SECOND ANNUAL SOLAR HEATING AND COOLING SYSTEMS OPERATIONAL RESULTS CONFERENCE

MLM-2657(OP)

November 27-30, 1979

Colorado Springs, Colorado

CONF-791105--1

MASTER

HEAT EXTRACTION FROM A LARGE, SALT-GRADIENT SOLAR POND

M. J. Harris and L. J. Wittenberg

Monsanto Research Corporation
Mound Facility*
Miamisburg, Ohio

ABSTRACT

The Miamisburg Solar Pond is the largest functional, salt-gradient solar pond in the U.S. It provides low-cost solar energy collection and low temperature heat storage. The heat in the pond is removed by use of a copper-tube heat exchanger which has a surface area of 138 m^2 (1500 ft^2). During the summer of 1979 the initial heat, 39,970 kW·hr (136 million BTU), was removed for heating an outdoor community swimming pool. Based upon the performance thus far, the pond could yield 381,000 kW·hr/yr (1300 million BTU/yr) of useful heat. An economic analysis based upon a 10-yr amortization of the installation costs of the pond indicates that the cost of the heat, 1.8¢/kW·hr ($5.40/million BTU), is already below the current price for heating with fuel oil.

INTRODUCTION

The construction of the largest salt gradient solar pond in the U.S., located in Miamisburg, Ohio, has provided the city of Miamisburg with an alternate energy source for the summer heating of its community outdoor swimming pool [1]. The solar pond concept provides low-cost solar energy collection as well as low temperature heat storage. Several research ponds have demonstrated the potential usefulness of such ponds in the U.S. [2,3]. A large pond, 7000 m^2, near the Dead Sea area in Israel has been used for commercial heating purposes and also was used to demonstrate the generation of electrical power when adapted to a low temperature turbine [4].

The solar pond in the city of Miamisburg is 55.4 m x 36.9 m (180 ft x 120 ft), nearly 2000 m^2 surface area, with sides tapered at an angle of 45° to a depth of approximately 3 m (10 ft). The pond was stabilized against normal convective flow when a salt concentration gradient was established which varied from 0% NaCl for the top convective layer to 18.5% NaCl for the bottom convective layer. Between the two convective layers was formed a nonconvective layer approximately 1 m thick, whose salt concentration increased with depth. The three-layer structure of the pond is clearly seen in the temperature-depth profile of the pond, Fig. 1. The top convective layer, approximately 0.4 m thick, is caused by the action of sunlight and wind. It nearly disappeared when the pond was covered with ice during February. The middle layer of the pond has a temperature, and salt, gradient which increases with depth. The bottom layer of the pond, nearly 1.5 m thick, contains the high temperature water. The seasonal changes in the temperature of the pond are noted in the figure.

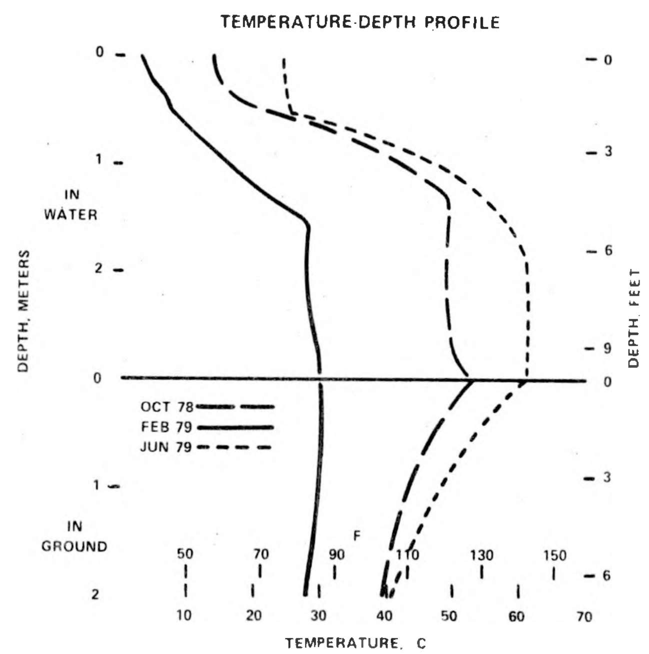

Fig. 1 - Temperature profile as a function of depth in the solar pond water and in the ground beneath the pond for three seasons of the year.

Some of the heat in the pond diffuses into the ground below the pond, as shown in Fig. 1. Part of the heat in the ground does return to the pond during the winter as determined from the shape of the thermal gradient in the ground during February.

*Mound Facility is operated by Monsanto Research Corporation for the U.S. Department of Energy under Contract No. DE-AC04-76-DP00053.

A heat exchanger lies near the interface between the gradient layer and the bottom convective layer for removal of heat from the high temperature storage layer. The heat exchange is made of 25.4 mm (1 in. O.D.) copper tubing having a total effective surface area of 138 m^2 (1500 ft^2), although only half has been used thus far. Water is circulated from the swimming pool through the heat exchanger and returned to the pool whenever the pool temperature drops below 26.7°C (80°F). Only gravity circulation causes water to flow across the heat exchanger.

The performance of the pond is recorded by the use of several instrumental techniques. Numerous temperature sensors measure the temperature of the pond water, the ground below the pond, and the performance of the heat exchanger. One pyranometer measures the total horizontal insolation at the site while another pyranometer scans the pond to determine the solar radiation penetration into the water. An additional meter records the heat delivered by the heat exchanger. All of this information is read and recorded periodically throughout the day by use of a small process computer.

POND PERFORMANCE

The pond was completed in August, 1978 and reached operational temperatures in June, 1979. The first heat extraction from the solar pond occurred during the summer months of 1979, as shown in Table 1. The total heat extracted for use in the swimming pool between June 26 and September 5 was 39,970 kW·hr (136 million BTU). The average heat extraction rate from the pond was 23.06 kW, or 340 W/m^2 of heat exchanger surface. On a particular day of high demand in July, the extraction rate approached 3600 W/m^2 by the heat exhanger for a temperature difference of 12°C between the intake and return water.

The thermal performance of the pond has to be based on an annual cycle because of the long-term heat storage in the pond; consequently, daily variations in solar insolation or heat use have little effect upon total pond performance. The thermal energy balance of the pond is, therefore, the net difference between the annual energy accumulation in the storage layer, which occurs by solar radiation absorbed in the storage water, and the amount of thermal energy removed annually as useful heat or lost by thermal diffusion to the environment.

Table I - HEAT EXTRACTION FROM THE SOLAR POND DURING THE 1979 SUMMER SEASON

	Heat Extraction	
Period	kW·hr	BTU(million)
Jun 26-30	7,030	24
Jul 01-31	19,340	66
Aug 01-31	12,720	43.4
Sep 01-05	880	3
Total	39,970	136.4

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 [5,6],

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

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

Based upon the local solar insolation, and ambient air and ground temperatures, the efficiency of the pond is theoretically predicted [7] to be nearly 20%, which would produce 381,000 kW·hr (1300 million BTU) of useful heat.

A projected utilization of the pond has been determined [1] based upon month-to-month actual performance data accumulated for one year at the pond and evaluated by use of Equation 1. In order to evaluate the solar energy collection in the pond, 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. 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. When the pond was covered with up to 0.2 m of ice and snow during January and February, a value of τ equal to 0.33 was used.

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. The term for the heat loss to the ground was evaluated based upon temperature measurements made at 0 and 0.5 m below the pond.

In order to complete the evaluation of Equation 1, reasonable heat use values, U, for each month were assumed, Table II, based principally upon the required heating demands. The predicted heat extraction for the summer months is 234,000 kW·hr (800 million BTU). The heat extracted in May will be used for the initial heating of the swimming pool which opens in late May. In addition to heating the swimming pool in the summer months, heat extracted from the solar pond can be used to heat the adjacent bathhouse from October through December, without the use of a heatpump. The total heat use predicted for the solar pond indicates

Table II - PROJECTED ANNUAL HEAT USE FROM THE SOLAR POND BASED UPON MEASURED PERFORMANCE DATA

Month	Air Temp. (°F)	Air Temp. (°C)	Insolation (W/m^2)	Heat Use (kW·hr x 10^3)
Jan	22.0	-5.6	61.6	0
Feb	30.9	-0.6	121.6	0
Mar	38.9	3.8	121.3	0
Apr	50.7	10.4	154.3	0
May	61.6	16.4	239.9	88
Jun	70.3	21.3	248.1	88
Jul	73.0	22.8	215.4	0
Aug	71.6	22.0	187.3	32
Sep	64.7	18.2	177.6	26
Oct	53.0	11.7	101.6	3
Nov	46.0	7.8	49.2	25
Dec	35.0	1.7	48.1	19

that approximately 15% of the incident solar radiation is utilized. The performance of the pond could approach the theoretical value, if, for instance, the pond was used to pre-heat domestic hot water during certain months of the year.

COST EVALUATION

The results from the Miamisburg Solar Pond indicate that it can be a viable source for low-temperature heat in most areas of the U.S. With proper match between the heat use and the pond parameters, the theoretical efficiency of the pond appears to be obtainable.

The entire pond system was installed by the city for approximately $70,000 and has a projected lifetime greater than 10 years. Based on the predicted full heat extraction from the pond (381,000 kW·hr/yr), the cost of heat is approximately 1.8¢/kW·hr (5.40/MBTU), which is very competitive with other conventional heating systems. This cost is already below the current price for heating with fuel oil. The operational and maintenance expenses appear to be small and consist chiefly of operations to maintain the optical clarity of the water. In this respect, it is similar to the maintenance of large swimming pools.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the cooperation of Richard S. Bryant, Parks and Recreation Director, City of Miamisburg, who has permitted us to place our instrumentaion at the pond site. Valuable consultations (and engineering support during the construction) with Dr. C. E. Nielsen, Ohio State University, R. P. Bowser, B. E. Pack and W. E. Kesling are also acknowledged. This evaluation study is sponsored by the U. S. Department of Energy, Office of Solar Applications.

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