SERI/TP-35-277

CONF-790541--14

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SALT CONCENTRATION GRADIENT SOLAR PONDS -- MODELING AND OPTIMIZATION

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PRESENTED AT THE ANNUAL MEETING OF THE INTERNATIONAL SOLAR ENERGY SOCIETY (ISES), ATLANTA, GEORGIA, MAY 28 - JUNE 1, 1979

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A Division of Midwest Research Institute

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

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ABSTRACT

A computer simulation design tool has been developed to simulate dynamic thermal performance for salinity gradient solar ponds. This program will be available to the public through the SERI Solar Analysis Methods Center. Dynamic programming techniques are applied to allow significant user flexibility in analyzing pond performance under realistic load and weather conditions. Finite element techniques describe conduction heat transfer through the pond, earth, and edges. Results are presented that illustrate typical thermal performance of salinity gradient ponds. Sensitivity studies of salty pond thermal performance with respect to geometry, load, and optical transmission are included.

1. INTRODUCTION

Salinity gradient solar ponds offer the advantages of relatively high operating temperatures and long-term storage for costs significantly below those of conventional active solar systems. The outlook for greatly increased interest in solar ponds appears favorable, and commercialization is close at hand. Development of solar pond engineering is a necessary step toward commercialization. Work at the Solar Energy Research Institute has been undertaken to address many of the engineering questions. This paper discusses a computer simulation program, SOLPOND, for predicting thermal performance of salty ponds. This computer design tool is to be made available to the public through the SERI Code and Methods Center. Previous analyses of salty solar ponds have discussed their optical, thermal, and hydrodynamic behavior and developed simplified, closed-form solutions of pond thermal performance (1,2). SOLPOND offers much greater versatility. Finite element techniques are employed to model pond thermal performance, and the program is structured to perform discrete time solutions. This approach allows considerable user flexibility because weather and load profiles are handled as discrete data. Additional versatility results from considering optical transmission characteristics of the pond solution as input data.

Simulation studies have investigated numerous performance characteristics, and representative results are included. These results illuminate the effects of load, salinity profile geometry, or optical transmission on seasonal response of the pond storage temperature. Additional simulation results evaluate thermal losses through the pond perimeter. A simple method for economic optimization of pond depth geometry is also discussed.

2. ANALYSIS OF LARGE PONDS

The thermal performance of the salinity gradient pond is modeled by the thermal network as shown in Fig. 1. This lumped-parameter, finite difference

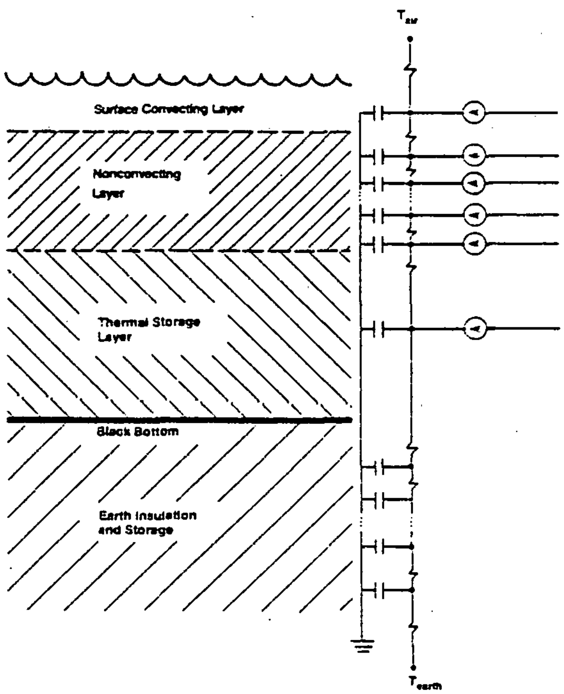

Fig. 1. One dimensional solar pond thermal network.

technique is a standard method for thermal analysis, and due to space limitations it is not detailed in this paper. However, several important aspects of the simulation program are as follows:

- Absorption of solar radiation within each finite element is modeled by a current source. The storage layer current source also accounts for the energy load delivered by the pond.
- Depths for the upper convection layer, nonconvecting layer, and storage layer, weather data, load data, optical transmission, simulation time step, thermal conductivities, and heat capacities are user selected inputs.
- The upper convecting layer and the storage layer are each described by a single finite element.
- The number of finite elements used to model the gradient layer and ground are user selected.
- In order to avoid numerical overstability, implicit finite difference equations compute the time solution.
- Dynamics of the nonconvecting layer are not modeled.
- The pond storage temperature never exceeds 100°C. It is assumed that excess energy is extracted when necessary to avoid overheating.

3. LARGE POND SIMULATION RESULTS

Knowledge of the thermal performance of salty solar ponds is of fundamental importance in assessing their market potential. For any salty pond, local weather, predicted load, geometry, and optical properties will greatly affect thermal performance. The potential combinations of these properties are limitless, but a general understanding of salty solar pond thermal performance is possible by examining several simulation results. Due to space limitations, results focus on aspects of pond thermal performance that would be difficult to investigate with previous solar pond thermal models. From these simulations, several significant design factors affecting thermal performance are investigated. The stationary parameters used for these simulations are listed in Table 1. Hourly weather data are averaged over each simulation time step. Reflected losses and the effective path length of the transmitted solar radiation are approximated by assuming the pond surface is horizontal and that the solar radiation strikes the surface at the angle of the sun's elevation. Reflection losses are calculated from Nielson's data (2), and the effective path length is determined by computing the weighted average of the secant of the angle of refraction and the transmitted solar radiation for each hour during the time step.

For all the following simulations (except where noted) optimistic optical transmission properties for the pond saline solution are assumed. Transmission is computed from Nielson's lumped representation of the solar spectrum and the associated exponential decay terms (2).

Table 1 - Assumed Parameter Values

Thermal conductivity of salt solution	0.65 (W/m°C)
Thermal conductivity of ground	1. (W/m°C)
Heat capacity of salt solution	3.98×10^6 (J/m^3°C)
Heat capacity of ground	$2. \times 10^6$ (J/m^3°C)
Ground temperature 10 metres below pond bottom	10 (°C)
Depth of upper convection layer	0.1 (m)
Simulation time step	14 (days)

All simulation results are based on pond thermal performance after initial heating is completed. Thus, the pond thermal response results are steady-state, periodic solutions. This approach is convenient and appropriate for initial study because the pond warmup transient is usually short-lived, being of minor importance after the first summer of operation.

3.1 Effect of Load Profile

Temperature and load matching between a particular application and solar pond thermal performance is of obvious design importance. The seasonal thermal performance of the pond is sensitive to total energy extraction and when this extraction occurs. To illustrate this effect, three simulation results are drawn in Fig. 2. For these runs, total annual energy extraction, pond geometry, and weather data were identical. The time of

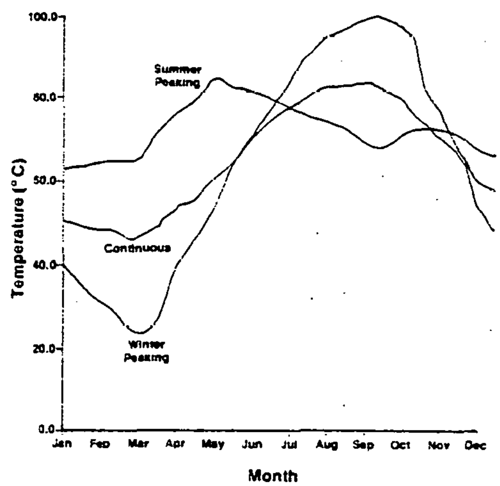

Fig. 2. Effect of seasonal load profile.

year when the load was applied to the pond was the only variable in these three simulations. The summer-peaking and winter-peaking loads extracted 70 W/m^2 continuously for 22 weeks beginning in May and November, respectively. The continuous load extracted 29.6 W/m^2 throughout the entire year.

As can be seen in Fig. 2, this pond would be capable of providing the summer-peaking load at temperatures above 65°C. The same pond would have a minimum storage temperature below 25°C if it were used for the winter-peaking load.

3.2 Effect of Storage Layer Depth for Winter Peaking Loads

The pond in Fig. 2 is poorly designed for a winter-peaking heating load requiring thermal energy above 35°C because the delivered energy temperature is too low during part of the operating season. One approach toward raising the minimum delivered energy temperature is to increase the thickness of the storage layer. Fig. 3 illustrates

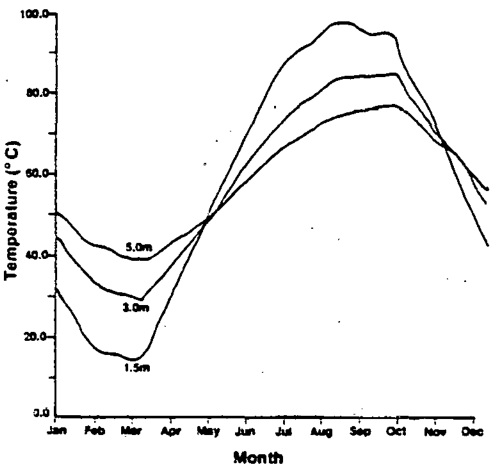

Fig. 3. Effect of storage depth.

this effect for a pond used for supplying a 55 W/m^2 heating load on a continuous basis from November through March in Madison, Wisconsin. A 5-m storage depth would be required to maintain the storage temperature above 40°C. A 3.0-m storage layer would have a minimum storage temperature near 30°C, and a pond with a 1.5-m storage layer would drop to about 15°C by the end of the heating season. If salty ponds are to be used for winter heating applications, they will have to be deeper than ponds yet constructed.

3.3 Effect of Optical Transmission

The variation in pond thermal performance due to variation in optical transmission of the salt solution is great. Pond thermal performance is sensitive to the amount of solar radiation absorbed in the nonconvecting layer and the amount that penetrates into the storage layer. Also, the solution optical transmission can vary greatly due to salt impurities, and inexpensive salts will contain impurities.

The optical transmission characteristics of the pond vary with the salt concentration. Pure water characteristics establish the upper bound on optical transmission. The dissolved salt further degrades transmission. The algorithm used by SOLPOND to calculate optical transmission superimposes absorption by water and salt. Since salt concentration varies with depth, the transmission through the upper regions of the pond is higher than the transmission in the more concentrated regions of the nonconvecting layer. Fig. 4 illustrates the optical degradation caused by using an inexpensive salt byproduct containing a few percent of impurities.

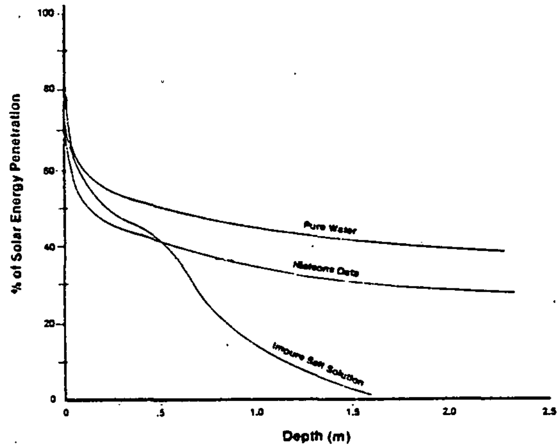

Fig. 4. Optical transmission through a salty pond.

The thermal performance of a pond using this salt byproduct has been simulated with SOLPOND. The resulting seasonal temperature profile is drawn in Fig. 5. For comparison, simulations iden-

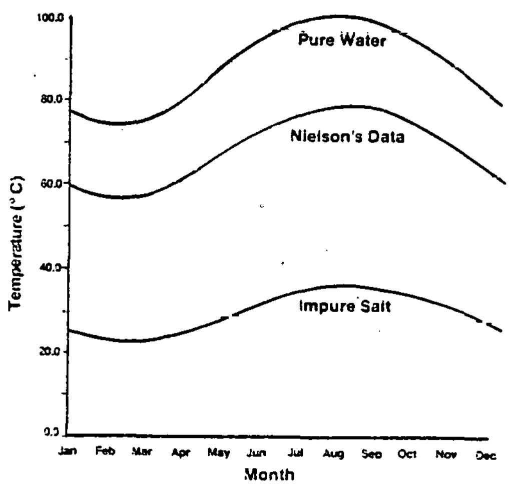

Fig. 5. Effect of optical transmission.

tical except in optical transmission have been performed, and their seasonal temperature profiles are included in Fig. 5. The obvious conclusion is that this salt byproduct would not be a desirable salt for solar pond applications unless the absorbing impurities could be removed inexpensively.

4. EDGE LOSS ANALYSIS

The detrimental effects of edge losses become important when the pond perimeter to surface area ratio becomes large (i.e., in a small pond). To account for edge losses, a three-dimensional analysis is necessary. For this modeling, which is an extension of the one-dimensional analysis suitable for large ponds, finite element techniques are used again. For simplicity, a circular pond is considered, and axial symmetry of temperatures and solar radiation is assumed. Thus, the three-dimensional analysis can be described by a two-dimensional finite element model revolved around the axis of symmetry. The element geometry is illustrated in Fig. 6.

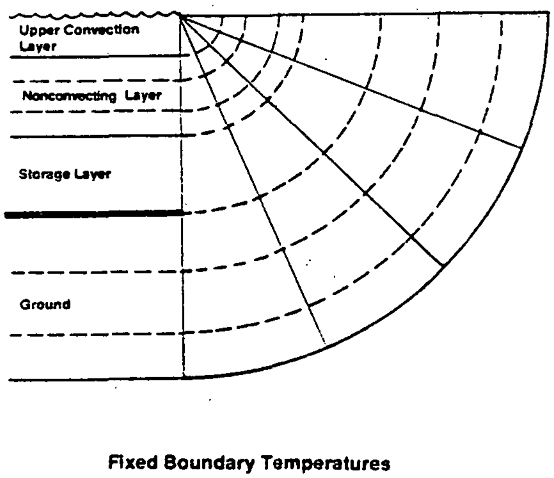

Fig. 6. Three-dimensional finite element geometry.

This model is incorporated within the solar pond simulation program and can be used for dynamic simulation of the thermal performance of smaller ponds. The following analysis of average annual thermal edge losses also made use of this model.

A convenient parameter for approximating average annual thermal losses through the pond edges is a perimeter heat loss coefficient. This parameter relates the edge loss per length of perimeter to the temperature difference between the pond storage layer and the ambient air. Using the material properties and ground temperature listed in Table 1 and a 0.3-m upper convection layer, several perimeter heat loss coefficients have been calculated. These are presented in the graph in Fig. 7, which illustrates the dependence between pond depth profile and the perimeter heat loss coefficient. Other factors, such as operating temperature and load profile, affect the value of the perimeter edge loss coefficient but to a much lesser degree.

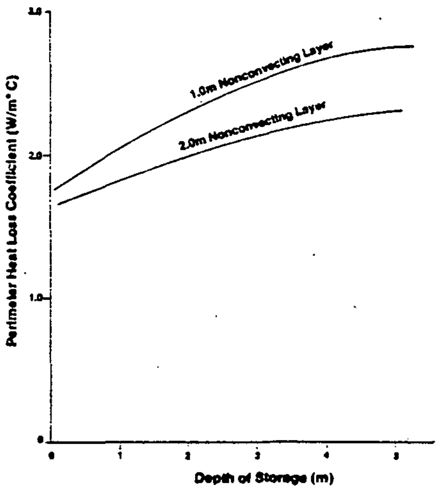

Fig. 7. Typical perimeter heat loss coefficients.

The importance of accounting for thermal losses through the pond edges can be highlighted by considering the degradation in delivered energy for several pond sizes. Table 2 lists the approximate load per unit surface area lost through the pond edges for three ponds having a 2.0 W/m°C perimeter heat loss coefficient and operating 50°C above ambient. The small pond, typical in size of research ponds in the United States, loses over 3 kW through the edges, which is equivalent to a 40 W/m^2 load on a pond with negligible edge losses. This is most of the potential load. The second pond has the same surface area to perimeter ratio as the Miamisburg pond* and, consequently, suffers similar thermal degradation which is more than 10 W/m^2 of pond surface for these operating assumptions (3). The 100-m diameter pond is quite large in comparison with ponds constructed in the United States and loses 4 W/m^2. This is about 10% of the delivered energy. The performance degradation due to edge losses is significant for small

Table 2 - Thermal Edge Losses for Three Ponds

	Thermal Edge Losses		
Diameter	per unit area	total	per unit area
10 m	100 W/m	3160 W	40. W/m^2
35 m	100 W/m	11,000 W	11.4 W/m^2
100 m	100 W/m	31,600 W	4. W/m^2

*An existing salinity gradient pond 55 m by 37 m in size.

ponds, and insulation may be desirable. SOLPOND may be used to simulate small ponds with insulation along the perimeter.

5. ECONOMIC OPTIMIZATION OF POND DESIGN

One obvious criterion of importance for solar pond design is delivered energy cost. Minimizing this cost is often a design objective. Many additional constraints, not least of which is delivered load temperature, must also be addressed during design. SOLPOND can be a useful tool in selecting pond design that meets the design constraints on thermal performance while minimizing delivered energy cost. A simplified economic analysis is presented to illustrate this design use.

There has been insufficient working experience with salty ponds to provide good estimates of material, construction, and operation and maintenance costs. However, for example, consider a salty solar pond designed to provide heating for a cluster of houses in Madison, Wisconsin. The district heating system requires energy at a source temperature at or above 40°C. The pond construction, land, and capitalized operation and maintenance costs are estimated to be $6.00/m^2$, and the delivered cost of salt is $15/ton. The heating load is assumed to be constant from November through March.

Simulations of various pond geometries were run to determine the maximum load that can be delivered by a large pond with the pond temperature remaining above 40°C. The cost of energy delivered by each of these ponds is computed by calculating the salt cost for the specific geometry and dividing the delivered energy by the sum of the pond construction and salt costs. Results of these simulations are drawn in Fig. 8. For this example, the delivered energy-to-capital investment ratio is maximized for a pond with a 2.0-m depth nonconvecting layer and a 2.5-m deep storage layer. This simple example is valid for comparing various pond geometries; however, the economics become more involved when attempting to compare solar ponds to other energy sources and are beyond the scope of this paper.

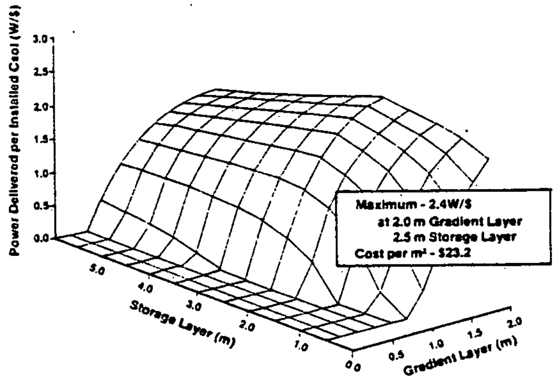

Fig. 8. Delivered energy vs. capital cost.

6. CONCLUSIONS

A simulation program, SOLPOND, has been developed to analyze solar pond thermal performance under realistic weather and energy extraction conditions. This program was used for several illustrative examples. Simulation results highlight pond sensitivity to seasonal load profile, storage layer depth, and optical transmission through the salt solution. Thermal losses through the pond edges were evaluated for several pond sizes and are shown to be significant for ponds as large as 100 m. A simple economic optimization technique to maximize delivered energy per capital cost was also presented.

7. REFERENCES

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