# PERFORMANCE OF A LARGE, SALT-GRADIENT SOLAR POND

Layton J. Wittenberg and Marc J. Harris
Monsanto Research Corporation
Mound Facility*
Miamisburg, Ohio 45342

## ABSTRACT

Initial performance data collected from the largest, salt-gradient solar pond in the U.S. indicate that it has the potential to be a very low-cost solar-heating system. The solar pond at Miamisburg, Ohio, occupies an area of 2000 $m^2$ and was installed for only \$35/$m^2$. The pond is predicted to deliver 281,000 kW·hr/yr to be used principally for heating an outdoor swimming pool in the summer and a recreation building during October-December. Based upon straight amortization of 10%/yr, this heat is predicted to cost 2.5¢/kW·hr.

## BACKGROUND

Preliminary performance data are being collected and evaluated during the first year of operation of the largest, salt-gradient, solar pond in the United States. This solar pond provides low-cost solar energy collection combined with annual cycle, low-temperature heat storage. Evaluation of the performance of this pond will provide the opportunity to demonstrate the viability of such a solar energy system to help meet this country's energy needs.

This large solar pond was constructed by the City of Miamisburg, Ohio, to reduce the dependency upon fossil fuel in its community park development project. The thermal energy collected and stored in the pond will supply heat when necessary to an outdoor swimming pool in the summer and to a recreational building in the winter. The City of Miamisburg solar pond is 55.4 m x 36.9 m (180 ft x 120 ft) at the top with sides tapered at an angle of 45° to a depth of approximately 3.0 m (10 ft). It is modeled after smaller experimental ponds described by Rabl and Nielsen (1**) at Ohio State University, Zangrando and Bryant (2) at the University of New Mexico, and earlier ponds in Israel (3). A salt concentration gradient in the top nonconvective gradient layer of water varies from zero to 18.5% NaCl at 1.5 m (5 ft). Below this layer is a convective layer approximately 1.5 m deep, composed of 18.5% NaCl. A copper-tube heat exchanger extends into the convective layer for thermal energy withdrawal as required.

The construction (4) of the pond was completed in August 1978 at a cost to the city of \$70,000. The total cost of \$35/$m^2$ (\$3.20/$ft^2$) for the installation of the solar pond with its combined solar energy collection and thermal storage capabilities is significantly less than the cost of \$220/$m^2$ (\$20/$ft^2$) for the presently available flat-plate collectors for building heat. The installed solar pond cost is competitive with the goal of \$5/$ft^2$ (\$55/$m^2$) for developmental nonconcentrating liquid collectors (5) which have not yet been tested on such a large scale. The efficiency of the solar pond needs to be determined, therefore, and compared with other types of solar energy systems. In order to make such a comparison, Mound Facility personnel have installed appropriate instrumentation and data collection systems so that the performance of the pond can be documented and evaluated.

## OBSERVATIONS OF POND PERFORMANCE

The solar pond is a unique solar energy collector because it absorbs radiation whenever the sun shines. On the other hand, it is an exposed long-term thermal storage system which continuously loses heat to the environment. The useful heat available from such a system is determined by the net difference between the long-term solar radiation absorbed by the storage layer and the amount of thermal energy lost to the environment over the same time period.

Because the pond was not completed until late August, 1978, little of the summer's peak solar insolation was collected; consequently, the pond attained a peak temperature of only 50°C by October 1978, too low to be useful for heating the recreation building. As a result, no useful heat has been removed from the pond. Only the natural thermal response of the pond has been observed during the fall and winter seasons. The only instrumentation available during this period was a pyranometer at some distance from the pond, which recorded total solar insolation, and thermal sensors at various locations and depths in the water and in the earth beneath the pond.

The observations indicated that the temperature of the storage layer of the solar pond (Figure 1) increased throughout September to a maximum of 50°C and then gradually decreased to a minimum of 28.4°C by the end of February. The ice cover on the pond altered slightly the rate of the temperature decrease during January and February. During March and April the pond's temperature increased as the solar insolation increased.

The temperature profiles as a function of depth in the pond and the ground beneath the pond indicated that the gradient zone was stable despite seasonal changes (Figure 2). The profile on the day of the pond's highest temperature, October 17, indicated a convective layer at the top of the pond, nearly 0.35 m deep, which was caused by the high absorptivity of solar radiation near the water-air interface and also the result of wave action. The thermal gradient layer was 0.90 m thick. The storage layer, 1.75 m thick, was constant at 50°C except for an increase of 3°C near the liner. The temperature profile as a function of depth in the ground had the shape expected for thermal diffusion from a constant temperature source (the pond) into a infinite medium (the ground) at a constant temperature of 12.8°C.

The temperature profile of the coldest day in the pond (Figure 2) indicated that the top convective zone had nearly disappeared as a result of the ice cover. The bottom of the nonconvective layer extended to a 0.3 m lower depth with the result that the gradient zone was significantly increased as compared to the October profile. The thermal storage zone was of constant temperature at 28.4°C with a 2°C temperature rise near the liner. The temperature profile in the ground had changed also, with the temperatures being nearly identical at 0 and 0.5 m below the pond and at nearly the same temperature as the thermal storage zone in the water. Such a profile would indicate that thermal diffusion from the pond to the ground had nearly ceased, and that some thermal diffusion may be occurring in the opposite direction.

After the ice melted in March, the thermal gradient zone extended to approximately the same depth as in February; however, a 0.3 m convective zone appeared

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**Numbers in parentheses designate References at end of paper.

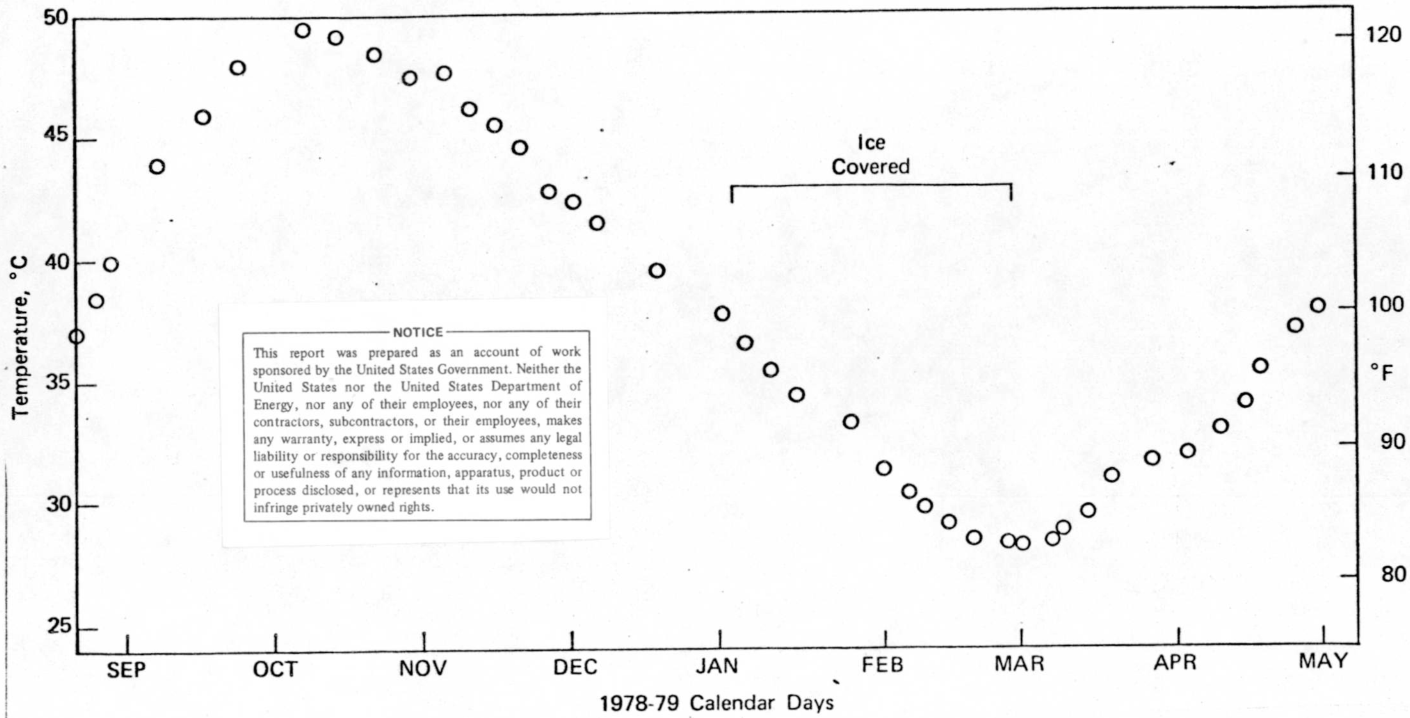




Fig. 1 - Seasonal variation of the storage water temperature

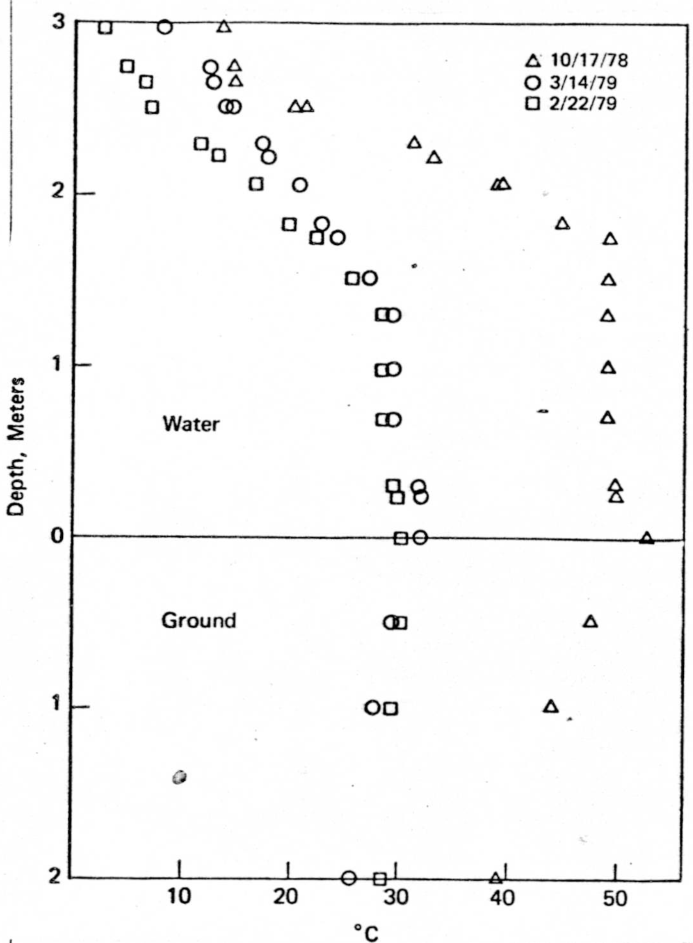


Fig. 2 - Temperature profiles in the solar pond and the adjacent ground

at the top surface, similar to the profile displayed before the top froze. The temperature profile in the ground indicated that some heat was again diffusing into the ground.

Based upon this limited information, preliminary evaluations have been made regarding the solar energy collection and thermal storage performances of the solar pond.

THERMAL ENERGY BALANCE

The thermal energy balance of the pond is the net difference between the energy accumulation in the storage layer, which occurs by solar radiation absorbed in the storage water, and the amount of thermal energy removed as useful heat or lost by thermal diffusion to the environment.

The principal loss mechanism is thermal diffusion upward through the temperature gradient caused by the air temperature being lower than the pond temperature. A minor heat-loss path is by thermal diffusion downward into the ground below the pond, although some of this thermal energy may return to the pond during the winter. Thermal losses do occur at the edges of the pond; however, such losses should be of minor consideration in such a large pond. The net thermal energy balance results in a temperature change in the storage water. This thermal balance is expressed by the relationship,

$$\frac{Cs\ (T_2-T_1)}{t} = \tau\ (e^{-\mu\lambda z_c})\ I_o - K_W\left(\frac{dT_W}{dz}\right)_{z=z_c}$$

$$-K_G\left(\frac{dT_G}{dz}\right)_{z=d} - \frac{U}{t} \qquad (1)$$

Table 1

CALCULATED STORAGE WATER TEMPERATURES OF THE SOLAR POND
BASED UPON MONTHLY HEAT REMOVAL VALUES

| Month | Monthly (kW·hr x $10^3$) Insolation | Heat Use | Temperature Storage Water (°C) Case 1 | Case 2 | OBS. |
|---|---|---|---|---|---|
| Oct '78 | 134.7 | 0 | 48.3* | 51.7* | 47.8 |
| Nov | 63.1 | 0 | 42.2 | 46.1 | 42.2 |
| Dec | 63.7 | 0 | 36.7 | 41.4 | 37.8 |
| Jan '79 | 87.0 | 0 | 30.6 | 35.6 | 31.1 |
| Feb | 115.9 | 0 | 28.9 | 33.9 | 28.3 |
| Mar | 160.9 | 0 | 35.0 | 43.3 | 32.8 |
| Apr | 170.2 | 0 | 41.7 | 51.7 | 38.3 |
| May | 302.6 | 88 | 33.9 | 48.3 | - |
| Jun | 323.3 | 88 | 32.2 | 50.0 | - |
| Jul | 323.3 | 0 | 55.6 | 76.7 | - |
| Aug | 296.5 | 32 | 61.1 | 82.8 | - |
| Sep | 221.0 | 26 | 60.0 | 81.1 | - |
| Oct | 134.7 | 3 | 53.9 | 73.3 | - |
| Nov | 63.1 | 25 | 39.4 | 56.1 | - |
| Dec | 63.7 | 19 | 29.4 | 43.9 | - |

*Initial Temperature = 51.1

where $C_s$ = heat capacity of the storage layer (°$C^{-1}$)

$T_1$ and $T_2$ = temperature of the storage water at the beginning and end of time period, t.
$I_o$ = incident solar radiation
$\tau$ = transmission corrected for reflection
$\mu_\lambda$ = absorption coefficient for wavelength $\lambda$ ($m^{-1}$)
z = depth of pond
$z_c$ = depth of the storage layer boundary below the pond's surface
$K_w$ and $K_G$ = thermal conductivity of water and ground, respectively
$T_w$ and $T_G$ = temperature of water and ground, respectively
d = total depth of the pond
U = heat removed

The energy accumulation in the system (first-term right hand side, Eq. 1), which occurs only by solar radiation absorption in the storage water, has been evaluated for two surface conditions, namely air-water interface during 10 months of the year and ice cover during January and February. In order to evaluate the open-water solar energy collection, the term, $\tau$, was corrected for reflection and $\mu_\lambda$ was corrected for refraction during each month of the year. The values of ($e^{-\mu_\lambda z_c}$) were evaluated after the solar radiation spectrum was divided into four wavelength groups (1,6). In addition, only 90% of $\tau$ was used to correct for diffuse sunlight, which is incident upon the pond at such a steep angle that it is not absorbed (7), and also to compensate for reflection from the bottom of the pond (8).

An evaluation has been made of the solar energy absorbed in the storage layer when the pond was covered with up to 0.2 m of ice and snow (9). A value of $\tau$ equal to 0.5 was calculated for days of highly directed beam insolation, but had to be corrected for days when the diffuse radiation dominates. A significant amount of this diffuse radiation would be reflected by ice and snow covering the pond and would not penetrate the ice. This loss of diffuse radiation transmission would be similar to that calculated through multiple glass layers (7). As a result, only 66% of $\tau$, i.e., only 33% ($e^{-\mu_\lambda z_c}$) was used for the months of January and February.

The evaluations of the heat loss terms (second and third terms right hand side of Equation 1) necessitate the determination of the temperature differentials in the water near the top of the storage layer zone, i.e., $(dT_w/dz)\ z{=}z_c$, and in the ground immediately below the pond, i.e., $(dT_G/dz)\ z{=}d$. Examination of the temperature differential in the water revealed that this term over a period of a month approached the value $(T_p-T_a)/\ell$ where $T_a$ and $T_p$ = temperatures of the air and storage pond, respectively, and $\ell$ = the thickness of the gradient zone. This conclusion is based upon observations that have been made principally during winter months when the total insolation is low. This term $(T_p-T_a)$ was used, therefore, to calculate the top loss term in Case I of Table 1.

The term for the heat loss to the ground was evaluated between two temperature measurements made at 0 and 0.5 m below the pond for both Case 1 and Case 2 in Table 1. For months when observed values were not available for loss to the ground, it was predicted based upon the relationship (10) $J = K_G(T_p-T_G)/(\pi\ k_G t_i)^{1/2}$ where the new terms are: J = heat flux at the surface, $k_G$ = thermal diffusivity of the ground, and, $t_i$ = time since initiation of the temperature gradient. As shown by Shelton (11), $t_i$ is within a factor of two from its steady-state value after 30 days; consequently, it does not have to be estimated precisely.

An alternative description of Equation 1 is obtained by solving the time independent heat conduction equation of heat flow in the gradient zone based upon the exponential absorption of solar radiation in this layer of water. These values have been obtained from References 1 and 6 and used as Case 2 in Table 1. In this case the total heating of the pond is higher than in Case 1 because the solar heating of the gradient-zone above the storage layer is included.

These relationships for solar energy heating of the pond together with the assumed relationship for thermal losses were tested by the use of Equation 1 to predict the temperature of the pond at the end of each month for the period October 1978 - April 1979. These results (Table 1) are based upon actual values of solar radiation and air, ground, and pond temperatures for the period. Predicted values for May-December are based upon average insolation values for this site.

## RESULTS AND DISCUSSION

The results (Table 1) show that predicted temperatures agree with observed temperatures more closely for Case 1 than for Case 2, thus far. Either set of predicted values are reasonably similar during the winter months but differ noticeably in the summer when the total insolation is large. These models will be used to compare the actual performance of the pond during the next few years and will be modified as new information is obtained.

The total heat extraction from the pond during the summer (total of 234,000 kW·hr, 800 million Btu) for heating the swimming pool only represents a very conservative use for the pond. The data presented in Table 1 indicate that an additional 47,000 kW·hr (160 million Btu) can be extracted to heat the recreation building during October, November, and December, without the need for a heat pump. Based upon this total use of 281,000 kW·hr (960 million Btu/yr), approximately 14.3% of the total incident radiation is being utilized. This heat is estimated to cost approximately 2.5¢/kW·hr ($7.20/million Btu), if the pond were amortized at a straight 10% per year. The cost of the pond heat is, therefore, approximately equivalent to heating with 65¢/gallon fuel oil.

The pond's efficiency would increase if its performance were better matched to the end use when used for direct heat transfer applications, or a heat pump could be considered to provide additional building heat during the winter.

In summary, the initial performance of the Miamisburg pond appears encouraging as a low-cost thermal energy system. Its performance should be typical of any proposed installations in the North Central or Northeastern United States.

## ACKNOWLEDGEMENT

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## REFERENCES

1. A. Rabl and C. E. Nielsen, "Solar Ponds for Space Heating," Solar Energy, Vol. 17, 1975, pp. 1-12.

2. F. Zangrando and H. C. Bryant, "A Salt-Gradient Solar Pond," Solar Age, Vol. 3, April 1978.

3. H. Tabor, "Large-Area Solar Collectors for Power Production," Solar Energy, Vol. 7, 1963, pp. 189-194.

4. R. S. Bryant, R. P. Bowser and L. J. Wittenberg, "Construction and Initial Operation of the Miamisburg Salt-Gradient Solar Pond," Proc. Int'l Solar Energy Congress, Atlanta, Georgia, May 28-June 1, 1979 (in press).

5. Proceedings 3rd Annual Solar Heating and Cooling R&D Branch Contractors Meeting, pp. 9-13, Department of Energy CONF-780983 (March 1979).

6. C. E. Nielsen, "Nonconvective Salt Gradient Solar Ponds," W. C. Dickinson and P. N. Cheremisinoff (ed.), Solar Energy Handbook, Marcel Dekker, 1979 (in press).

7. V. M. Puri, "Transmission of Diffuse Radiation Through a Series of Parallel Regions," Solar Energy, Vol. 22, 1979, pp. 183-185.

8. R. Viskanta and J. S. Torr, "Absorption of Solar Radiation in Ponds," Solar Energy, Vol. 21, 1978, pp. 17-26.

9. L. J. Wittenberg and M. J. Harris, "Evaluation of a Large Nonconvective Solar Pond," Proc. Solar Energy Storage Options, San Antonio, Texas, March 19-20, 1979 (in press).

10. H. S. Carslaw and J. C. Jaeger, "Conduction of Heat in Solids," 2nd Ed., Clarendon Press, Oxford, 1960, pp. 60-61.

11. J. Shelton, "Underground Storage of Heat in Solar Heating Systems," Solar Energy, Vol. 17, 1975, pp. 137-143.