditions for an LLL pond with good bottom insulation. For typical winter conditions, an equivalent set of curves (based on the results of our computer program discussed below) can be constructed. Typical percentage contributions in winter are similar to summer contributions, with the percent optical loss somewhat higher (near 40%), the percent collected heat somewhat lower, and the percent thermal loss about the same as in summer.

We have written a computer program — based on the HWB collector model — to calculate the amount of heat collected by an SSP on either an hourly or daily basis. The program operates in either a continuous flow or daily batch heating mode.² In Appendix B of Ref. 3, we showed that the calculated heat collection from an SSP (using hourly insolation data and hourly ambient air temperatures over a period of a month) agrees quite closely with the value obtained by using the monthly average daily insolation and monthly average daytime ambient temperature. Therefore, it is adequate to calculate daily collection efficiencies and daily collected heat.

Figures 6a and 6b show calculated values of η (average daily collection efficiency) vs average daytime ambient air temperature for several values of $T_{\min}$ (the SSP water temperature at sunrise). On the left half of each figure, the curves are for an SSP water depth of 10 cm and on the right half, a depth of 5 cm. Note that for the same values of $\bar{T}_a$ and $T_{\min}$, the collection efficiency is reduced for the 5-cm depth relative to the 10-cm depth.

In Fig. 6a the upper sets of curves are for the equinoctial months of March and September and the lower sets for the summer solstice month of June. We chose values of $\bar{H}$ (the monthly average daily insolation) that are representative of both Livermore and the New Mexico Sohio site. However, we have found³ that values of daily collection efficiency are quite insensitive to reasonable variations of $\bar{H}$. These curves should be used to obtain daily collection efficiencies, which can then be multiplied by actual values of $\bar{H}$ to obtain values of $\bar{Q}$.

In Fig. 6b we present sets of curves for the winter solstice month of December for two different values of $\bar{H}$. The upper sets of curves are for an $\bar{H}$ that is typical of Livermore; whereas the lower set is for a higher $\bar{H}$ typical of the Sohio site. This was found to be necessary because, for December, the daily collection efficiency becomes somewhat dependent on the value of $\bar{H}$,

Fig. 6a. Curves relating daily collection efficiency to average daytime ambient temperature, $\bar{T}_a$, minimum SSP water temperature, T_{min} , and average daily total insolation, $\bar{H}$. Daily collection efficiencies for March/September (top of Fig. 6a) and June (bottom of Fig. 6a) are essentially independent of $\bar{H}$ but, for December (Fig. 6b), efficiencies should be obtained by interpolating the actual $\bar{H}$ between the LLL curves at the top and the Sohio curves at bottom. [Multiply by 88.1 to convert MJ/m² to Btu/ft².]

Fig. 6b. Curves relating daily collection efficiency to average daytime ambient temperature, $\bar{T}_a$, minimum SSP water temperature, $T_{\min}$, and average daily total insolation, $\bar{H}$. Daily collection efficiencies for March/September (top of Fig. 6a) and June (bottom of Fig. 6a) are essentially independent of $\bar{H}$ but, for December (Fig. 6b), efficiencies should be obtained by interpolating the actual $\bar{H}$ between the LLL curves at the top and the Sohio curves at bottom. [Multiply by 88.1 to convert MJ/m² to Btu/ft².]

particularly for very low ambient air temperatures and high initial water temperatures where the heat loss is high. For a given value of $\bar{H}$ in December, one should obtain the proper value of daily collection efficiency by interpolating the curves of Fig. 6b.

The suggested way to use Figs. 6a and 6b is to obtain monthly average values of minimum water temperature, $\bar{T}_{\min}$, and average daytime ambient temperature, $\bar{T}_a$, and obtain corresponding values of daily collection efficiency, η , from the curves. Multiplying η by the appropriate $\bar{H}$ then gives the monthly average value of daily heat collected, $\bar{Q}$. An alternative approach is to use daily values of $T_{\min}$ and T_a , and use the curves to obtain daily values of η . Multiplying by daily values of H then gives daily Q . If this is done for each day of a month, the resultant value of $\bar{Q} = \frac{1}{n} \sum Q_i$ is found to agree generally to within 1% with the value of $\bar{Q}$ obtained in the first approach.

If the values of $\bar{Q}$ are obtained for the 4 months of March, June, September, and December, then it is possible to sketch a smooth curve for an entire year (guided, if desired, by the shapes of the curves shown in Fig. 1 of Ref. 3). In the following section we present experimental values of $\bar{Q}$ for both the LLL and Sohio ponds and compare them with calculated values obtained from Figs. 6a and 6b.

PERFORMANCE DATA ON LLL AND SOHIO SSPs

We have measured daily collected heat on the three 11.5 ft $\times$ 50 ft SSPs at LLL over continuous periods of from 10 to 15 days each in March, July, September, and December. Similar measurements were made on the two 11.5 ft $\times$ 200 ft three-layer PVC SSPs at the Sohio site in July, September, and December and the 11.5 ft $\times$ 200 ft acrylic panel SSP in September and December. Table 2 is a summary of the data and includes calculated values of collected heat obtained from Fig. 6a.

We have found that the three-layer PVC-designed ponds at LLL and Sohio performed the same -- within experimental uncertainty -- as the acrylic panel design, provided the bottom insulation was the same. Therefore, some redundant SSP data are not included in Table 2.

Table 2 shows that the agreement between experimental and calculated values of $\bar{Q}$ (the average daily collected heat over each measurement period*) is generally better than 10%. This is excellent agreement considering the

*This is for SSP's with bottom insulation only. The heat loss is considerably greater for SSPs with only 4 in. of sand for bottom insulation (see below).

Table 2a. Summary of 1975 experimental and calculated SSP performance data (pond depth in all cases about 4 in.; all values refer to averages taken over the listed measuring period; S.I. units).

LLL Ponds [3.5 m × 15 m]										
Pond type	Bottom insulation ^a	Measurement period	$\bar{T}_{\min}$, ^b	$\bar{T}_a$, ^c	$\bar{H}$, ^d	$\bar{Q}$, ^e	$\bar{Q}_{\text{calc}}$, ^f	$\bar{Q}$	($T_{\min} = 15^\circ\text{C}$) $\bar{Q}_{\text{calc}}$	($T_{\min} = 25^\circ\text{C}$) $\bar{Q}_{\text{calc}}$
			°C	°C		MJ/m ² ·day		$\bar{Q}_{\text{calc}}$		MJ/m ² ·day
Three-layer PVC	Yes	3/14- 3/31	18.1	11.6	17.5	9.65	8.34	1.15	8.86	7.24
Acrylic panel	Yes	7/1 - 7/13	24.3	22.8	29.2	13.2	14.4	0.91	17.0	15.0
Acrylic panel	Yes	9/22- 9/29	24.3	24.2	19.6	9.18	9.71	0.95	11.8	10.3
Acrylic panel	Yes	12/18-12/29	11.4	9.6	8.72	3.82	4.00	0.96	3.49	1.92
Sohio ponds [3.5 m × 60 m]										
Pond type	Bottom insulation ^a	Measurement period ^g	$\bar{T}_{\min}$, ^b	$\bar{T}_a$, ^c	$\bar{H}$, ^d	$\bar{Q}$, ^e	$\bar{Q}_{\text{calc}}$, ^f	$\bar{Q}$	($T_{\min} = 15^\circ\text{C}$) $\bar{Q}_{\text{calc}}$	($T_{\min} = 25^\circ\text{C}$) $\bar{Q}_{\text{calc}}$
			°C	°C		MJ/m ² ·day		$\bar{Q}_{\text{calc}}$		MJ/m ² ·day
Three-layer PVC	Yes	7/1 - 7/10	44.3	25.0	24.5	8.96	9.50	0.94	14.6	13.0
Three-layer PVC	No	7/1 - 7/10	41.4	25.0	24.5	8.33				
Three-layer PVC	Yes	9/22- 9/30	24.6	14.8	18.5	7.71	8.36	0.92	9.90	8.21
Three-layer PVC	No	9/22- 9/30	24.8	14.8	18.5	6.48				
Acrylic panel	No	9/22- 9/30	25.2	14.8	18.5	6.21				
Three-layer PVC	Yes	12/16-12/20	7.3	-1.7	11.3	3.72	3.94	0.94	2.93	1.51
Acrylic panel	No	12/16-12/20	10.3	-1.7	11.3	3.86				

^aFive-cm polyurethane foam slabs.

^b $\bar{T}_{\min}$ = pond water temperature at sunrise.

^c $\bar{T}_a$ = daytime average ambient air temperature.

^d $\bar{H}$ = total daily solar insolation on horizontal surface.

^e $\bar{Q}$ = measured daily heat collected by pond.

^f $\bar{Q}_{\text{calc}}$ = daily heat collected by pond (Fig. 6).

^gPonds not yet operable in March.

Table 2b. Summary of 1975 experimental and calculated SSP performance data (pond depth in all cases about 4 in.; all values refer to averages taken over the listed measuring period; English units).

LLL Ponds [11.5 ft x 50 ft]										
Pond type	Bottom insulation ^a	Measurement period	$\bar{T}_{\min},^b$	$\bar{T}_a,^c$	$\bar{H},^d$	$\bar{Q},^e$	$\bar{Q}_{\text{calc}},^f$	$\bar{Q}$	$(T_{\min} = 59^\circ\text{F})$	$(T_{\min} = 77^\circ\text{F})$
			$^\circ\text{F}$	$^\circ\text{F}$	Btu/ft ² ·day		$\bar{Q}_{\text{calc}}$		Btu/ft ² ·day	
Three-layer PVC	Yes	3/14- 3/31	64.6	52.9	1540	850	735	1.15	780	638
Acrylic panel	Yes	7/1 - 7/13	75.7	73.0	2570	1160	1270	0.91	1500	1320
Acrylic panel	Yes	9/22- 9/29	75.7	75.6	1730	810	860	0.95	1040	910
Acrylic panel	Yes	12/18-12/29	52.5	49.3	770	337	352	0.96	307	169
Sohio ponds [11.5 ft x 200 ft]										
Pond type	Bottom insulation ^a	Measurement period ^g	$\bar{T}_{\min},^b$	$\bar{T}_a,^c$	$\bar{H},^d$	$\bar{Q},^e$	$\bar{Q}_{\text{calc}},^f$	$\bar{Q}$	$(T_{\min} = 59^\circ\text{F})$	$(T_{\min} = 77^\circ\text{F})$
			$^\circ\text{F}$	$^\circ\text{F}$	Btu/ft ² ·day		$\bar{Q}_{\text{calc}}$		Btu/ft ² ·day	
Three-layer PVC	Yes	7/1 - 7/10	112	77.0	2160	790	837	0.94	1290	1150
Three-layer PVC	No	7/1 - 7/10	107	77.0	2160	734				
Three-layer PVC	Yes	9/22- 9/30	76.3	58.6	1630	680	737	0.92	872	723
Three-layer PVC	No	9/22- 9/30	76.6	58.6	1630	570				
Acrylic panel	No	9/22- 9/30	77.4	58.6	1630	547				
Three-layer PVC	Yes	12/16-12/20	45.1	28.9	996	328	347	0.94	258	133
Acrylic panel	No	12/16-12/20	50.5	28.9	996	340				

^aTwo-in. polyurethane foam slabs.

^b $\bar{T}_{\min}$ = pond water temperature at sunrise.

^c $\bar{T}_a$ = daytime average ambient air temperature.

^d $\bar{H}$ = total daily solar insolation on horizontal surface.

^e $\bar{Q}$ = measured daily heat collected by pond.

^f $\bar{Q}_{\text{calc}}$ = daily heat collected by pond (Fig. 6).

^gPonds not yet operable in March.

combined experimental uncertainties in water and air temperatures, water depth, varying wind conditions, and insolation measurements, as well as certain simplifying assumptions in the computer program. Since the experimental data were obtained over the different seasons of the year and for various values of minimum water temperature, $T_{\min}$, and average daytime ambient temperature, $\bar{T}_a$, the good agreement between experimental and calculated values of $\bar{Q}$ gives us confidence in the reliability of Fig. 6. In particular, we expect that well water temperatures at the Sohio site will be in the range of 15°C (59°F) to 25°C (77°F). Hence, in the last two columns of Table 2 we list values of $\bar{Q}_{\text{calc}}$ obtained from Fig. 6 for these two values of $T_{\min}$, using measured values of $\bar{T}_a$ as given in Table 2.

Figure 7 plots the Table 2 values of $\bar{Q}_{\text{calc}}$ for $T_{\min} = 15^\circ\text{C}$ and 25°C for the LLL ponds. Figure 7 also shows the histogram of 1975 LLL measured values of $\bar{H}$, the monthly average daily total insolation on a horizontal surface. Similar data for the Sohio ponds are presented in Fig. 8. We obtained the dashed curves joining the bars by assuming a linear variation of daily collection efficiency between measurement periods and multiplying the resultant estimates of monthly average efficiency by the corresponding values of $\bar{H}$.*

Table 3 summarizes the results of integrating the monthly data presented in Figs. 7 and 8 over the year. This integration was done over the entire 12 months as well as over a 9-month period from Feb. 15 to Nov. 15. We found that the total heat collected over 12 months is only about 10% greater than that collected over the 9-month period. Because of the snow and cold weather at the Sohio site during these 3 winter months, it may not be worth the required operation and maintenance costs to operate the SSPs. Rather they could be drained and put in a winter standby condition about Nov. 15 and placed back in regular operation about Feb. 15.

The other interesting conclusion from Table 3 is that the annual collected heat for $T_{\min} = 15^\circ\text{C}$ is about 20% greater than for $T_{\min} = 25^\circ\text{C}$. This applies to both the LLL and Sohio SSPs. If the average value of $T_{\min}$ for the Sohio site turns out to be about 15°C (59°F) then we can conclude from Table 3 that a 12-month average collection efficiency of $(48 \pm 5)\%$ can be expected. For a 9-month operating period, the average collection efficiency rises to

*The Sohio SSPs were not yet in operation in March, 1975 so the March values of $\bar{Q}_{\text{calc}}$ shown in Fig. 8 were obtained from Fig. 6, using the measured value of $\bar{T}_a$ for March.

Table 3. Twelve- and nine-month sums and annual average SSP efficiencies for 1975.

		$T_{\min} = 59^{\circ}\text{F} (15^{\circ}\text{C})$		$T_{\min} = 77^{\circ}\text{F} (25^{\circ}\text{C})$	
	$\sum \bar{H}^a$	$\sum \bar{Q}_{\text{calc}}^a$	$\bar{\eta}^b$	$\sum \bar{Q}_{\text{calc}}^a$	$\bar{\eta}^b$
<u>12 months</u>					
LLL	0.566	0.306	0.54	0.256	0.45
Sohio	0.630	0.301	0.48	0.247	0.39
<u>9 months [2/15 to 11/15]</u>					
LLL	0.488	0.272	0.56	0.233	0.48
Sohio	0.532	0.269	0.51	0.226	0.43

^aUnits are MBtu/ft²·yr. Multiply by 11.35 to convert to GJ/m²·yr.

$$\bar{\eta}^b \equiv \sum \bar{Q}_{\text{calc}} / \sum \bar{H}.$$

Fig. 7. Values for 1975 of $\bar{Q}_{calc}$ at $T_{min} = 15^\circ\text{C}$ and 25°C for LLL ponds. Also shown are measured values of $\bar{H}$ (monthly average daily total insolation on a horizontal surface). Bars show values of $\bar{Q}_{calc}$ for the equinoctial and solstice measurements (Table 2).

Fig. 8. Values for 1975 of $\bar{Q}_{calc}$ at $T_{min} = 15^\circ\text{C}$ and 25°C for Sohio ponds. Also shown are measured values of $\bar{H}$ (monthly average daily total insolation on a horizontal surface).

(51 ± 5)%.* When these efficiencies are multiplied by the total incident solar radiation over the corresponding period, the product is total collected heat. Although the annual solar radiation can be expected to vary by perhaps as much as 20% from year to year,[†] the efficiencies given in Table 3 (based on both experimental data and a reliable calculational model) should be quite insensitive to total radiation.

Table 3 indicates that the annual collected energy of the LLL ponds is about the same as the Sohio ponds, even though the annual insolation at the Sohio site is about 10% higher than at LLL. This can be attributed to the lower ambient air temperature at the Sohio site, resulting in lower collection efficiencies.

The Effect of Bottom Insulation

Table 2 data for the Sohio SSPs in September show that the average daily collected heat for the SSP with good bottom insulation was about 20% greater than the average value for the two SSPs with only 4 in. of sand for bottom insulation. In July the measured difference was only 7-1/2%. However, if we use the graphs of Fig. 6a to reduce the $\bar{T}_{\min}$ for the bottom-insulated SSP to the same value as for the SSP with 4 in. of sand bottom insulation, the corrected difference was about 14%. For December, the average daily collected heat was about the same for the two SSPs. [This may be because the average water temperatures were very low (~10 to 12°C), which would reduce heat loss into the ground.]

*The uncertainty quoted here is an estimate based on combined uncertainties in measurement of temperature, water depth, and solar insolation.

[†]The average annual solar radiation for Albuquerque for the 5-year period 1969-1973 was 0.650 MBtu/ft²; for 1975, it was 0.622 MBtu/ft². Therefore, 1975 was pretty much an average solar year for Albuquerque and, hence, the Sohio site.

We conclude that good bottom insulation increases average collected heat over the year by approximately 15 to 20%.^{*} An added advantage of foamed glass is that it provides a dry, impermeable flat base for the PVC water bags, protecting the bags from possible rodent or insect damage.

The Effect of Dust on the Top Glazing

The two three-layer PVC ponds at the Sohio site — differing only in that one pond rests on a 2-in. polyurethane foam base and the other on a sand bed — became covered with a rather heavy layer of dust during the summer and fall months of 1975. The natural washing action of the frequent rainstorms was not sufficient to remove this dust.

After the September performance measurements were completed we thoroughly washed the top glazing of one of these ponds; this required using a detergent solution and scrubbing. Comparing the daily heat collected by this pond to the heat collected by its unwashed twin for a 4-day period before and after the washing gave us a rather accurate measurement of the decrease in heat collection due to the dust. The result was that the average increase in daily heat collected after washing was $(13 \pm 3)\%$. We conclude that this decrease in collected heat is equivalent to a 15 to 20% increase in the daily optical losses (Fig. 5).

We have observed that the dust build-up on the acrylic panel SSP over the past 6 months is considerably less than on the PVC SSPs.[†] This would also be the case for the Filon Supreme panels that will probably be used on the full-sized system. Therefore, it is expected that the effect of dust will not be important and that regular washing of the glazings will not be required.

^{*}As mentioned previously, we have been using a 2-in. layer of polyurethane foam for bottom insulation. This gives a calculated daily heat loss downward of about 2% of daily collected heat (or about 6% of upward heat loss). For future ponds we plan to use a 1-1/2-in. layer of foamed glass, which has a thermal conductivity per unit thickness two to three times higher than does the polyurethane foam. This increases the calculated downward heat loss to about 6 to 8% of daily collected heat.

For a 4-in. dry sand bottom insulation, the calculated downward heat loss rises to about 20% of daily collected heat (in rough agreement with experimental results quoted above). However, there is no dependable way to prevent the sand from picking up moisture over a period of time. This can increase its thermal conductivity by almost an order of magnitude and would appreciably reduce the expected daily collected heat.

[†]The top PVC glazing on these two SSPs has a file finish, facing upward. This is a finish that roughens the surface. We hoped that this roughening of the top surface might reduce specular reflection and hence increase transmission. The roughened surface probably picks up and holds considerably more dust than would a smooth PVC surface.

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