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CONSTRUCTION AND INITIAL OPERATION OF THE MIAMISBURG SALT-GRADIENT SOLAR POND

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ABSTRACT

The largest salt-gradient solar pond in the U. S. occupies an area of 2020 m^2 and was installed for only \$35/m^2. A new technique was successfully demonstrated for the formation of the gradient zone, approximately 1-m thick, in which fresh water was injected horizontally below the surface of the concentrated salt solution. Without any useful heat removed, the storage layer water, ∿18.5% NaCl, reached a peak temperature of 51.1°C in October 1978 and a minimum temperature of 28.4°C during February 1979. 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 from October to December. The projected heat cost is 2.5¢/kW·hr, based upon amortization of 10%/yr.

1. INTRODUCTION

The construction of the largest working, salt-gradient, solar pond in the U. S. and one of the largest in the world has been completed and its operations initiated. This pond, occupying 2020 m^2, was constructed by the City of Miamisburg, Ohio, as part of its Community Park Development Project at a cost of \$70,000. The thermal energy collected in the pond will be used to heat a 50-m outdoor swimming pool in the summer and the bath-house during part of the winter for use in "passive" recreational activities as well as for meeting rooms and office space (Fig. 1).

Several renewable energy concepts were evaluated for this purpose but were discarded because of their high cost. Finally, the solar pond studies by Dr. C. E. Nielsen at Ohio State University were brought to our attention. After consultation with him, plans were made to proceed with the construction of the Miamisburg solar pond. The U. S. Department of Energy has funded nearby Mound Facility personnel to install appropriate instrumentation and a data collection system. From this information the performance of the pond can be documented and evaluated for its potential viability to help meet the nation's energy needs.

2. DESIGN AND CONSTRUCTION

The Miamisburg solar pond is 54.5 m x 36.4 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).

Construction of the solar pond and adjacent recreational building began in 1977 and the recreational building was ready for use in June 1978. Excavation work for the solar pond was completed by October 1977 but further work was interrupted by the winter of 1978. After the winter snow melted, the excavation drained rapidly, which indicated that the ground water level was below the pond.

Work on the solar pond resumed with the installation of the heavy-duty plastic liner during May 1978. The liner, 0.7 mm thick, is a chemically resistant polymer-coated polyester fabric. The liner fabric, tested in outdoor exposure tests to 117°C, should outperform the 8-10 yr lifetime of vinyl-coated fabrics. The fabric, supplied in 1.42-m widths and of sufficient lengths to extend across the width of the solar pond, was fabricated in-plant into four large sections, which were heat welded together as they were placed in the solar pond.

The pond was partially filled with water, ∿1.5 m deep, and truck loads of salt, approximately 23 tonnes each, were dumped directly into the pond. High pressure water hoses were used to wash the salt into the pond.

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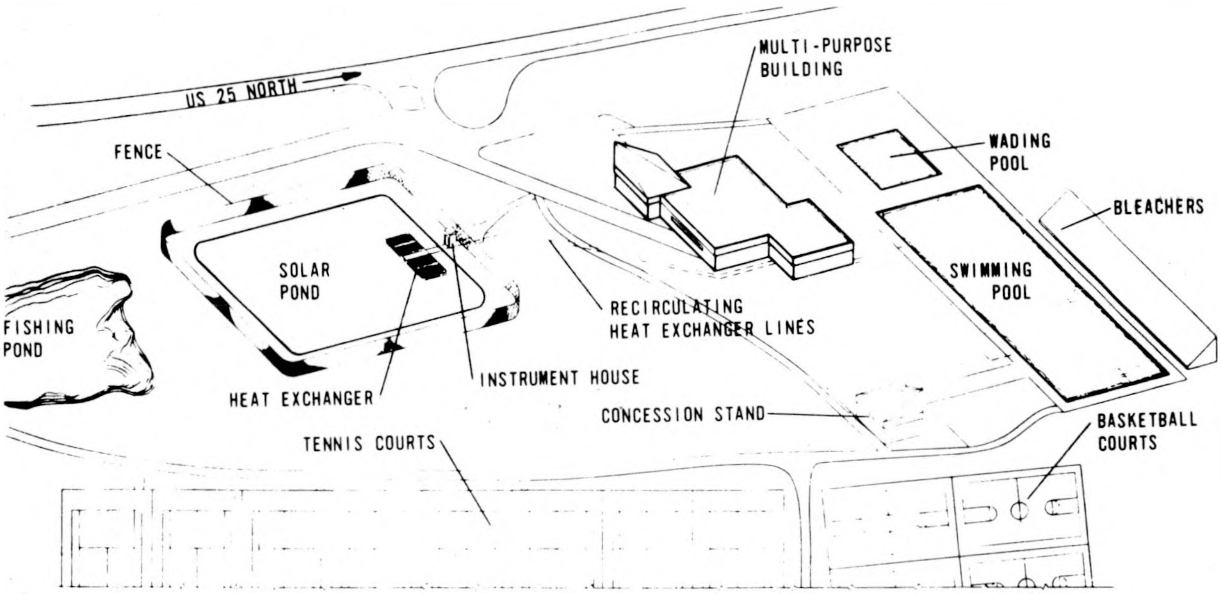

Fig. 1 Isometric view of the Miamisburg recreational area with the solar pond.

Analyses of random samples of the salt showed it to contain 98.6 $\pm$ 0.4% NaCl.

When all of the salt was in the pond, sufficient water was added to bring the depth to 2.1 m. The average salt concentration of the pond water was $\sim$14%, but large piles of undissolved salt were evident. A large portable water pump, with a capacity of 9×10^{-2} m^3 /s, was used to circulate the pond water and dissolve the remaining salt. During this process, requiring nearly four weeks, the salt concentration approached 18.5% at all locations and depths in the pond and salt crystals were no longer visible along the bottom of the pond.

During the dissolution of the salt the pH increased from 7.2 to 7.6. Because copper sulfate was to be used for algae control, the pond water was acidified to a pH of $\sim$6.1 by the addition of 440 liters of concentrated hydrochloric acid. Sufficient copper sulfate was added to achieve a copper ion concentraion of 2 ppm. The pond water has retained good transparency since this treatment.

The mixing of the acid, copper sulfate, and water brought the depth of the pond to 2.3 m. A new technique for the formation of the salt gradient in a large pond was employed, as suggested to us by F. Zangrando (4). In this procedure, a circular water distributor (1.2 m diameter) was placed 460 mm below the surface of the salt water. High pressure water was pumped through a 3.2 mm slit at the edge of the distributor at the rate of 7.4×10^{-3} m^3/s. The velocity of this water, 0.6 m/s (2 ft/sec), was sufficient to inject a horizontal layer of fresh water across the width of the pond at the same depth as the distributor. Successive layers of fresh water were added in this fashion to give 25 mm thicknesses of fresh water, and then the distributor was raised 50 mm for the next injection of fresh water. Density measurements taken at various depths during this procedure, Fig. 2, confirmed that the salt solutions were progressively diluted above the level of the injected water. The top 150 mm of the pond was covered with fresh water.

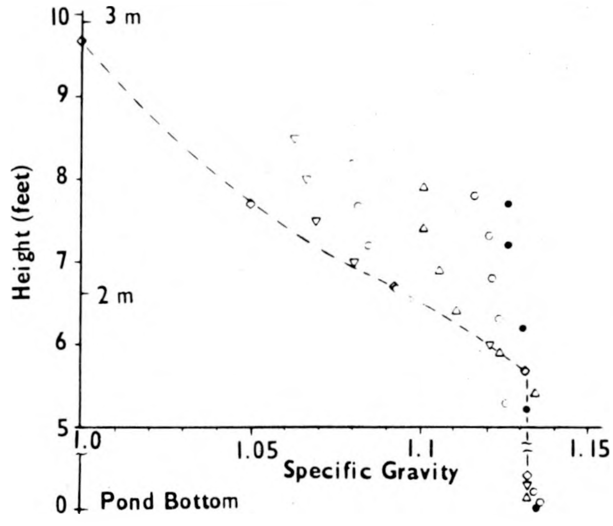

Fig. 2 Density measurements as a function of depth in the solar pond during the formation of the salt-gradient zone. Data points, progressing from right to left, indicate chronological measurements of density as a function of depth.

The heat exchanger, which is placed in the north end of the pond for heat removal, consists of two tiers of pipe mounted at the 1.5 and 1.8 m levels above the bottom of the solar pond. Each tier is approximately 12.12 x 6.06 m and has eight circuits connecting to a central supply and return header. A typical circuit consists of 16 lengths of 25.4 mm diameter (type M copper) x 6.06 m long tubes connected together by U-bends. The total heat exchange area is approximately 138 m^2 with internal water flow rates up to 6.7 liters/s. The supports for the heat exchanger, fabricated from 51 mm diameter copper tubing, rest on the bottom of the pond.

The construction costs for the pond, Table 1, indicate that the liner and the salt represent the largest capital investment, although no expense has been included for land use. The excavation and miscellaneous work were provided by regular city labor crews and, therefore, did not represent an additional expense of money. The total installed cost of the pond, \$35/m^2, with its combined solar energy collection and thermal storage, represents a significant decrease from the costs of flat-plate collector systems at \$220/m^2.

Table 1

CONSTRUCTION COSTS

Solar Pond Cost

Salt, 1,100 tons @ \$17.60/ton	=	\$19,400
Liner plus installation	=	22,000
Heat exchanger	=	6,800
Miscellaneous supplies	=	11,800
Labor (excavation, etc.)	=	10,000
Total Installation	=	\$70,000

During the construction of the pond, appropriate instrumentation was installed to monitor the performance of the pond. For this purpose, temperature sensors were placed at various depths and locations to measure the heat stored in the pond and the ground beneath the pond. Instrumentation was also provided to measure meteorological information, the incident solar radiation and solar energy transmitted as a function of depth in the pond. An automated data collection system stores the information for later digital computerized retrieval.

OBSERVATION OF POND PERFORMANCE

The temperature of the storage layer of the solar pond increased rapidly upon completion of the pond to a maximum of 50°C by October 1978. Because this temperature was too low to be useful for heating the recreation building, this year, only the natural thermal response of the pond has been observed (5) during the fall and winter seasons. The solar pond temperature 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 (5). The profile on the day of the pond's highest temperature indicated a convective layer at the top of the pond, nearly 0.35 m deep. 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 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 than in October 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.

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

3. 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 gradient zone 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. 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 which results in a temperature change in the storage water is expressed by the relationship,

$$\frac{C_s\ (T_2-T_1)}{t} = \tau\ (e^{-\mu_\lambda z_c})\ I_o - K_w\left(\frac{dT_w}{dz}\right)_{z=z_c} - K_G\left(\frac{dT_G}{dz}\right)_{z=d} - \frac{U}{t} \qquad (1)$$

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
τ = transmission corrected for reflection
μ_λ = absorption coefficient for wavelength λ (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, τ, was corrected for reflection and μ_λ 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 τ 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 was 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 (5) during January and February. A value of τ equal to 0.33 was calculated and used in Table 2.

The evaluations of the heat loss terms (second and third terms right hand side of Equation 1) necessitated 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 pond, respectively, and ℓ = the thickness of the gradient zone. This value, used in Table 2, is based upon observations made principally during winter months when the total insolation is low and may need to be modified during high insolation months.

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 and used to calculate Table 2. For months when observed values were not available for loss to the ground, it was predicted based upon the relationship (9) $J = K_G(T_p-T_G)/(\pi k_G t_i)^{\frac{1}{2}}$ 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 (10), J decreases less than 50% after 30 days; consequently, t_i does not have to be estimated precisely.

These relationships for solar energy heating of the pond together with the assumed relationship for thermal losses were tested by the use of Eq. 1 to predict the temperature of the pond at the end of each month for the period October 1978 - April 1979, Table 2, based upon actual values of solar radiation and air, ground, and pond temperatures for the period. Predicted values for May-December are based upon monthly average insolation and temperature values for this site.

Table 2

COMPARISON OF CALCULATED AND OBSERVED STORAGE WATER TEMPERATURES AT END OF MONTH BASED UPON HEAT-BALANCE EQUATION

Month	Heat Use (kW·hr x 10^3)	Temp. (°C) Calc.	Obs.
Oct '78	0	48.3*	47.8
Nov	0	42.2	42.2
Dec	0	36.7	37.8
Jan '79	0	30.7	31.1
Feb	0	28.7	28.3
Mar	0	35.2	32.8
Apr	0	41.7	38.3
May	88	33.9	-
Jun	88	32.2	-
Jul	0	55.6	-
Aug	32	61.1	-
Sep	26	60.0	-
Oct	3	53.9	-
Nov	25	39.4	-
Dec	19	29.4	-

*Initial temperature = 51.1°C.

4. RESULTS AND DISCUSSION

The results (Table 2) indicate that the predicted temperatures agree well with observed values, except for April when the total insolation was unusually low. This model 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 (234,000 kW·hr, 800 million Btu) for heating only the swimming pool represents a very conservative use for the pond. The data (Table 2) indicate that an additional 47,000 kW·hr (160 million Btu) can be extracted to heat the recreation building during October to December, without the need for a heat pump. Based upon this total use of 281,000 kW·hr/yr (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¢/gal fuel oil.

The interest by the City of Miamisburg in this demonstration project has been functional and it has proved to be not only innovative, but highly practical for municipal as well as potential commercial applications. Its performance should be typical for any proposed installations in the North Central or Northeastern United States.

5. ACKNOWLEDGEMENTS

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6. 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) F. Zangrando, University of New Mexico, private communication, 1978.

(5) 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).

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

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