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A Simple Design Tool For Sizing Solar Ponds

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A Division of Midwest Research Institute

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FOREWORD

This report presents a simple tool and method of analysis to aid practitioners in the planning and implementation of solar energy systems. This simple design tool for sizing solar ponds should aid analysts and planners in assessing the feasibility of solar ponds for any specified application, and in drawing up a preliminary plan for their implementation. Work was performed under the Systems Analysis and Testing Program, a major program element in the Systems Development Division, Office of Solar Applications.

The assistance of David K. Benson in providing a careful review of this report is gratefully acknowledged.

Approved for:

SOLAR ENERGY RESEARCH INSTITUTE

Neil H. Woodley by

Neil Woodley, Chief
Systems Analysis Branch

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SUMMARY

Solar ponds are probably the simplest technology available for thermal conversion of solar energy. The salt gradient solar pond was developed in Israel in the early 1960s where research has been rejuvenated recently by the escalation in oil prices. Solar pond research and development has been pursued in the United States since 1970 with one salt gradient solar pond now operating commercially in Miamisburg, Ohio.

Although further research and development of solar ponds is desirable to perfect the technique, the basic technology is proven. The solar pond has been shown to be technically feasible and economically viable for many applications. Given an annual load profile and required output temperatures, a solar pond may be sized to meet temperature and load requirements. After a start-up period ranging from about a month or two to one year, the solar pond achieves "steady state" operation. The start-up period is necessary to heat the pond water and the ground surrounding it.

This report provides simple formulas in "cookbook" form to calculate the required pond surface area and depth. These formulas will enable a potential user to determine the approximate size solar pond needed for the contemplated application and location. In addition, examples are given of solar pond sizes at various locations in the United States.

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SECTION 1.0

INTRODUCTION

The solar pond is simultaneously a collector of solar radiation and a large body of thermal storage. Any pond collects heat in the form of insolation absorbed into the pond itself and at its bottom. The ordinary natural pond loses the heat through vertical convection currents and evaporation and convection at the pond surface. The solar pond has artificial means to prevent vertical convection within the pond, evaporation and convection at the surface, or both. Due to the pond's massive thermal storage and the measures taken to retard heat loss, a temperature loss of 10°C takes weeks, even in the absence of insolation. Thus, the solar pond converts an intermittent energy source--solar radiation--into a reliable source.

The efficiency of conversion from insolation to thermal energy ranges from about 10% to 30%, depending on pond location and output temperature. Although conversion efficiency is low, cost and complexity are very low. As a result, solar ponds provide a simple, economical, and reliable source of thermal energy suitable for applications such as district heating and cooling, low-temperature industrial process heating, or preheating for industrial processes. In addition, solar ponds in combination with organic Rankine engines or thermoelectric devices can be used as a continuous source of electricity. The economics of solar pond electricity production are currently favorable but only for remote applications.

This report provides a simple method for determining the required surface area and depth of a solar pond. In general, the surface area controls the average annual output temperature of the pond. The larger the surface area, the larger the received insolation compared to the load and, therefore, the higher the temperature of the heat delivered. Once the surface area is determined, the depth controls the seasonal variation in output temperature. The greater the depth, the larger the thermal mass and, therefore, the smaller the amplitude of seasonal temperature fluctuations.

The report begins by describing a base case salt gradient solar pond design and providing simple steps to determine the required surface area and depth for a pond of this design (Section 2.0). Section 3.0 gives an example of the method and includes the results of a full-scale computer simulation for the same example. Section 4.0 uses the simple method presented in this report to obtain estimated pond sizes for various locations in the United States with only the base case salt gradient solar pond design being considered. Section 5.0 outlines the method for the more general solar pond including salt gradient ponds diverging from the base case design and saltless ponds. Section 6.0 contains a discussion of the origins of errors in the simple method. Section 7.0 turns the method around by showing how to obtain estimated output temperatures for a pond given its size and shape. It also describes how to obtain the demand served when output temperatures are specified. Section 8.0 provides hints on how to apply the method to a practical sizing problem. The Appendix gives the theoretical derivation of the simple method.

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SECTION 2.0

THE BASE CASE SALT GRADIENT SOLAR POND

The salt gradient solar pond is the most thoroughly researched and well-established variety of solar pond (Nielsen, forthcoming; Tabor and Weinberger, forthcoming; Rabl and Nielsen 1975; Zangrando and Bryant 1978). These ponds have been successfully operating for years in Ohio and New Mexico, as well as Israel and other areas. The salt gradient pond (Fig. 2-1) contains three layers: the surface layer--a thin layer of nearly saltless water in which there are vertical convection currents due to wind and evaporation; the nonconvecting layer--a layer in which a salt concentration gradient (positive downward) prevents vertical convection; and the lower convecting layer--a storage layer in which the salt concentration is constant. The nonconvecting layer serves to insulate the storage layer, preventing most of the heat loss. The convection of the surface layer is unavoidable, due to the effects of wind and evaporation. The bottom of the pond is usually lined with a blackened plastic film, to prevent leakage and to absorb the insolation that reaches the bottom. Heat removal to serve the load takes place in the storage layer either through a heat exchanger placed in the lower depths of the pond or by running the water through a heat exchanger placed nearby.

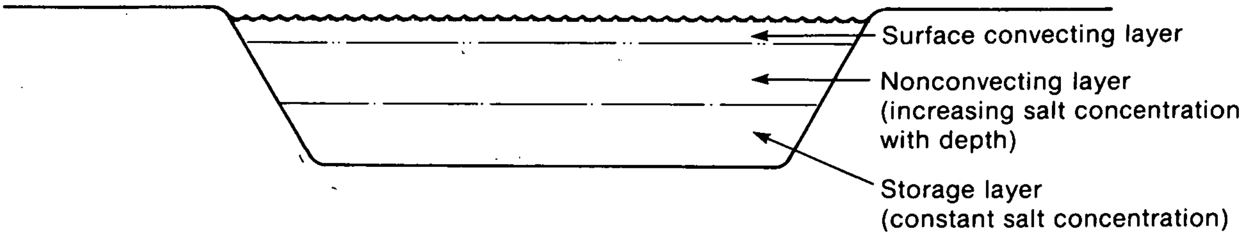

Figure 2-1. Salt Gradient Solar Pond

For the simplest version of the solar pond sizing method, which is presented in this section, a "base case" salt gradient pond with a surface convecting layer 0.3 m thick and a nonconvecting layer 1.2 m thick is assumed. These parameters are not necessarily optimal for every location and application, but they provide a conservative estimate of required pond size. The sizing method for more general salt gradient ponds and for saltless ponds is presented in Section 5.0.

For the base case salt gradient pond, an average optical transmission of 0.31 through the surface convecting and nonconvecting layers is assumed. Surface heat losses are assumed to be 0.4 W/m^2 °C; bottom losses, 0.1 W/m^2 °C (differential between pond and ground temperatures); and edge losses, 2.2 W/°C per meter of pond perimeter (this would be reduced substantially if the edges were insulated). These assumptions are summarized in Table 2-1. Note that heat loss coefficients and optical transmission vary with local conditions and pond construction. If better estimates of these parameters than those assumed for the base case can be obtained, the expanded method described in Section 5.0 should be used. An explanation of the choice of transmission and heat loss coefficients for the base case salt gradient pond is also contained in Section 5.1.

Table 2-1. BASE CASE SALT GRADIENT POND ASSUMPTIONS

Parameter	Value	Comments
Surface convecting layer thickness	0.3 m	Varies with surface conditions
Nonconvecting layer thickness	1.2 m	May not be optimal
Average optical transmission through top two layers	0.31	Should be lower at high latitudes
Heat loss from pond surface through nonconvecting layer	0.4 W/m^2 °C	
Edge losses	2.2 W/°C per meter of perimeter	Varies with soil content, elevation of pond surface above/below grade, and presence of edge insulation
Losses from pond bottom to ground	0.1 W/m^2 °C	Varies with soil content and existence/depth of ground water

2.1 ESTIMATING SURFACE AREA FOR THE BASE CASE POND

The required solar pond surface area is a function of desired annual average pond temperature, annual average ambient temperature, annual insolation, annual load, and latitude. The surface area increases as either the desired average pond temperature or the annual load increases, and the surface area decreases as the annual average ambient temperature or insolation increases. The latitude indicates only the average elevation angle of the sun and, therefore, the surface reflective losses, which are greater at higher latitudes. Hence, because of larger reflective losses and the likelihood of decreased ambient temperature and insolation, the required pond surface area tends to increase with increasing latitude.

2.1.1 Inputs

Inputs required are:

$\overline{T}$ = annual average pond temperature desired in °C (if in °F, subtract 32 and multiply by 5/9);

$\overline{T}_a$ = annual average ambient temperature in °C;

$\overline{I}$ = annual average insolation in W/m^2 (if in langleys per day, multiply by 0.4845);

$\overline{L}$ = annual average load in watts (if in Btu/yr, multiply by 3.34×10^{-5}); and

ϕ = latitude in degrees.

2.1.2 Calculations

(1) Multiply the insolation $\overline{I}$ by the adjustment factor f to obtain $\overline{I}_r$, the insolation received after adjustment for surface reflection losses. The factor f is a function of latitude ϕ, as shown in Table 2-2.

(2) Multiply $\overline{I}_r$ by 0.31 to obtain $\overline{I}_p$, the insolation received in the pond after adjustment for reflection and transmission losses.

(3) Let $T_d = \overline{T} - \overline{T}_a$. Then, the equation for the radius r (in meters) of a circular pond to meet the requirements is:

$$r = \frac{2.2T_d + [4.84T_d^2 + \overline{L}(0.3183\overline{I}_p - 0.1592T_d))]^{1/2}}{\overline{I}_p - 0.5T_d} \tag{2-1}$$

(4) Once the radius is determined, use $A = \pi r^2$ to find the required surface area in square meters. To obtain the required area in acres, multiply by 0.000247.

The fact that some of the constants have several significant digits does not imply a like accuracy in the result.

Table 2-2. REFLECTION LOSS ADJUSTMENT FACTORS

Latitude ϕ range (degrees)	Reflection Loss adjustment factor f
0 to 29	0.98
30 to 43	0.97
44 to 49	0.96
50 to 53	0.95
54 to 56	0.94
57 to 58	0.93
59 to 60	0.92
61 to 62	0.91
63	0.90
64	0.89
65	0.88
66	0.87
67	0.86
68	0.85
69	0.84
70	0.83
71	0.81
72	0.80
73	0.78
74	0.76
75	0.74
76	0.71
77	0.69
78	0.66
79	0.63
80	0.59
81	0.56
82	0.52
83	0.47
84	0.42
85	0.37

2.2 ESTIMATING DEPTH REQUIREMENT FOR THE BASE CASE POND

The greater the depth of the pond, the greater its thermal mass and, therefore, the smaller its seasonal temperature fluctuations. Because of excavation and salt costs, it is desirable to keep the depth at the minimum that assures a specified minimum pond temperature.

The calculation of the depth requirement is more complex than the calculation of the surface area requirement. It does not yield a closed form solution for the required depth; rather, a depth is input and a resulting minimum pond temperature is obtained. The required depth to satisfy a specified minimum temperature requirement must be obtained by trial and error. Nevertheless, the calculations can be executed easily on a hand-held programmable calculator.

2.2.1 Inputs

Inputs required are: $\bar{T}$, $\bar{T}_a$, $\bar{L}$, ϕ, as specified in Section 2.1.1; $\bar{I}_p$, as calculated in Section 2.1.2;

A = the pond surface area in square meters, as calculated in Section 2.1.2 (if in acres, multiply by 4047);

T_{min} = minimum desired pond temperature (°C);

$T_{a,min}$ = average ambient temperature in the coldest month of the year (°C);

I_{min} = average insolation in the least sunny month of the year (W/m^2);

L_{max} = average load in the month with the highest demand (watts); and

M = the number of the month with the highest demand. If in northern hemisphere, $M = 1$ for January, $M = 2$ for February, etc. If in southern hemisphere, $M = 7$ for January, $M = 8$ for February, etc., with $M = 6$ for December.

2.2.2 Calculations

(1) Adjust I_{min} for reflection at the pond's surface by looking up the factor in Table 2-2 for ϕ + 24°, then multiplying this factor by I_{min} to obtain $I_{r,min}$.

(2) Multiply $I_{r,min}$ by 0.29 to obtain $I_{p,min}$.

(3) Let

$$\tilde{T}_a = \bar{T}_a - T_{a,min}$$

$$\tilde{I} = \bar{I}_p - I_{p,min}$$

$$\tilde{L} = (L_{max} - \bar{L})/A$$

$$\alpha = (M - 0.5)/12 - 0.25$$

(4) Let

$$a = 0.7069\tilde{I} - 0.4633\tilde{T}_a - 3.7722\tilde{L} \cos 2\pi\alpha$$

$$b = -3.7054\tilde{I} - 1.4351\tilde{T}_a + 3.7722\tilde{L} \sin 2\pi\alpha$$

$$c = -1.1775\tilde{I} + 0.7766\tilde{T}_a + 6.2832\tilde{L} \cos 2\pi\alpha$$

$$d = -6.1720\tilde{I} - 2.3904\tilde{T}_a + 6.2832\tilde{L} \sin 2\pi\alpha$$

To facilitate these calculations, Table 2-3 gives values of cos $2\pi\alpha$ and sin $2\pi\alpha$ for the various values of M.

(5) Determine the required depth by trial and error. Select a trial depth D and compute t_{min}, the resulting minimum pond temperature, as follows:

$$t_{min} = \overline{T} - \frac{\left[(a + dD)^2 + (b + cD)^2\right]^{1/2}}{5.2327D^2 + 1.8861} \qquad (2\text{-}2)$$

Repeat with another trial D until a value of D is found such that $t_{min} = T_{min}$, the desired minimum pond temperature. The value of D thus obtained is the depth of the pond's storage layer.

(6) Add 1.5 m to D to account for the surface convecting layer and the nonconvecting layer to obtain the total pond depth.

Table 2-3. VALUES OF COS $2\pi\alpha$ AND SIN $2\pi\alpha$ FOR VARIOUS VALUES OF M

M	cos $2\pi\alpha$	sin $2\pi\alpha$
1	0.2588	-0.9659
2	0.7071	-0.7071
3	0.9659	-0.2588
4	0.9659	0.2588
5	0.7071	0.7071
6	0.2588	0.9659
7	-0.2588	0.9659
8	-0.7071	0.7071
9	-0.9659	0.2588
10	-0.9659	-0.2588
11	-0.7071	-0.7071
12	-0.2588	-0.9659

SECTION 3.0

EXAMPLES

A solar pond is to be sized to provide heat to an office building in winter, hot water year-round, and heat to run an absorption cooler in the summer. The average annual load has been determined to be 280 kW_{th}, with the load reaching a maximum of 480 kW_{th} in July. For the heating load in winter, the pond output temperature should be at least 48°C. In summer, the pond output temperature must be at least 75°C to run the absorption cooler. Therefore, it is assumed that an annual average pond temperature of 70°C with a winter minimum of 48°C should be sufficient to provide the heat required.

The site at which the pond is to be built is at a latitude 39°. The average annual ambient temperature is 10°C, reaching a minimum average of −2°C for the month of January. The average annual insolation is 206 W/m^2 with a minimum of 96 W/m^2 for the month of December. Symbolically,

$\overline{T}$ = 70°C, the average annual desired pond temperature;

$\overline{T}_a$ = 10°C, the average annual ambient temperature;

$\overline{I}$ = 206 W/m^2, the average annual insolation;

$\overline{L}$ = 280,000 W, the average annual load;

ϕ = 39°, the latitude;

T_{min} = 48°C, the minimum desired pond temperature;

$T_{a,min}$ = −2°C, the average ambient temperature in the coldest month;

I_{min} = 96 W/m^2 the average insolation in the least sunny month;

L_{max} = 480,000 W, the average load in the month with the highest demand;

M = 7, the number of the month (July) with the highest demand.

3.1 SURFACE AREA CALCULATION

Using Section 2.1.2 as a reference, do the following calculations.

(1) From Table 2-2, the reflection loss adjustment factor f at latitude 39° is 0.97; hence, the average annual insolation adjusted for reflection losses $\overline{I}_r$ is $0.97 \times 206 = 200\ W/m^2$.

(2) $\overline{I}_p = 0.31 \times \overline{I}_r = 0.31 \times 200 = 62\ W/m^2$, the average annual insolation reaching the pond's storage layer.

(3) The average temperature difference T_d between pond and ambient, $\overline{T} - \overline{T}_a$, is 70°C − 10°C = 60°C. Applying Eq. 2-1, the radius (in meters) of the required circular pond is:

$$r = \frac{2.2T_d + [4.84T_d^2 + \bar{L}(0.3183\bar{I}_p - 0.1592T_d)]^{1/2}}{\bar{I}_p - 0.5T_d}$$

$$= \frac{2.2(60) + \{4.84(60)^2 + (280,000)[0.3183(62) - 0.1592(60)]\}^{1/2}}{62 - 0.5(60)}$$

$$= 57 \text{ m}.$$

(4) The required surface area in square meters is, therefore, $A = \pi r^2 = 3.1416(57)^2 = 10,200 \text{ m}^2$, and the required surface area in acres is $10,200 \times 0.000247 = 2.5$ acres.

For a pond of a more conservative design, require the annual average pond temperature to be 77°C; then the required surface area is 11,800 m^2 or 2.9 acres.

3.2 DEPTH CALCULATION

Using Section 2.2.2 as a reference, do the following calculations.

(1) Adjust I_{min} for the reflection at the pond's surface by multiplying I_{min} by the factor f associated with $\phi + 24°$. The latitude $\phi + 24°$ is $39° + 24° = 63°$, and the factor f from Table 2-2 is 0.90. Hence, $I_{r,min} = 0.90 \times I_{min} = 86.4 \text{ W/m}^2$.

(2) Adjust for transmission losses through the surface convecting and nonconvecting layers by multiplying $I_{r,min}$ by 0.29. (Note that attenuation due to transmission losses increases at the lower solar elevation angle at which I_{min} occurs.) Thus, $I_{p,min} = 0.29 \times I_{r,min} = 0.29 \times 86.4 = 25 \text{ W/m}^2$.

(3) Let

$$\tilde{T}_a = \bar{T}_a - T_{a,min} = 10 - (-2) = 12°\text{C};$$

$$\tilde{I} = \bar{I}_p - I_{p,min} = 62 - 25 = 37 \text{ W/m}^2;$$

$$\tilde{L} = (L_{max} - \bar{L})/A = (480,000 - 280,000)/10,200$$

$$= 19.6 \text{ W/m}^2; \text{ and}$$

$$\alpha = (7 - 0.5)/12 - 0.25 = 0.29.$$

(4) Let

$$a = 0.7069\tilde{I} - 0.4663\tilde{T}_a - 3.7722\tilde{L} \cos 2\pi\alpha = 38.9466$$

$$b = -3.7054\tilde{I} - 1.4351\tilde{T}_a + 3.7722\tilde{L} \sin 2\pi\alpha = -82.7087$$

$$c = -1.1775\tilde{I} + 0.7766\tilde{T}_a + 6.2832\tilde{L} \cos 2\pi\alpha = -64.8006$$

$$d = -6.1720\tilde{I} - 2.3904\tilde{T}_a + 6.2832\tilde{L} \sin 2\pi\alpha = -137.7671$$

(5) Try various values of D in Eq. 2-2 until one is found that satisfies the requirement that $T_{min} = 48°C$. That is,

$$48 = \overline{T} - \frac{[(a + dD)^2 + (b + cD)^2]^{1/2}}{5.2327D^2 + 1.8861}$$

$$= 70 - \frac{[(38.9466 - 137.7671D)^2 + (-82.7087 - 64.8006D)^2]^{1/2}}{5.2327D^2 + 1.8861}$$

is satisfied when D = 1.2.

(6) Add 1.5 m to D, 1.2 + 1.5 = 2.7 m, which gives the overall depth of the required pond including surface convecting and nonconvecting layers.

For a pond of a more conservative design, assume that the average annual pond temperature must be 77°C and the minimum must be 60°C. It was noted above that for the pond's average annual temperature to be 77°C, the surface area must be 11,800 m^2. Recomputing $\tilde{L}$,

$$\tilde{L} = (L_{max} - \overline{L})/A = (480,000 - 280,000)/11,800 \quad ,$$

one gets $\tilde{L} = 16.9\ W/m^2$.

With this revised value of $\tilde{L}$, the revised values of a, b, c, and d are:

$a = 36.4137$
$b = -92.5736$
$c = -60.6557$
$d = -154.1988 \quad .$

After a trial and error application of Eq. 2-2, it is found that a 1.8 m depth of storage satisfies the requirement that $T_{min} = 60°C$. Hence, the total pond depth requirement is 1.8 + 1.5 = 3.3 m.

3.3 VALIDATION OF EXAMPLE

The example in this section was analyzed with a finite element computer program designed specifically for the simulation of salt gradient solar ponds (Jayadev and Henderson 1979). The simulation used hourly ambient temperature and insolation data and monthly load data. After several iterative runs with different pond areas and depths, a "minimal pond" (for average 70°C and minimum 48°C temperatures) and a "conservative pond" (for average 77°C and minimum

60°C temperatures) were found. Table 3-1 shows the monthly average inputs and the resulting monthly pond temperatures in each case.

The minimal pond that was sized using the detailed finite element computer program is 9500 m^2 in surface area (2.35 acres) and 2.5 m deep. By comparison, the pond designed using the simple method measured 10,200 m^2 (2.5 acres) in surface area and 2.7 m in depth. The conservative pond that was obtained using the finite element program is 11,300 m^2 (2.8 acres) in surface area and 3.5 m in depth, while its counterpart designed with the simple method is 11,800 m^2 (2.9 acres) in surface area and 3.3 m in depth. The agreement, in these cases, is within 10% with the simple method usually erring on the conservative side.

Table 3-1. SIMULATED PERFORMANCE OF SALT-GRADIENT SOLAR POND

	Loads (10^8 Btu) (average kW in parentheses)						Pond Temperatures (°C at month end)	
	Heating	Cooling	Hot Water	Total	Ambient Temp. (°C)	Insolation (W/m^2)	Conservative Pond[a] (2.8 acres, 3.5 m deep)	Minimal Pond[a] (2.35 acres, 2.5 m deep)
Jan.	6.0 (236)	0.0 (0)	0.7 (28)	6.7 (264)	-1.6	110	62	48
Feb.	5.0 (218)	0.0 (0)	0.7 (30)	5.7 (249)	0.4	148	60	48
Mar.	3.75 (148)	0.0 (0)	0.7 (28)	4.45 (176)	2.8	201	64	58
Apr.	1.75 (71)	2.5 (102)	0.7 (28)	4.95 (201)	8.6	247	73	73
May	0.75 (30)	5.0 (197)	0.7 (28)	6.45 (255)	13.9	281	82	82
June	0.0 (0)	10.0 (407)	0.7 (28)	10.7 (435)	18.9	309	87	86
July	0.0 (0)	11.5 (453)	0.7 (28)	12.2 (481)	22.8	299	89	86
Aug.	0.0 (0)	11.0 (433)	0.7 (28)	11.7 (461)	22.0	269	89	85
Sept.	0.25 (10)	5.0 (203)	0.7 (28)	5.95 (241)	17.1	227	86	78
Oct.	1.0 (39)	2.5 (98)	0.7 (28)	4.2 (165)	11.1	171	84	75
Nov.	3.5 (142)	0.0 (0)	0.7 (28)	4.2 (170)	4.1	116	77	67
Dec.	5.5 (217)	0.0 (0)	0.7 (28)	6.2 (245)	0.3	96	69	55
Annual	27.5 (92)	47.5 (159)	8.8 (29)	83.8 (280)	10.1	206	77	70

[a] Pond assumed circular with 0.3 m upper convecting layer and 1.2 m nonconvecting layer.

SECTION 4.0

PREDICTED RESULTS FOR LOCATIONS IN THE UNITED STATES

Table 4-1 shows the results of sizing the base case salt gradient solar pond using the simple technique described in Section 2.0, at various locations in the United States. The load is assumed to be 50 kW_{th} on the average, attaining a maximum of 70 kW_{th} during the peak demand period. Sizing calculations were performed for winter peaking and summer peaking loads. Summer peaking loads are more likely at lower latitudes where solar ponds may be used for cooling. The surface area requirement is unaffected by the timing of the peak demand. The depth requirement is affected, however; greater depth is required for a winter peaking load. Sizing was performed both for a "hot pond" (75°C average/50°C minimum) and a "warm pond" (60°C average/40°C minimum) at each location.

The surface area requirement for the hot pond to serve the specified load ranges from about one-half acre in Miami, Fla. and Los Angeles, Calif. to a little over two acres in Boston, Mass. Surface area requirements for the warm pond range from a little over one-third of an acre in Miami and Los Angeles to almost one acre in Boston. The depth requirement ranges from 1.9 m for a summer peaking load in Miami for both hot and warm ponds to 4.5 m for a winter peaking load and a warm pond in Denver. (Note that the depth requirement may be relaxed by increasing the surface area and thereby raising the entire temperature profile of the pond. See also Section 8.0).

Table 4-1. REQUIRED SOLAR POND SURFACE AREAS AND DEPTHS AT VARIOUS LOCATIONS IN THE UNITED STATES

						Pond Sizes for 50 kW_{th} Avg./70 kW_{th} Max. Load[a]			
						Winter Peaking		Summer Peaking	
Region	Location	Latitude (°)	Insolation (W/m^2) Avg./Min.	Ambient Temp. (°C) Avg./Min.	Pond Temp. (°C) Avg./Min.	Area (acres)	Depth (m)	Area (acres)	Depth (m)
Pacific	Los Angeles	34	209/112	16.5/12.5	75/50	0.52	3.5	0.52	2.6
	Los Angeles	34	209/112	16.5/12.5	60/40	0.38	4.2	0.38	2.7
Mountain	Denver	39	206/96	10.1/-1.2	75/50	0.63	3.7	0.63	3.0
	Denver	39	206/96	10.1/-1.2	60/40	0.44	4.5	0.44	3.3
West N. Central	Omaha	41	174/67	9.7/-6.6	75/50	1.04	3.6	1.04	3.2
	Omaha	41	174/67	9.7/-6.6	60/40	0.64	4.3	0.64	3.4
West S. Central	Dallas	33	193/103	19.0/7.4	75/50	0.59	3.4	0.59	2.6
	Dallas	33	193/103	19.0/7.4	60/40	0.42	4.2	0.42	2.8
East N. Central	Chicago	41	160/53	10.3/-4.3	75/50	1.37	3.5	1.37	3.1
	Chicago	41	160/53	10.3/-4.3	60/40	0.75	4.2	0.76	3.4
East S. Central	Jackson, MS	32	185/93	18.3/8.4	75/50	0.65	3.4	0.66	2.7
	Jackson, MS	32	185/93	18.3/8.4	60/40	0.45	4.1	0.45	3.3
New England	Boston	42	145/53	10.7/-1.6	75/50	2.07	3.2	2.07	2.9
	Boston	42	145/53	10.7/-1.6	60/40	0.95	3.8	0.96	3.2
Middle Atlantic	Philadelphia	40	154/62	12.6/0.2	75/50	1.42	3.2	1.42	2.9
	Philadelphia	40	154/62	12.6/0.2	60/40	0.77	3.9	0.77	3.1
South Atlantic	Miami	25	194/134	24.2/19.6	75/50	0.50	2.9	0.50	1.9
	Miami	25	194/134	24.2/19.6	60/40	0.37	3.6	0.37	1.9

[a] Approximately the demand of 25 to 30 households.

SECTION 5.0

THE GENERAL SOLAR POND

5.1 ESTIMATING SURFACE AREA REQUIREMENT FOR THE GENERAL SOLAR POND

Recall that certain assumptions, listed in Table 2-1, were made for the base case salt gradient pond. These assumptions are reflected in the steps given in Section 2.0 for calculating the required surface area and depth for the base case salt gradient pond. With a different pond design, however, the assumptions become different and the constants in the formulas must be changed. The thickness of the nonconvecting layer in the salt gradient pond might be altered,* for example, or the conductivity of the earth might be different from that assumed in the base case. The solar pond may not be a salt gradient pond at all but a saltless pond with surface glazings and temporary night insulation (Jayadev et al. 1979). This section and Section 5.2 describe the steps for calculating surface area and depth, for the general solar pond using the simple method.

5.1.1 Inputs for Calculating Surface Area Requirement

In addition to the inputs listed in Section 2.1, the following are required for the general solar pond surface area calculations:

$\overline{\tau\alpha}$ = the average optical transmission; i.e., the fraction of incoming (and nonreflected) insolation that reaches the pond's storage area;

U_s = the average heat loss coefficient from the surface of the pond to the ambient air (in W/m^2 °C);

U_e = the average heat loss coefficient from the edges of the pond (in W/°C per meter of pond perimeter); and

U_b = the average heat loss coefficient from the bottom of the pond to the earth (in W/m^2 °C).

5.1.1.1 Average Optical Transmission

For the salt gradient pond, an approximate value of $\overline{\tau\alpha}$ may be read from Fig. 5-1. For example, in the base case salt gradient pond of Section 2.0, the combined depth of the surface convecting layer and the nonconvecting layer is 1.5 m. The distance a sunbeam has to traverse actually is greater than 1.5 m, on the average, due to its oblique angle of incidence. Note, however, that refraction will bend the direction of the sunbeam toward the normal. Assuming a path length slightly greater than 1.5 m, an optical transmission $\overline{\tau\alpha}$ of about 0.31 is read from Fig. 5-1. That is the same value used for the base case pond. The optical transmission may be read from Fig. 5-1 in a

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*Bear in mind that limitations on this thickness exist, depending on pond and ambient temperatures and salt type (see Tabor and Weinberger, forthcoming).

similar way for any salt gradient pond with any path length. For a saltless pond, the optical transmission is a function of the number of glazings placed over the surface and the optical transmission of each of the glazings.

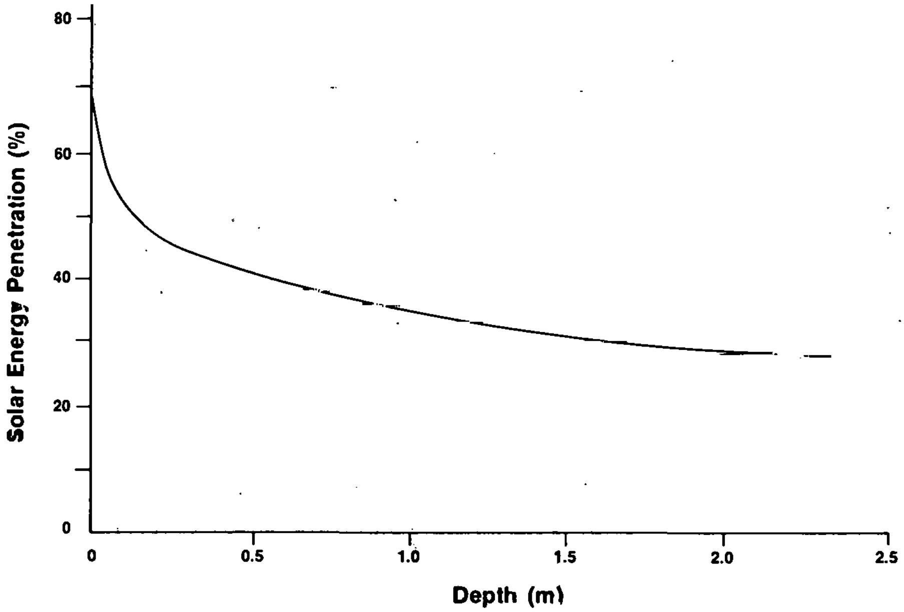

Figure 5-1. Optical Transmission $\overline{\tau\alpha}$ as a Function of the Depth of the Surface-Convecting and Nonconvecting Layers Combined

5.1.1.2 Surface Heat Loss Coefficient

For the salt gradient pond, the surface heat loss coefficient U_s is a function of the thickness of the nonconvecting layer and, to a lesser degree, the thickness of the surface convecting layer. A conductivity in these layers of about 0.6 W-m/m^2 °C was assumed for the base case. Using a combined nonconvecting layer and surface convecting layer thickness of 1.5 m leads to an assumed heat loss coefficient of about 0.4 W/m^2 °C. (If the surface convecting layer were assumed to have no insulation value whatever, the heat loss coefficient would be closer to 0.5 W/m^2 °C). For a salt gradient pond with a different nonconvecting layer thickness, the surface heat loss coefficient will vary in inverse proportion to the thickness. For the saltless pond, the surface heat loss coefficient is a property of the surface configuration and glazings, and also of any night insulation that may be used. In the case of the saltless pond with night insulation, it probably is reasonable to average the daytime and nighttime surface heat loss coefficients to obtain U_s.

5.1.1.3 Edge Heat Loss Coefficient

For the salt gradient pond, the edge heat loss coefficient U_e may be estimated from Fig. 5-2. Since the surface area is calculated before depth in the simple sizing method, the storage layer depth can only be approximated. For example, the base case pond with a nonconvecting layer of 1.2 m used an edge loss coefficient of 2.2 W/m °C. This represented a fairly conservative assumption consistent with a storage depth of about 2-2.5 m (and overall pond depth of about 3.5-4 m). The accuracy of the method probably does not warrant the effort, but it would be possible to do a second iteration after the pond depth has been ascertained.

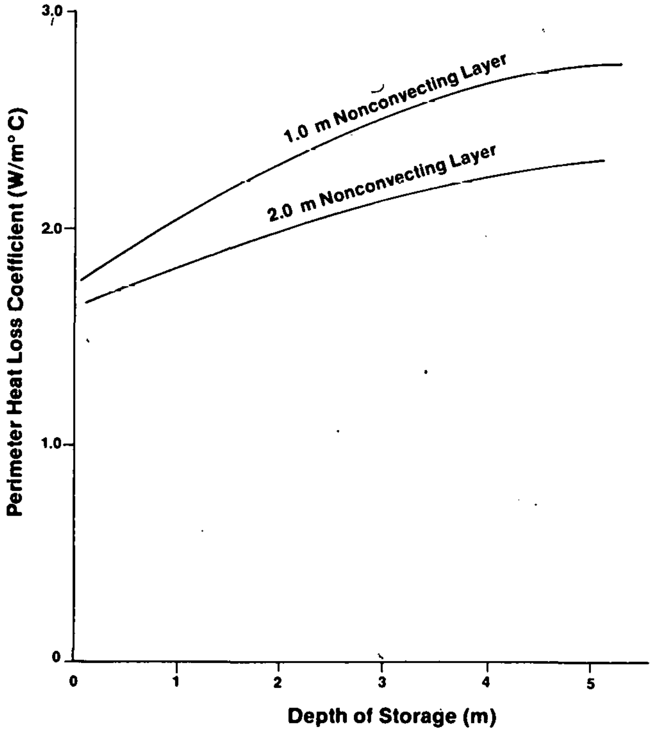

Figure 5-2. Perimeter Heat Loss Coefficient of Salt Gradient Pond as a Function of the Nonconvecting and Storage Layer Depths

The edge losses displayed in Fig. 5-2 were calculated based on an assumed conductivity of the earth equal to 1.0 W-m/m^2 °C. This conductivity can vary widely with different types of soil. If the conductivity is not 1.0, the number read from Fig. 5-2 should be multiplied by the true value of the conductivity to obtain the corrected value of U_e. Another caution is that the calculations on which Fig. 5-2 was based assumed that the pond surface was level with the surrounding earth. If, in fact, the pond surface is above grade (with earth banked around the edges), then U_e will be larger than the value obtained from Fig. 5-2, and if the pond surface is below grade, U_e will be smaller.

Less data on edge losses have been generated for the saltless pond, but it is reasonable to assume an edge loss coefficient U_e of 4 W/m °C (for an earth conductivity of 1.0 W-m/m^2 °C). "Sinking" the surface of the saltless pond, i.e., filling to well below the surface of the earth, reduces edge losses considerably.

5.1.1.4 Bottom Heat Loss Coefficient

The bottom heat loss coefficient U_b is the most difficult parameter to estimate but, in general, the least important. For the base case pond, U_b was assumed to be 0.1 W/m^2 °C. This was roughly based on the assumptions that the conductivity of the earth is 1.0 W-m/m^2 °C, and that ground water (and therefore a heat sink) exists 10 m below the bottom of the pond. Different earth conductivities and groundwater conditions will alter U_b in obvious ways.

5.1.2 Calculations

(1) Multiply $\overline{I}$ by the adjustment factor f found in Table 2-2 for the given latitude ϕ to obtain $\overline{I}_r$ (as in Section 2.1.2, step 1).

(2) Multiply $\overline{I}_r$ by $\overline{\tau\alpha}$ to obtain $\overline{I}_p$.

(3) Let $T_d = \overline{T} - \overline{T}_a$. Then the radius r (in meters) of a circular pond needed to meet the requirements is given by

$$r = \frac{U_e T_d + \left\{(U_e T_d)^2 + \overline{L}\left[\overline{I}_p - (U_s + U_b)T_d\right]/\pi\right\}^{1/2}}{\overline{I}_p - (U_s + U_b)T_d} \qquad (5\text{-}1)$$

(4) Find the required surface area (in square meters) by using $A = \pi r^2$. To obtain the required area in acres, multiply by 0.000247.

5.2 ESTIMATING DEPTH REQUIREMENT FOR THE GENERAL SOLAR POND

5.2.1 Inputs

The inputs are the same as those listed in Section 2.2.1, plus $\overline{\tau\alpha}$, U_s, U_e and U_b as described in Section 5.1.1.

5.2.2 Calculations

(1) Multiply I_{min} by the factor f read from Table 2-2 for $\phi + 24°$ to obtain $I_{r,min}$.

(2) Estimate the optical transmission $\overline{\tau\alpha}_{min}$ when the sun is at the winter solstice, which will be less than the average transmission $\overline{\tau\alpha}$ discussed in Section 5.1.1. (For the base case pond, $\overline{\tau\alpha}_{min}$ was assumed to be 0.29 while $\overline{\tau\alpha}$ was assumed to be 0.31. These assumptions correspond to a sunbeam path length about 0.5 m longer at the winter solstice than at the equinox). Multiply $I_{r,min}$ by $\overline{\tau\alpha}_{min}$ to obtain $I_{p,min}$.

(3) Let

$$\tilde{T}_a = \overline{T}_a - T_{a,min}$$

$$\tilde{I} = \overline{I}_p - I_{p,min}$$

$$\tilde{L} = (L_{max} - \overline{L})/A$$

$$\alpha = (M - 0.5)/12 - 0.25 ,$$

as in Section 2.2.2, step 3.

(4) Let

$$a = (1.4138\tilde{I} - 2.3313U_s\tilde{T}_a - 7.5445\tilde{L} \cos 2\pi\alpha)(U_s + U_b)$$

$$b = (-7.4110\tilde{I} - 7.1756U_s\tilde{T}_a + 7.5445\tilde{L} \sin 2\pi\alpha)(U_s + U_b)$$

$$c = -1.1775\tilde{I} + 1.9415U_s\tilde{T}_a + 6.2832\tilde{L} \cos 2\pi\alpha$$

$$d = -6.1720\tilde{I} - 5.9759U_s\tilde{T}_a + 6.2832\tilde{L} \sin 2\pi\alpha .$$

The values of $\cos 2\pi\alpha$ and $\sin 2\pi\alpha$ may be found in Table 2-3, as in Section 2.2.2, step 4.

(5) Determine the required depth by trial and error. Select a trial depth D and compute the resulting minimum pond temperature t_{min} as follows:

$$t_{min} = \overline{T} - \frac{\left[(a + dD)^2 + (b + cD)^2\right]^{1/2}}{5.2327D^2 + 7.5445(U_s + U_b)^2} . \tag{5-2}$$

Repeat with another trial D until a value of D is found such that $t_{min} = T_{min}$, the desired minimum pond temperature. The value of D thus obtained is the depth of the pond's storage layer.

(6) If the pond being sized is a salt gradient pond, add D to the depths of the surface convecting layer and the nonconvecting layer to obtain the total depth.

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SECTION 6.0

ASSESSMENT OF LIKELY ERROR

Two sources of error must be considered: deviations in the results of the simple method from results of more detailed methods and deviations of the results of more detailed methods from experience. Numerical estimates of the statistical magnitudes of these deviations must await extensive testing of the simple method against detailed methods and against experience. A qualitative discussion, however, provides some insight into the origins and magnitudes of these errors.

6.1 SOURCES OF DEVIATION IN THE RESULTS OF THE SIMPLE METHOD FROM RESULTS OF DETAILED METHODS

The deviations arise from the use of the assumptions in the simple sizing method. Chief among these assumptions is the neglect of the thermal storage in the ground and, for the salt gradient pond, in the nonconvecting layer. This thermal storage can be taken into account by detailed finite element computer programs. This neglect represents a source of conservatism in the estimates of size, particularly in the estimate of depth.

A second important assumption of the simple sizing method is that the variations in insolation, ambient temperature, and load with time can be described by sine waves (see the Appendix). The averages of the sine functions are assumed to be $\bar{I}$, $\bar{T}_a$, and $\bar{L}$, respectively, and the amplitudes of their deviations are assumed to be $\tilde{I}$, $\tilde{T}_a$, and $\tilde{L}$. Obviously, to the extent that the profiles of these variables over time can not be described by sine waves, errors will be introduced. Daily and, perhaps, even weekly deviations from the sine wave form should have little effect, but long term deviations will have a definite impact. The size and direction of error will depend on the actual profiles of the variables. The most likely candidates for error are locations where seasonal rainy or cloudy periods impose perturbations on the annual profiles. During such periods the pond temperature might be lower than that predicted by the model. Different circumstances will bring about different estimation errors.

6.2 SOURCES OF DEVIATION IN THE RESULTS OF MORE DETAILED METHODS FROM RESULTS OF EXPERIENCE

To put these simple method errors in perspective it must be noted that most sizing methods, no matter how detailed, deviate significantly from reality. Foremost of these deviations is the fact that a real solar pond has sloping and irregular sides, while a detailed model will represent it with vertical or regular sides. Also, it is not obvious whether "surface area" should be interpreted as the area of the upper pond face (surface), the area of the lower pond face (bottom), or something in between. It is apparent that there is much leeway for interpretation and judgment on the part of the user, and, therefore, precise calculations of pond area are likely to be a waste of effort.

Both simple and detailed models must make assumptions about the optical transmissivity of the water. This transmissivity can vary significantly depending upon the quantity of suspended dust or other particles; surface impurities, such as floating leaves; bacterial growth within the pond; and the type of salt used. The transmissivity estimates represented by Fig. 5-1 are the best currently available; however, the sensitivity of the required pond size to variations in the transmissivity assumptions may be tested by using the simple sizing method described in this report.

All detailed models currently devised ignore horizontal convection currents and temperature gradients within the pond. This could be an important source of error since edge temperatures are likely to be lower than center pond temperatures. All models also ignore the effects of localized heat extraction from the pond. Most models, in fact, ignore edge effects entirely and simply solve for temperatures along a vertical axis within the pond.

These remarks suggest that the simple sizing method contains a number of sources for error, but even the most detailed simulation method will contain many of these sources of error. For preliminary investigations the simple sizing method is probably accurate enough and requires relatively little calculation effort.

SECTION 7.0

DETERMINATION OF OUTPUT WHEN POND SIZE AND SHAPE ARE SPECIFIED

7.1 FINDING AVERAGE AND MINIMUM TEMPERATURE FOR A GIVEN POND

Suppose that instead of desiring to fit a solar pond to a specified load, the designer has a specified area available for a solar pond and he wishes to determine what output it can provide. He may either specify the average and maximum demands to be served and inquire as to what the consequent average and minimum pond temperatures will be; or specify the average and minimum output temperatures required and inquire as to what average and maximum demands can be served at those temperatures.

This section addresses the first possibility while Section 7.2 deals with the second possibility.

7.1.1 Inputs

Required inputs are $\overline{T}_a$, $\overline{L}$, ϕ, $\overline{I}$, $T_{a,min}$, I_{min}, L_{max}, M, $\overline{\tau\alpha}$, U_s, U_e, and U_b as specified in Sections 2.1.1, 2.2.1, and 5.1.1. In addition, the pond area A (in square meters) and perimeter P and depth D (in meters) are required as inputs. (Note: if any or all of $T_{a,min}$, I_{min}, L_{max}, M, or D are unavailable, steps 1 through 3 of the calculations below may still be executed to find the average pond temperature.)

7.1.2 Calculations

(1) Multiply $\overline{I}$ by the adjustment factor f found in Table 2-2 for the given latitude ϕ to obtain $\overline{I}_r$ (same as Sections 2.1.2 and 5.1.2, step 1).

(2) Multiply $\overline{I}_r$ by $\overline{\tau\alpha}$ to obtain $\overline{I}_p$ (same as Section 5.1.2, step 2).

(3) Find the average annual pond temperature by

$$\overline{T} = \overline{T}_a + \frac{A\overline{I}_p - \overline{L}}{(U_s + U_b)A + U_eP} \quad . \qquad (7\text{-}1)$$

(4) Multiply I_{min} by the factor f read from Table 2-2 for ϕ + 24° to obtain $I_{r,min}$ (same as Sections 2.2.2 and 5.2.2, step 1).

(5) Estimate the optical transmission $\overline{\tau\alpha}_{min}$ at the winter solstice, as in Section 5.2.2, step 2. Multiply $I_{r,min}$ by $\overline{\tau\alpha}_{min}$ to obtain $I_{p,min}$.

(6) Let

$$\tilde{T}_a = \overline{T}_a - T_{a,min}$$

$$\tilde{I} = \overline{I}_p - I_{p,min}$$

$$\tilde{L} = (L_{max} - \overline{L})/A$$

$$\alpha = (M - 0.5)/12 - 0.25$$

(same as Sections 2.2.2 and 5.2.2, step 3).

(7) Let

$$a = (1.4138\tilde{I} - 2.3313U_s\tilde{T}_a - 7.5445\tilde{L} \cos 2\pi\alpha)(U_s + U_b)$$

$$b = (-7.4110\tilde{I} - 7.1756U_s\tilde{T}_a + 7.5445\tilde{L} \sin 2\pi\alpha)(U_s + U_b)$$

$$c = -1.1775\tilde{I} + 1.9415U_s\tilde{T}_a + 6.2832\tilde{L} \cos 2\pi\alpha$$

$$d = -6.1720\tilde{I} - 5.9759U_s\tilde{T}_a + 6.2832\tilde{L} \sin 2\pi\alpha$$

Values of cos $2\pi\alpha$ and sin $2\pi\alpha$ may be found in Table 2-3 (same as Sections 2.2.2 and 5.2.2, step 4).

(8) Then find the minimum pond temperature by

$$t_{min} = \overline{T} - \frac{\left[(a + dD)^2 + (b + cD)^2\right]^{1/2}}{5.2327D^2 + 7.5445(U_s + U_b)^2} \tag{7-2}$$

7.2 FINDING AVERAGE AND MAXIMUM DEMAND SERVED BY A GIVEN POND

If the size of the pond and the required average and minimum output temperatures are specified, the average and maximum demand served can be calculated.

7.2.1 Inputs

Required inputs are $\overline{T}$, $\overline{T}_a$, ϕ, $\overline{I}$, T_{min}, $T_{a,min}$, I_{min}, M, $\overline{\tau\alpha}$, U_s, U_e, and U_b as specified in Sections 2.1.1, 2.2.1, and 5.1.1. In addition, the pond area A (in square meters) and perimeter P and depth D (in meters) are required as inputs. (If any or all of T_{min}, $T_{a,min}$, I_{min}, M, or D are unavailable, steps 1 through 3 of the calculations below may still be executed to find the average demand served.)

7.2.2 Calculations

(1) Multiply $\overline{I}$ by the adjustment factor f found in Table 2-2 for the given latitude to obtain $\overline{I}_p$ (same as Sections 2.1.2, 5.1.2, and 7.1.2, step 1).

(2) Multiply $\overline{I}_r$ by $\overline{\tau\alpha}$ to obtain $\overline{I}_p$ (same as Sections 5.1.2 and 7.1.2, step 2).

(3) The average annual load in watts is

$$\overline{L} = A\overline{I}_p - (\overline{T} - \overline{T}_a)\left[(U_s + U_b)A + U_eP\right] \tag{7-3}$$

(to express in Btu/yr, multiply by 29,900).

(4) Multiply I_{min} by the factor f read from Table 2-2 for ϕ + 24° to obtain $I_{r,min}$ (same as Sections 2.2.2 and 5.2.2, step 1, and Section 7.1.2, step 4).

(5) Estimate the optical transmission $\overline{\tau\alpha}_{min}$ at the winter solstice, as in Section 5.2.2, step 2. Multiply $I_{r,min}$ by $\overline{\tau\alpha}_{min}$ to obtain $I_{p,min}$.

(6) Let

$$\tilde{T} = \overline{T} - T_{min}$$

$$\tilde{T}_a = \overline{T}_a - T_{a,min}$$

$$\tilde{I} = \overline{I}_p - I_{p,min}$$

$$\alpha = (M - 0.5)/12 - 0.25$$

(7) Let

$$p = (1.4138\tilde{I} - 2.3313U_s\tilde{T}_a)(U_s + U_b) - (6.1720\tilde{I} + 5.9759U_s\tilde{T}_a)D$$

$$q = -7.5445(U_s + U_b) \cos 2\pi\alpha + 6.2832D \sin 2\pi\alpha$$

$$r = (-7.4110\tilde{I} - 7.1756U_s\tilde{T}_a)(U_s + U_b) - (1.1775\tilde{I} - 1.9415U_s\tilde{T}_a)D$$

$$s = 7.5445(U_s + U_b) \sin 2\pi\alpha + 6.2832D \cos 2\pi\alpha$$

$$z = \tilde{T}\left[5.2327D^2 + 7.5445(U_s + U_b)^2\right]$$

where cos $2\pi\alpha$ and sin $2\pi\alpha$ may be read from Table 2-3.

(8) Then, find the maximum load by

$$L_{max} = \overline{L} + \frac{\left[(pq + rs)^2 - (q^2 + s^2)(p^2 + r^2 - z^2)\right]^{1/2} - (pq + rs)}{q^2 + s^2} . \tag{7-4}$$

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SECTION 8.0

HINTS FOR APPLICATION OF THE METHOD

In solving a practical sizing problem, any of the calculations from Sections 2.0, 5.0, and 7.0 may be used. First, one might calculate surface area and depth for a base case salt gradient pond using Section 2.0. If transmission and heat loss coefficients are known and diverge significantly from those of the base case pond, Section 5.0 may be used instead. If the depth requirement happens to be greater than desirable, considering the ground conditions where the pond will be built, a larger surface area may be selected and the calculations rerun. A larger surface area raises the entire temperature profile of the pond, and, therefore, decreases the depth required to achieve the specified minimum temperature. To find the new average annual temperature, apply the calculations in Section 7.1. If the pond will not be circular but, say, oblong with a specified width restriction, the size obtained from the sizing calculations for the circular pond will give some indication as to how long the pond must be. To test a trial length and width configuration for the oblong pond, run the calculations in Section 7.1 to see if the average and minimum temperatures meet the requirements. If they do not, the pond may be lengthened and the calculations retried. In this manner--investigating various pond configurations, output temperatures, and loads by first applying one calculation, then revising and trying another, and so on--one may design, with relative ease, a pond whose size and shape fits into a particular context and whose output serves a satisfactory load.

SECTION 9.0

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APPENDIX

DERIVATION OF THE METHOD

Whatever their differences, the various solar pond designs have a very large body of thermal storage in common. It is assumed that this storage is so large that daily fluctuations in ambient temperature and insolation have a negligible effect on the temperature of storage and that only seasonal variations in the environment need be considered.

It is assumed also that the heat loss from storage is related linearly to the difference between the temperature of storage and the temperature of the ambient air and to the difference between the temperature of storage and the temperature of the ground. This means there must be effective heat loss coefficients U_a and U_g such that the rate of heat loss is $U_a(T - T_a) + U_g(T - T_g)$, where T_a is the ambient temperature, T_g is the ground temperature (presumably equal to $\overline{T}_a$, the average annual ambient temperature), and T is the temperature of the storage layer of the pond. In the saltless pond, T is assumed to be the temperature at any point.

Suppose that characteristic heat loss coefficients U_s, U_e, and U_b can be identified for a pond of surface area A, perimeter P, and depth D where U_s is the coefficient of heat loss from the surface of the pond (in W/m^2 °C), U_e is the coefficient of heat loss from the edges of the pond (in W/m^2 °C), U_b is the coefficient of heat loss from the bottom of the pond (in W/m^2 °C), and A is measured in square meters with P and D measured in meters. Then, the coefficients of heat loss to the ambient air U_a and to the ground U_g, respectively, can be expressed in terms of U_s, U_e, U_b, A, and P as follows:

$$U_a = AU_s + PU_e, \text{ and } U_g \doteq AU_b \quad .$$

It is a reasonable approximation to model the insolation and the ambient temperature as sine waves, and, for simplicity, it is also assumed that the load can be represented as a sine wave.

Thus, let

$$T_a(t) = \overline{T}_a + \tilde{T}_a \sin 2\pi(t - \phi_T)$$

$$I(t) = \overline{I} + \tilde{I} \sin 2\pi(t - \phi_I)$$

$$L(t) = \overline{L} + \tilde{L} \sin 2\pi(t - \phi_L)$$

The time t and the phase angles ϕ_T, ϕ_I, ϕ_L are measured in years. If insolation peaks in June, then ϕ_I is approximately 0.22; if ambient temperature peaks about a month afterward, then ϕ_T is approximately 0.30.

Let A signify the solar collection area, $\overline{\tau\alpha}$ the fraction of insolation transmitted to the storage area of the pond, and $\rho V c_p$ the total heat capacity of storage (where ρ is the water density, V is the volume of storage, and c_p is its heat capacity per unit mass).

An energy balance yields

$$\overline{\tau\alpha}AI(t) = L(t) + U_a[T(t) - T_a(t)] + U_g[T(t) - \overline{T}_a] + \rho Vc_p\dot{T}(t)$$

or

$$\dot{T}(t) + \frac{U_a + U_g}{\rho Vc_p} T(t) = \frac{1}{\rho Vc_p} \Big[\overline{\tau\alpha}A\overline{I} + (U_a + U_g)\overline{T}_a - \overline{L}$$
$$+ \overline{\tau\alpha}A\tilde{I} \sin 2\pi(t - \phi_I)$$
$$+ U_a\tilde{T}_a \sin 2\pi(t - \phi_T)$$
$$- \tilde{L} \sin 2\pi(t - \phi_L)\Big] \quad .$$

The solution to this differential equation is

$$T(t) = \overline{T} + \psi(t) - C(t_o)\, e^{-\sigma t} \tag{A-1}$$

where

$$\overline{T} = \overline{T}_a + \frac{\overline{\tau\alpha}A\overline{I} - \overline{L}}{U_a + U_g}$$

$$\psi(t) = \frac{S}{\rho Vc_p} \left[\overline{\tau\alpha}A\tilde{I}\ h(t - \phi_I) + U_a\tilde{T}_a\ h(t - \phi_T) - \tilde{L}\ h(t - \phi_L)\right]$$

$$h(t - \phi) = \left[\sigma \sin 2\pi(t - \phi) - 2\pi \cos 2\pi(t - \phi)\right]/\left[(2\pi)^2 + \sigma^2\right]$$

$$\sigma = S(U_a + U_g)/\rho Vc_p$$

$$C(t_o) = \overline{T} - \overline{T}_a + \psi(t_o)\, e^{\sigma t_o} \ ,$$

and t_o is the startup date for the pond (in years from January 1), at which time it is assumed $T = \overline{T}_a$. S is the number of seconds in a year if I and L are expressed in watts.

Note that Eq. A-1 expresses the pond storage temperature as the sum of the long term average pond temperature $\overline{T}$, a periodic temperature deviation $\psi(t)$, and a transient term $C(t_o)e^{\sigma t}$.

Setting the derivative of Eq. A-1 equal to zero, one finds that in the steady state extreme temperatures occur at the times $(1/2\pi)\tan^{-1}[\psi(0.25)/\psi(0)]$. By plugging these times into Eq. A-1 one can find the maximum and minimum temperatures.

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16. Abstract (Limit: 200 words)

This report provides a simple method for estimating the required surface area and depth of a solar pond given the load it will serve, the desired output temperatures, and the climatic conditions. The method can easily be implemented on a hand-held calculator. It is estimated that the pond size calculated by the simple method will be within 20% of the size that would be obtained with a detailed computer simulation. The report presents results using the simple method of sizing a solar pond at various locations in the United States.

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