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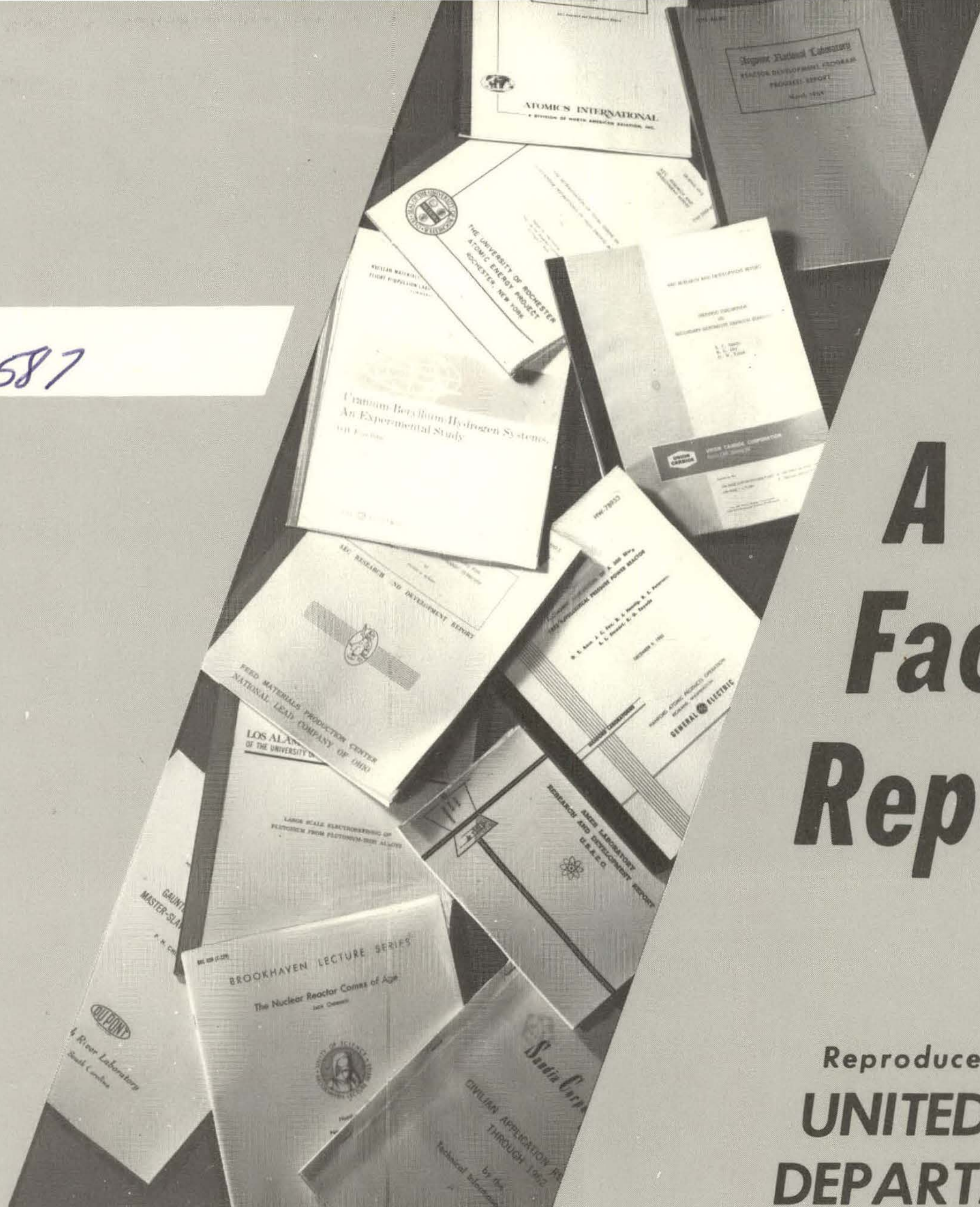

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Solar ponds are probably the simplest and least expensive technology for conversion of solar energy to thermal energy. The solar pond is unique in its ability to act both as collector and storage. The cost of a solar pond per unit area is considerably less than that of any active collector available today. The conbination of their economic and technical factors makes solar ponds attractive for district heating and industrial process heat applications. Solar ponds have the potential to displace significant quantities of fossil fuel in low-temperatur heating applications in nonurban areas.

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T. S. Jayadev
Michael Edesess

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SOLAR PONDS

T. S. JAYADEV
M. EDESESS

APRIL 1980

PREPARED UNDER TASK NO. 3525.12

Solar Energy Research Institute

1536 Cole Boulevard
Golden, Colorado 80401

A Division of Midwest Research Institute

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PREFACE

This report is a compendium of analytic work on solar ponds performed at SERI during the past year. The work investigates the performance, economics, applications, and total quad potential of the various types of solar ponds, particularly the nonconvecting salt gradient pond. The overall finding is that solar ponds are a viable and economic technology with the potential for diplacing very significant quantities of conventional energy. Work was performed under the Systems Analysis and Testing Program, a major program element in the Systems Development Division, Office of Solar Applications.

T. S. Jayadev by M.E.
T. S. Jayadev, Leader
Solar Ponds Subtask

Approved for

SOLAR ENERGY RESEARCH INSTITUTE

Charles J Bishop
Charles Bishop, Chief
Systems Development Branch

Neil Woodley
Neil Woodley, Manager
Utilities and Industry Division

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SUMMARY

Solar ponds are probably the simplest and least expensive technology for conversion of solar energy to thermal energy. The solar pond is unique in its ability to act both as collector and storage. The cost of a solar pond per unit area is considerably less than that of any active collector available today. A combination of their economic and technical factors makes solar ponds attractive for district heating and industrial process heat applications. Solar ponds have the potential to displace significant quantities of fossil fuel in low-temperature heating applications in nonurban areas.

This report first describes the different types of solar ponds, including the nonconvecting salt gradient pond and various saltless pond designs. It then discusses the availability and cost of salts for salt gradient ponds, and compares the economics of salty and saltless ponds as a function of salt cost. A simple computational model is developed to approximate solar pond performance. This model is later used to size solar ponds for district heating and industrial process heat applications. For district heating, ponds are sized to provide space conditioning for a group of homes, in different regions of the United States. Size requirement is on the order of one acre for a group of 25 to 50 homes. An economic analysis is performed of solar ponds used in two industrial process heat applications. The analysis finds that solar ponds are competitive when conventional heat sources are priced at \$5 per million Btu and expected to rise in price at a rate of 10% per year. The application of solar ponds to the generation of electricity is also discussed. Total solar pond potential for displacing conventional energy sources is estimated in the range of from one to six quadrillion Btu per year in the near and intermediate future.

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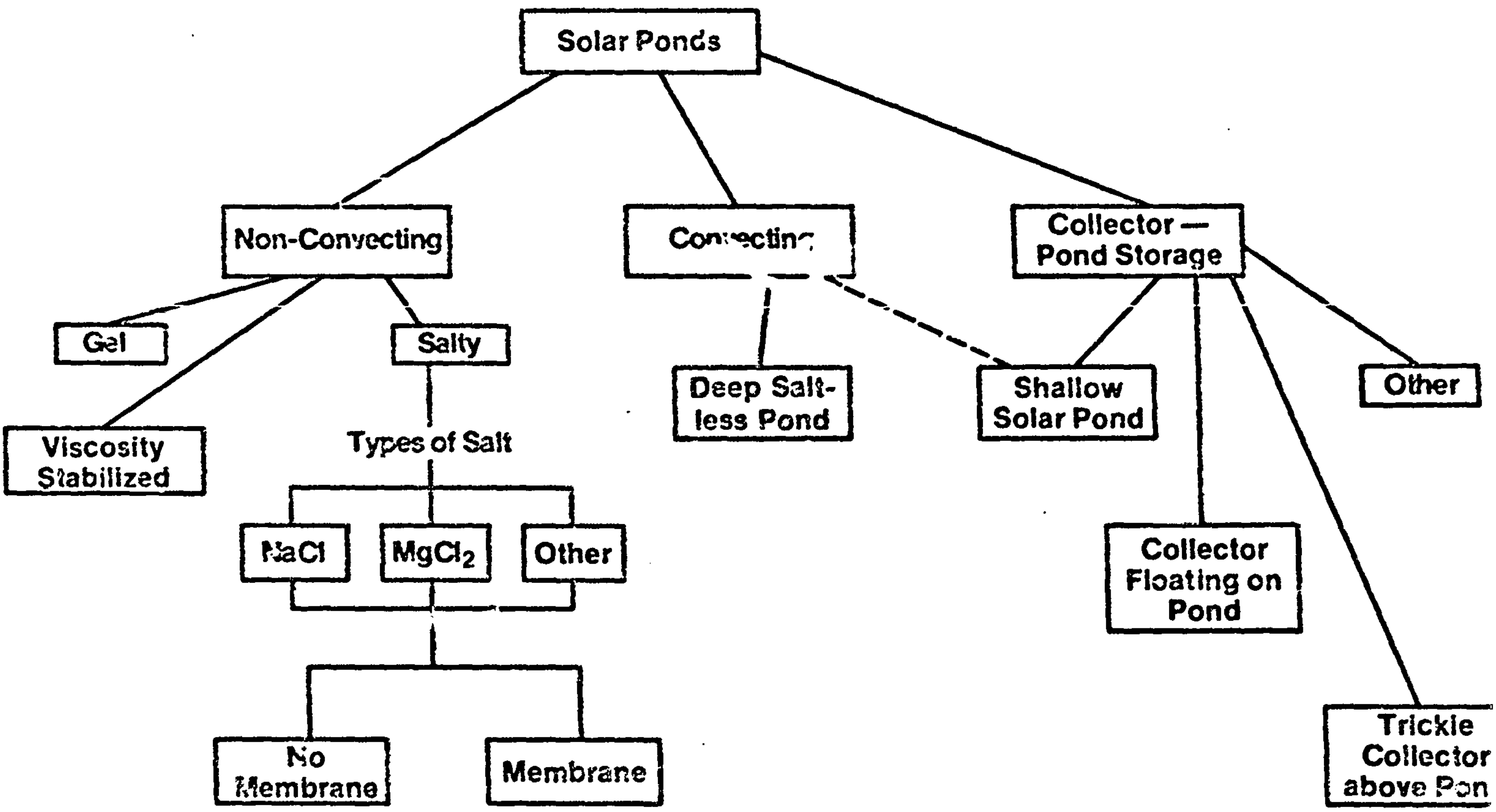

Figure 1. Solar Pond Taxonomy

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2.1.1 SALT GRADIENT PONDS - Most studied of the solar ponds is the nonconvecting, salt gradient pond (Tabor, 1963, 1965 and 1980; Nielsen, 1979; Rabl, 1975; Zangrando, 1978).

The salt gradient pond is a pond in which salt has been dissolved, in high concentrations near the bottom, and decreasing to low concentrations near the surface. Salts most commonly used are NaCl and $MgCl_2$, although there are numerous other possibilities (see Section 3.1).

Solar radiation enters the pond, and whatever is not absorbed in the water on the way down is absorbed on the dark bottom (which may be an artificially blackened liner). As a result of this heat collection at the bottom, the deeper waters become warm.

Higher concentrations of salt prevail in the lower pond regions than in the upper regions, so the warmer, deep waters contain a higher density of dissolved salt than the colder waters near the surface. Pure water, when warmed, becomes less dense. If there were no salt concentration gradient in the pond there would be continuous convection of the warmed water from the bottom of the pond to the cooler layers near the top. However, the increased density created by the salt prevents this thermal buoyancy convection. Heat transfer to the surface of the pond occurs primarily by conduction, which is slow enough to enable the lower regions of the pond to maintain a high temperature (100°C has been measured in actual ponds).

In practice, the salt gradient pond has three layers, as shown in Figure 2. In the top layer vertical convection takes place due to the effects of wind and evaporation. This layer serves no useful purpose and is kept as thin as practically possible. The next layer, which may be approximately 1-m thick, contains an increasing concentration of salt with increasing depth and is nonconvecting. The bottom layer is a convecting layer which provides most of the thermal storage and facilitates heat extraction.

Variants on the simplest salt gradient pond design have been proposed to aid in controlling the boundaries of these layers. The so-called "membrane pond" (Rabl, 1975) contains a horizontal partition to separate the lower convecting zone from the middle nonconvecting zone and, possibly, a second partition slightly below the surface of the pond to minimize the surface convecting layer.

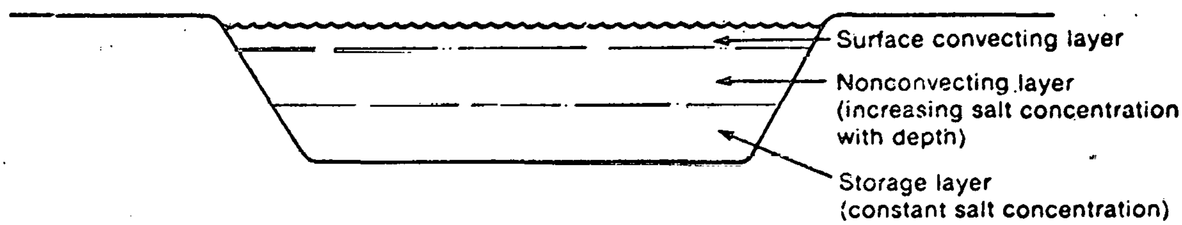

Figure 2. Salt Gradient Solar Pond

Salt gradient ponds have been built and operated in such diverse locations as Israel (Sargent, 1979) and Canada (Saulnier, 1975) and in Ohio (Nielsen, 1979) and New Mexico (Zangrando, 1978) in the United States.

2.1.2 OTHER NONCONVECTING PONDS - Proposed alternatives to the salt gradient pond in the nonconvecting pond category are the viscosity stabilized pond (Battelle, 1975) and the gel pond. Both of them retard internal convection by decreased fluidity of the water in the pond and have not yet advanced significantly beyond the conceptual stage.

2.2 CONVECTING PONDS

2.2.1 SHALLOW SOLAR POND - The single well-researched example of the convecting pond is the shallow solar pond proposed and designed by Lawrence Livermore Laboratories (Dickinson, 1976; Casamajor, 1979). The shallow solar pond (see Figure 3) is about a 10-cm depth of pure water enclosed in a large water bag (typically 5 m by 60 m) with a blackened bottom, insulated below with foam insulation and on top with glazings. The water from many such ponds is pumped into a large storage tank for night storage and back into the water bags each morning, in an operating method called the "batch" mode. The shallow solar pond may also be operated in the "flow through" mode, in which the water flows continuously through the water bags in such a way as to maintain control over the outlet temperature.

Especially when operated in the flow-through mode, the shallow solar pond is almost the same as a flat-plate collector with water storage, the main difference being that the solar pond collector is fixed in a horizontal position and is less costly than the usual flat-plate collector. For this reason Figure 1 classifies the shallow solar pond in the collector-pond storage category described below.

2.2.2 DEEP SALTLESS POND - Although the shallow convecting pond develops high-temperature water in a fairly short time, it requires pipes and plumbing to shuttle water out of the "ponds" each evening and storage tanks to hold the water at night. It also requires insulation under the water bags because the ground is allowed to cool off each night after the water is removed from the bags.

A more economical approach is to leave the water in the pond at night and to provide as much extra insulation as possible on top of the pond. During the daytime, when insolation must be received through the top of the pond, there is a limit as to how much top insulation can be used, and double glazing similar to that used in the shallow solar pond would be employed. But at night or during periods of low insolation additional insulation could be provided. An obvious and simple method would be to lay extra insulation over the top of the pond, either automatically or manually, whenever insolation falls below a prescribed level.

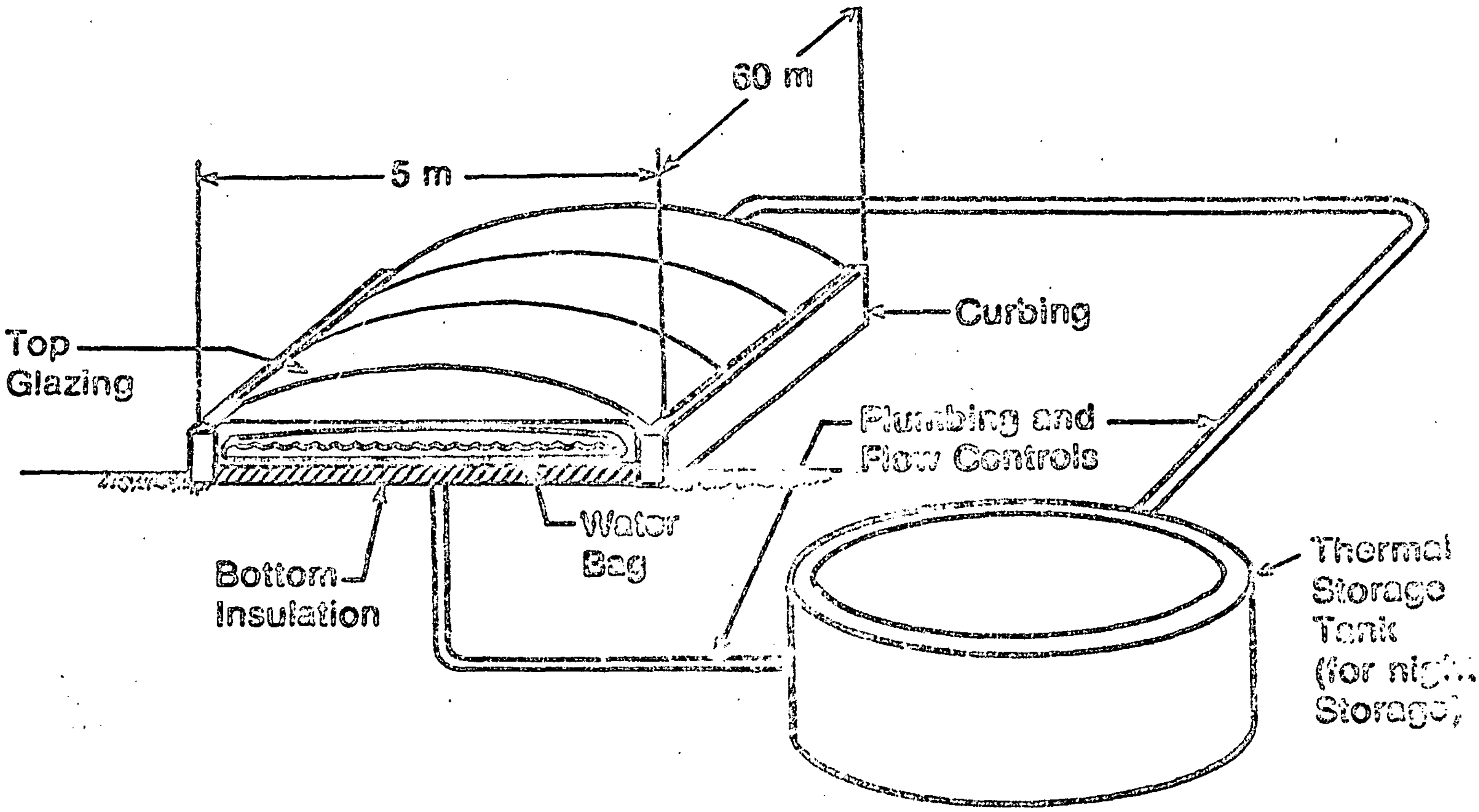

Figure 3. Shallow Solar Pond Design

A more interesting and economical possibility is to spray foam insulation between the glazings and between glazing and pond when insolation drops below the prescribed level (Figure 4). A spray foam has been used successfully to provide night insulation for greenhouses (Groh, 1977). It has been found in practice to reduce the heat loss by at least 50%, although in theory an 85% reduction should be attainable. It should be noted that the spray foam used in greenhouse experiments is a material normally used for firefighting. It seems likely that improvements could be made in the material for purposes of pond insulation.

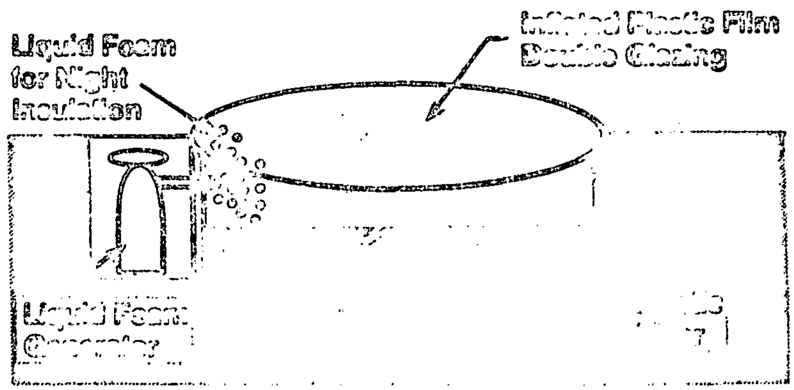

Figure 4. Example of Deep Saltless Pond Design

In the morning, the spray foam insulation would be allowed to settle and run off, leaving a negligible residue. The capital cost of using spray foam to provide supplemental night insulation is estimated at less than $\$1/m^2$ of pond.

Besides eliminating the need for pipes, pumps, and plumbing to transport the water to nighttime storage, this "stationary" pond would not require bottom insulation. After a warmup period, the temperature of the ground would approach that of the pond water, providing good insulation. The only additional insulation that might be desired would be along the sides of the pond to prevent edge losses.

To provide sufficient storage to even out daily and seasonal temperature fluctuations, the stationary convecting pond would be a deep pond, not a shallow one.

The deep saltless pond concept was proposed by Taylor (1977). There has been much less research as yet on the deep saltless pond than on the salt gradient pond. In Section 3.2, these two pond types will be compared as to projected costs and performance.

2.3 COLLECTOR-POND STORAGE COMBINATIONS - Several collector-storage combinations have been suggested in which the thermal storage is provided by a large pond embedded in the ground.

In a Swedish design (Margen, 1978) a bank of tilted collectors is floated on a raft of insulation on top of a large pond. The heated water is drained into the pond and the collectors are fed with cooler water pumped back up from the pond.

A pond tested at the University of Virginia (Beard, 1978) had a trickle collector mounted just above the surface of a square pond. Between the pond surface and the collector was a layer of foam insulation "beads" through which the heated water trickled into the pond.

An Italian proposal (Cavalleri, 1977) calls for focusing collectors to heat water to a high temperature and deposit it in a pond of several square kilometers surface area. According to the proposal, this water can then be transported long distances in underground pipes to heat a city.

When the shallow solar pond concept is compared with the collector-pond storage designs, it is apparent that the shallow pond is analogous to the collector, and the night storage tank is analogous to the thermal storage.

3.0 SOLAR POND COSTS AND PERFORMANCE

For the salt gradient pond and the deep saltless pond--that is, essentially, for those solar ponds that are not collector/pond storage combinations--the chief costs are for earth moving, bottom liner, and for salt in the case of the salt gradient pond or for surface glazings and additional insulation in the case of the deep saltless pond. The costs of salt for the salt gradient pond may vary very widely. Therefore the relative attractiveness of salt gradient or saltless pond is primarily a function of the highly site-dependent salt cost.

3.1 LOW-COST SALTS FOR SALT GRADIENT SOLAR PONDS - The costs of salts for a solar pond represent a sizable fraction of the total initial investment. Depending upon the design details and the proximity to a source of salt, a typical NaCl salt pond may require 30% to 60% of the initial investment for the initial charge of NaCl (Apte, 1978; Battelle, 1975). Therefore, the identification of suitable, low-cost alternative salts could strongly affect the overall economic favorability of a salt pond.

A suitable salt must meet several criteria:

- it must be adequately soluble (with a solubility that increases with temperature);
- its solution must be adequately transparent to solar radiation;
- it must be widely available, so that its transportation costs do not offset the advantages of its low purchase costs; and
- it must be environmentally benign.

The amount of salt required and its necessary solubility and optical characteristics cannot be established theoretically because the understanding of stability in a stratified pond is not very well developed (Leshuk, 1978). However, certain sufficient conditions for pond stability can be inferred by analogy with successful NaCl ponds, and the overall thermal performance of a salty pond can be simulated by computer modeling when the solubility and optical properties of the alternative salt are known.

A typical NaCl pond has a solution concentration ranging from nearly zero at the surface to a maximum of 17 weight percent in the storage layer. This corresponds to a density gradient of only about 0.05 g cm^{-3} per meter depth. An alternative salt having a similar or lower diffusivity and which can provide a similar density gradient at operating temperatures should also produce a stable stratification. Figure 5 shows the solubility of some candidate salts. In all cases, the diffusivities of the alternative salts are lower than that of NaCl and the temperature dependence of solubility is greater. Therefore, a concentration sufficient to p[illegible] density gradient of 0.05 g cm^{-3} per meter depth in a typical [illegible] temperature gradient (≈20°C m^{-1}) should provide as great or greater [illegible] stability as would the NaCl salt.

Table 1 summarizes some properties of the candidate salts. Costs are only approximate since they vary substantially with location and time because of transportation costs; however, it is clear that only those salts that can be obtained as "waste" products offer substantial economic advantage. The magnesium chloride "bitterns" are available from plants that refine NaCl, and these sites are numerous (Figure 6). Sodium sulfate, however, has the potential for much more widespread availability in the next few years as a waste product from flue gas desulfurization at coal-fired power plants.

Enforcement of existing EPA air quality standards will require all new coal-fired power plants and most gas- and oil-fired power plants that will be converted to coal (as required by the National Energy Act) to have some flue gas desulfurization. Several different desulfurization processes are under development by industry and evaluation by [illegible] ([illegible], 1978); two of the most promising use Na_2CO_3 and/or $NaHCO_3$ and produce Na_2SO_4 as a flue gas desulfurization (FGD) waste product. These processes are being developed by joint ventures of Joy Industrial Equipment Company with Niro Atomizer Company (Felsvang, 1978) and Wheelabrator-Frye, Inc., with Rockwell International (Escourt, 1978).

The quantities of FGD waste produced by a plant are enormous. A typical 500-MW_e plant (burning ~0.2% sulfur coal) would produce approximately 250 tons of FGD waste per day. Hundreds of oil- and gas-fired power plants around the country are potential future sites for production of the FGD waste. In the southwestern United States alone the capacity of such candidate plants is greater than 76 GW_e, and these plants are widely dispersed around the countryside with about 50% in rural areas near potential solar pond sites. Thus FGD waste salt may meet cost and availability criteria in the future.

Preliminary measurements at the Solar Energy Research Institute (SERI) indicate that the FGD waste salt's optical properties may also be acceptable, although, because of impurities, the FGD salt solutions are not as transparent

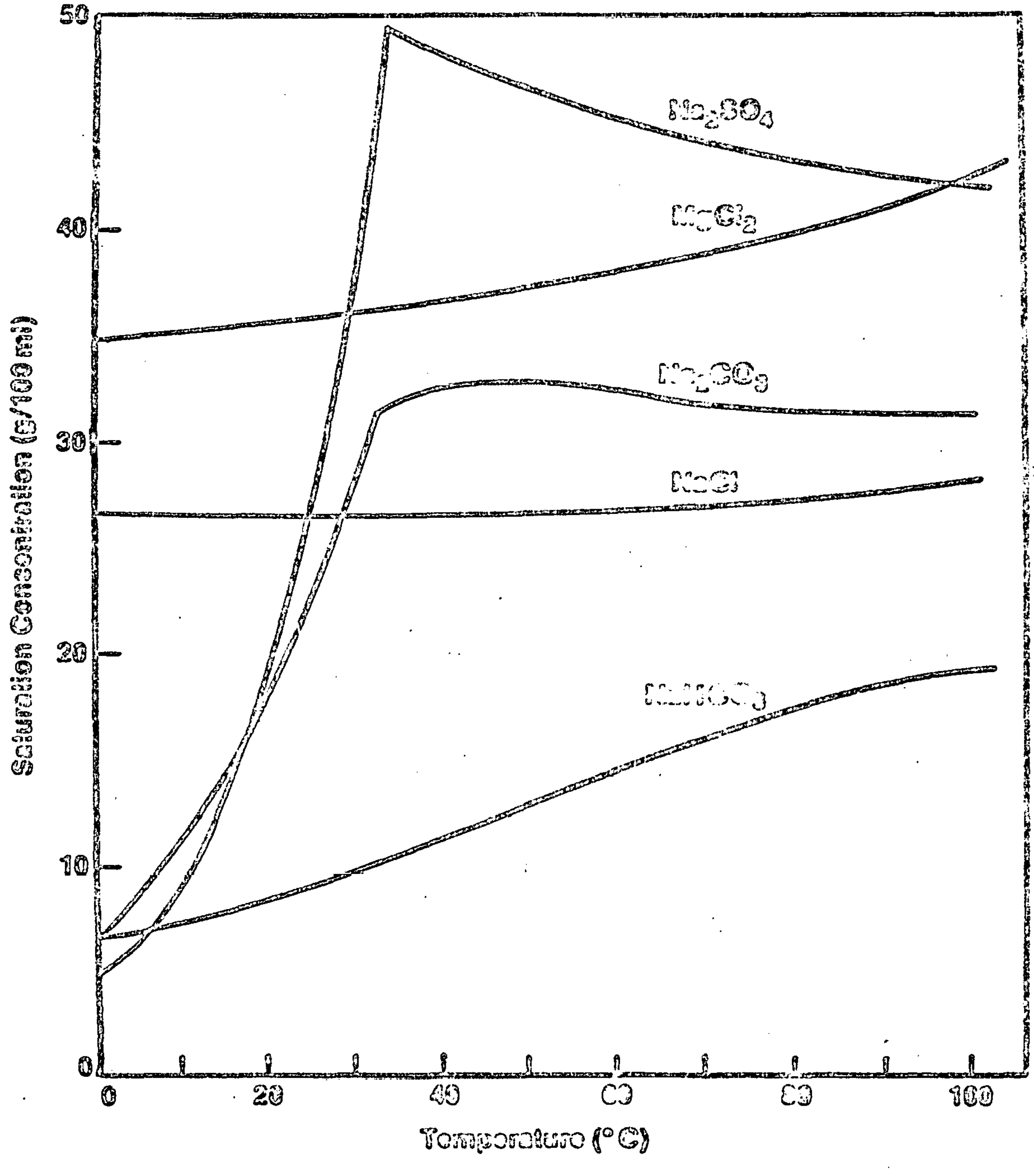

Figure 5. Solubility of Candidate Salts for Solar Ponds (Linke, 1965)

Table 1. PROPERTIES OF CANDIDATE SALTS

Salt	Formula	Source	Cost ($/10^3 kg)	Comments
Sodium chloride	NaCl	(see Fig. 2)	20	
Sodium carbonate	$Na_2CO_3 \cdot H_2O$	synthetic (Solvay Process)	98	East coast price
		as Trona (Green River, Wy.)	61	Wyoming price
		as Trona (Green River, Wy.)	70	California price
Sodium bicarbonate	$NaHCO_3$	Nahcolite (Piceance Creek Basin, Wy.)	(~35)*	Byproduct of oil shale mining (not yet in production)
Sodium sulfate	Na_2SO_4	"salt cake"	47	East coast price
		"salt cake"	45	West coast price
		as Flue Gas Desulfurization waste	(~10)*	Price depends on proximity of other markets
Magnesium chloride	$MgCl_2$	salt plants (see Fig. 2)	140	99% pure, hydrated salt
		as bitterns (see Fig. 2)	(~22)*	Waste product also containing other salts (not normally sold).

*Estimated prices

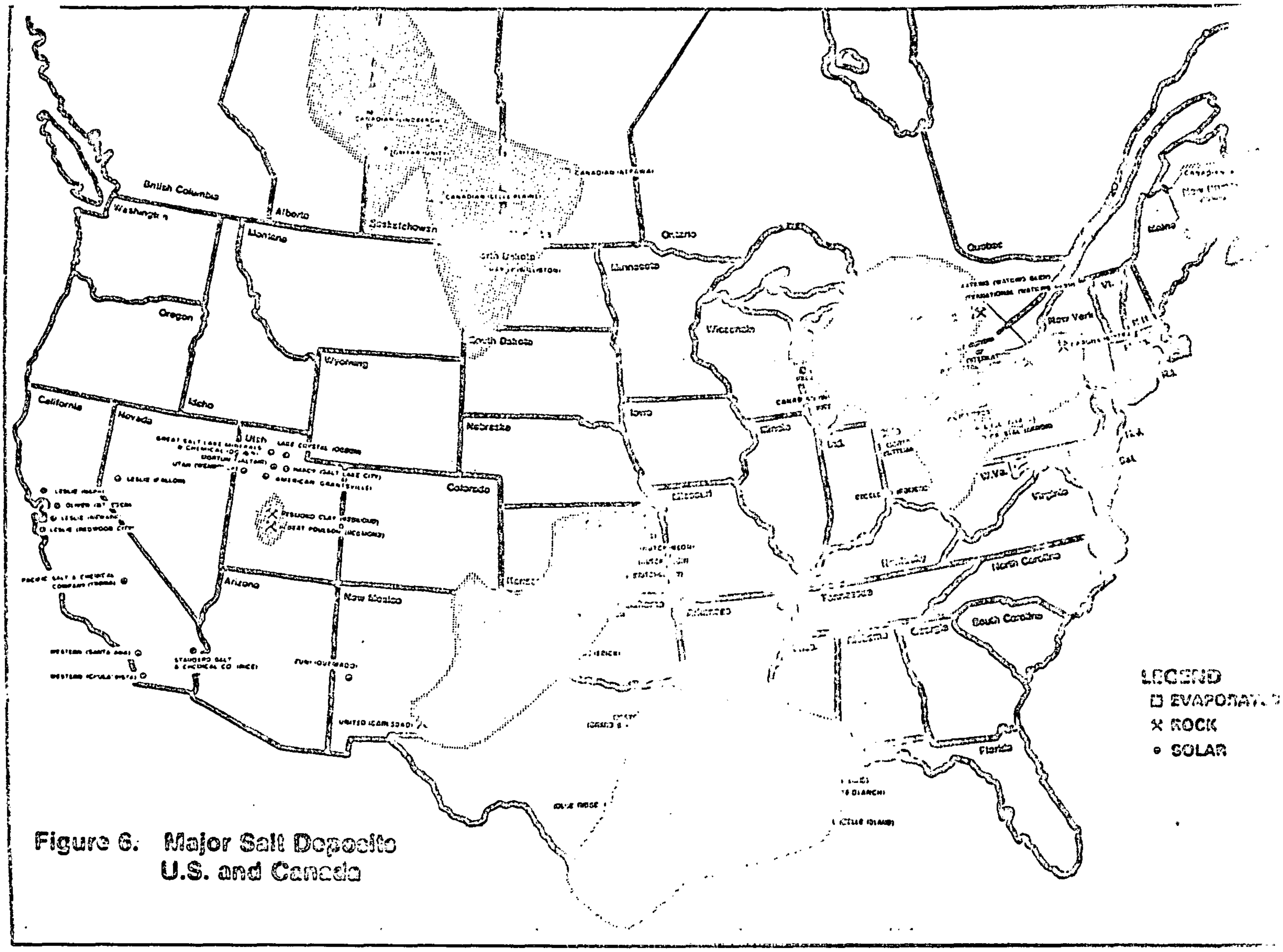

Figure 6. Major Salt Deposits U.S. and Canada

as fresh NaCl solutions. The FGD salt solution appears to meet the requirements for optical clarity but may not perform as well as NaCl. Continuing experiments at SERI will resolve these questions.

The environmental acceptability of FGD salts remains a moot question. The Resource Conservation and Recovery Act of 1976 requires the EPA to identify hazardous wastes. Fly ash and flue gas scrubber sludges may be so designated (Ray, 1978). If so, then the FGD salt may require some purification before it can be used in solar ponds. How this purification might affect availability, cost, and performance remains to be determined.

3.2 COMPARISON OF SALT GRADIENT AND SALTLESS PONDS

3.2.1 PERFORMANCE COMPARISON - A computer simulation was run of a hypothetical salty solar pond at Barstow, Calif. Employing a finite element model of the pond (Jayadev, May 1979), the simulation took into account edge losses and ground storage as well as losses through the surface, losses to the ground, and pond storage.

The pond was assumed to be 30 m in diameter, roughly the size that could be used to heat a small group of houses. The pond was assumed to have a storage layer 1 m in depth, a nonconvecting layer 1.5 m in thickness, and a surface convecting layer 0.3 m thick. (The surface convecting layer is caused by wind turbulence and evaporation and cannot be avoided.) No insulation around the pond was assumed except that provided by the ground itself.

It was further assumed that a constant load of 35,343 W (50 W/m^2 of pond surface area) was extracted from the pond.

The simulation showed that the average annual temperature of the pond's storage layer would be 61°C. It would reach a maximum of 81°C about mid-August and a minimum of 41°C in Mid-February.

Next, a saltless solar pond was simulated at the same location. The saltless pond was assumed to be convecting with the same temperature maintained throughout. It was assumed to have glazings over the top with a heat loss coefficient of 3 W/m^2°C and additional night insulation resulting in a nighttime heat loss coefficient of 1 W/m^2°C. Therefore the surface heat loss coefficient averaged about 2 W/m^2°C.

Transmissivity of the surface glazing to solar radiation was assumed to be 0.65.

By an iterative modeling process, a saltless solar pond was found that would have nearly the same temperature profile, under the same 50 W/m^2 constant load, as the salty pond. The saltless pond would be 30 m in diameter and would have only ground insulation--like the salty pond--but would be 10-m deep, much deeper than the salty pond. As noted, the additional depth--i.e., the additional thermal mass--is required to even out the temperature fluctuations in the saltless pond.

A computer simulation run on the saltless pond showed that its average temperature would be 60°C. Its maximum temperature, reached in August, would be 80°C and its minimum temperature, in mid-February, would be 40°C. Thus its temperature profile throughout the year would be much like that of the salty pond.

Figure 7 shows the temperature profiles of the two ponds.

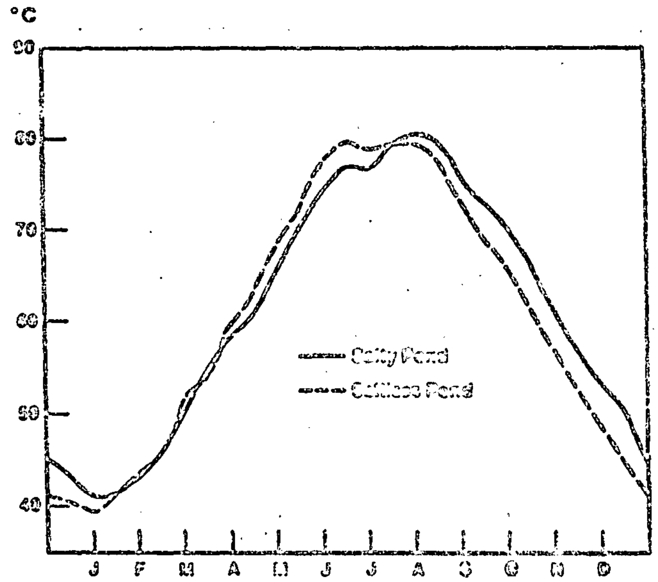

Figure 7. Annual Temperature Profiles for Salty and Saltless Solar Ponds at Barstow, Calif.

3.2.2 ECONOMIC COMPARISON - At the present stage of their development, solar pond costs can be only roughly estimated. These estimates will serve, however, to suggest economic comparisons between the salty and saltless ponds.

Capital expenses for the salty solar pond include excavation expense, the cost of a blackened liner for the bottom of the pond, and the cost of the salt.

The salty pond is 30 m in diameter and 2.8 m deep, so that at an excavation cost of $\$2/m^3$, the total excavation cost would be $4,000, or about $\$5.60/m^2$ of pond surface area. The liner for the bottom of the pond must be a durable material like Hypalon®, at a cost of $\$10/m^2$ or about $8,000 for the entire pond (including sides).

The salty pond used in the simulations would require about 0.5 ton of salt per square meter of pond surface area. The cost of salt varies widely with proximity to the supply and may be treated as a variable in economic comparisons with the saltless pond.

Capital expenses for the saltless solar pond include excavation expense, the cost of the liner, the cost of the surface structure and glazings, and the cost for night insulation.

The saltless pond that yielded approximately the same output as the salty pond was 10-m deep. At a cost of $\$2/m^3$ the excavation expense is about \$14,000, or $\$20/m^2$ of pond surface area—$\$14.40/m^2$ more than the salty pond. However, the cost of the liner could be reduced to about $\$2/m^2$ due to the much reduced requirement for retardation of leakage. For the entire pond, the liner cost would be about \$1,600.

The cost of the surface structure and glazings depends upon the means of implementation. One possible scheme is to have a lattice structure that would be placed over the top of the pond. To this structure would be fastened sections of double-layered plastic film glazing, inflated by air at low pressure. For this design a conservative cost of $\$10/m^2$ is assumed.

If liquid foam insulation were used for night insulation, it could be sprayed into the space between the inflated plastic glazings. The cost of the liquid foam generating equipment averages less than $\$1/m^2$.

Table 2 summarizes rough costs for the salty and the saltless pond.

At a salt cost of $\$16.40/m^2$ pond surface area the cost for the salty pond equals that of the saltless pond. Since 0.5 ton of salt is required for each square meter of pond surface area, the break-even price for salt is \$32.80 per ton. At a cost of salt lower than this, the salty pond is more economical. At a cost of salt higher than this, the saltless pond is more economical. For the $\$33.30/m^2$ cost of the saltless pond, the capital cost for energy at the 50 W/m^2 extraction rate is $\$666/kW_{thermal}$.

Table 2. ESTIMATED COSTS FOR SALTY AND SALTLESS PONDS

	Salty Pond ($1250\ m^2$ X 2.8 m)		Saltless Pond ($1250\ m^2$ X 10 m)	
Pond Component	Total Cost (\$)	Cost/m^2 (\$/m^2)	Total Cost (\$)	Cost/m^2 (\$/m^2)
Excavation	4,000	5.60	14,000	20.00
Liner	8,000	11.30	1,600	2.30
Glazings			7,000	10.00
Night Insulation			700	1.00
Salt		x		
Total/m^2		\$16.90 + x		\$33.30

There has been insufficient working experience with solar ponds to provide a good estimate of operation and maintenance costs. With the salty pond, there is a requirement for frequent maintenance to preserve the salt concentration gradient and to maintain water clarity. There is no reason to expect higher operation and maintenance costs with the saltless pond than with the salty pond. In fact, there is reason to expect these costs to be lower with the saltless pond since it is covered and has no salt gradient to maintain.

3.3 SIMPLIFIED SOLAR POND PERFORMANCE MODEL - A simple method that enables easy calculation of solar pond sizes and outputs has been developed (Edesess, 1979).

3.3.1 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 $\bar{T}_a$, 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 °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:

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

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

$$T_a(t) = \bar{T}_a + \tilde{T}_a \sin 2\pi(t - \phi_T)$$
$$I(t) = \bar{I} + \tilde{I} \sin 2\pi(t - \phi_I)$$
$$L(t) = \bar{L} + \tilde{L} \sin 2\pi(t - \phi_L)$$

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

$$\overline{\tau\alpha} A I(t) = L(t) + U_a[T(t) - T_a(t)] + U_g[T(t) - \bar{T}_a] + \rho V c_p \mathring{T}(t)$$

or

$$\mathring{T}(t) + \frac{U_a + U_g}{\rho V c_p} T(t) = \frac{1}{\rho V c_p} [\overline{\tau\alpha} A \bar{I} + (U_a + U_g)\bar{T}_a - \bar{L}$$
$$+ \overline{\tau\alpha} A \tilde{I} \sin 2\pi(t - \phi_I)$$
$$+ U_a \tilde{T}_a \sin 2\pi(t - \phi_T)$$
$$- \tilde{L} \sin 2\pi(t - \phi_L)] \; .$$

The solution to this differential equation is

$$T(t) = T + \Psi(t) - C(t_o) e^{-\sigma t} \tag{1}$$

where

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

$$\Psi(t) = \frac{S}{\rho V c_p} [\overline{\tau\alpha} A \tilde{I} \, h(t - \phi_I) + U_a \tilde{T}_a \, h(t - \phi_T) - \tilde{L} \, h(t - \phi_L)]$$

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

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

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

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

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

Setting the derivative of Equation 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 Equation 1, one can find the maximum and minimum temperatures.

3.3.2 EXAMPLE - For a circular salty pond simulated by Nielsen (1979), of 12-m radius and 2-m depth, wall losses were 3573 W and floor losses were 2920 W when the pond temperature was 50°C and ambient temperature was 10°C. (Note that only earth insulation was used in this simulation.) Assuming that the coefficient of heat loss to ambient is U_a = 3573/(50°-10°) or U_a = 89.3 W/°C, and the coefficient of heat loss to ground is U_g = 2920/(50°-10°) = 73 W/°C, the projected pond temperatures shown in Table 3 are obtained with the formulas just developed. (The pond is assumed to have been started on April 1. Transmission through the nonconvective layer is assumed to be 25%, ambient temperatures are 10±15°C, and insolation is 200±50 W/m^2.)

3.3.3 APPLICATION TO ESTIMATING THE AREA REQUIRED FOR A SALT GRADIENT POND - The formulas developed in 3.3.1 can be applied to estimating the required size of a solar pond. For the simplest version of the solar pond sizing method, 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.

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 4. Note that heat loss coefficients and optical transmission vary with local conditions and pond

QUAD POTENTIAL OF SOLAR PONDS BY APPLICATION

NON-METROPOLITAN AND METROPOLITAN AREAS OUTSIDE CITIES

	PERCENTAGE OF PENETRATION		
	15%	30%	100%
RESIDENTIAL	1.61	3.22	10.7[illegible]
COMMERCIAL	0.73	1.46	4.[illegible]
INDUSTRIAL	0.63	1.26	4.[illegible]
AGRICULTURAL	0.09	0.18	0.[illegible]
TOTAL	3.06	6.12	20.[illegible]

Table C.

Table 3. PROJECTED POND TEMPERATURES OBTAINED USING DEVELOPED FORMULAS

Year	Month	Projected Temperatures: No Load	5 kW Constant Load	5+3 kW Summer Peaking	5+3 kW Winter Peaking
	July 1	51.0	44.1	40.8	47.4
	Oct. 1	63.3	56.7	53.7	59.7
Year 1					
	Jan. 1	53.7	43.0	45.1	40.9
	Apr. 1	49.8	33.7	41.2	36.1
	July 1	67.1	55.7	53.4	58.0
	Oct. 1	72.8	61.4	58.7	64.0
Year 2					
	Jan. 1	56.3	44.9	47.1	42.6
	Apr. 1	[illegible]	[illegible]	42.0	36.8
	July 1	67.5	[illegible]	53.7	58.3
	Oct. 1	73.6	61.5	58.9	64.1
Year 3					
	Jan. 1	[illegible]	44.9	47.2	42.7
	Apr. 1	[illegible]	[illegible]	42.0	36.8
Steady State	Average	62.0	[illegible]	50.5	50.5
	Minimum	40.6	[illegible]	41.4	34.8
	Maximum	74.4	62.9	59.6	66.2

construction. If better estimates of these parameters than those assumed for the base case can be obtained, the expanded method described in Edesess (1979) should be used. An explanation of the choice of transmission and heat loss coefficients for the base-case salt gradient pond is also contained there.

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.

Table 4. 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

Inputs required are:

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

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

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

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

ϕ = latitude in degrees.

(1) Multiply the insolation $\bar{I}$ by the adjustment factor f to obtain $\bar{I}_r$, the insolation received after adjustment for surface reflection losses. The factor f is a function of latitude ϕ, as shown in Table 5.

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

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

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

(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.

Some specimen pond areas calculated using this method are given in Section 4.2.1. Pond depths and outputs may also be estimated using the formulas developed in Section 3.3.1. Methods for so doing are detailed in Edesess (1979).

4.0 SOLAR POND APPLICATIONS

Solar ponds are readily applicable to such low-temperature uses as residential or commercial heating and hot water, low-temperature industrial or agricultural process heat, or preheating for higher temperature industrial process heat (IPH) application. Combined with organic Rankine cycle engines or thermoelectric devices, solar ponds may be used for electric power generation. By using the heat to run an absorption chiller, solar ponds may be used for cooling.

4.1 SOLAR POND POTENTIAL - The potential of solar ponds for displacing fossil fuels in the United States is great. To estimate potential market size, the approximate number of quads (10^{15} Btu) of energy used in each potential solar pond application was compiled in Table 6. It was assumed that no market for solar ponds is possible within urban areas, but that nonmetropolitan areas (i.e., rural) have prime potential, and metropolitan areas outside cities (i.e., suburban) also have potential for solar pond penetration. Energy end use was assumed to be divided in proportion to the population among nonmetropolitan areas, metropolitan areas outside cities, and cities.

Table 7 shows the potential of solar ponds in nonmetropolitan areas alone at 15%, 30%, and 100% penetration rates. At 15% penetration, solar ponds would provide 1-1/4 quads, and at 30% penetration, they would provide 2-1/2 quads.

Table 5. 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

QUAD POTENTIAL OF SOLAR PONDS IN THE U.S.
(80 QUAD TOTAL U.S. ENERGY CONSUMPTION ASSUMED)

APPLICATION		Market Size				
		Region				
		Northeast	North Central	South	West	Total
Space Heating	Residential: Non-Metro	.52	1.39	.82	.44	3.17
	Resid.: Metro., Outside City	1.53	1.75	.86	.78	4.9
	Commercial: Non-Metro	.24	.64	.33	.20	1.46
	Commer.: Metro, Outside City	.71	.67	.80	.36	2.27
Water Heating	Residential: Non-Metro	.09	[illegible]	[illegible]	.09	[illegible]
	Resid.: Metro., Outside City	.27	.26	.28	.20	1.01
	Commercial: Non-Metro	.02	.05	.07	.02	.16
	Commer.: Metro, Outside City	.07	.07	.07	.05	.26
Cooling	Residential: Non-Metro	0	[illegible]	.2	.05	[illegible]
	Resid.: Metro, Outside City	0	.12	.2	.14	.46
	Commercial: Non-Metro	0	.03	.16	.05	.23
	Commer.: Metro, Outside City	.02	.03	.17	.14	.42
Industrial Process Heat	Low-Grade Heat	.16	[illegible]	.12	.07	[illegible]
	Pre-Heat	1.67	[illegible]	.03	.43	3.07
Agriculture	Low-Grade Heat	--	[illegible]	.1	.1	.3
Electricity	Irrigation	--	.1	.1	.1	.3
Clothes Drying	Residential: Non-Metro	.01	[illegible]	.03	.01	.03
	Resid.: Metro, Outside City	.03	.03	.04	.02	.12

Table 6.

QUAD POTENTIAL OF SOLAR PONDS BY APPLICATION
NON-METROPOLITAN AREAS ONLY

	PERCENTAGE OF PENETRATION		
	15%	30%	100%
RESIDENTIAL	0.64	1.28	4.25
COMMERCIAL	0.28	.57	1.90
INDUSTRIAL	0.23	.47	1.57
AGRICULTURAL	0.09	0.18	0.6
TOTAL	1.25	2.50	8.32

Table V.

Table 8 shows the potential of solar ponds in both nonmetropolitan areas and metropolitan areas outside cities. At 15% penetration the potential is over three quads, and at 30% penetration it is more than six quads.

4.2 DISTRICT HEATING APPLICATIONS - To minimize heat losses at the pond edges, it is best to maximize the ratio of pond area to pond perimeter. Therefore a small pond will not be as efficient as a larger one. Thus, it is better for residential heating applications to build one large pond for a group of houses than to build a small pond for each house.

Table 9 shows the results of sizing the base-case salt gradient solar pond using the simple technique described in Section 3.3, 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.)

The pond sized in each case, with allowance for different climates and consequent user loads, would be sufficient to serve roughly 25 to 50 households.

4.3 INDUSTRIAL PROCESS HEAT APPLICATIONS - To assess the feasibility of solar pond technology for IPH applications and compare the suitability of ponds with more conventional solar technology, two industrial applications as reported in the Solar Energy Research Institute's (SERI) case studies (Brown, 1979; Hooker, forthcoming) were selected for analysis.

One application focuses upon the hot water requirements for aluminum can washing in a Colorado manufacturing plant where cans are shaped and trimmed from sheet stock, then washed and dried before being sent for bottom coating and painting. On the average, the can processing lines operate 24 h per day, 6.5 days per week, and 50 weeks during the year. Most of the energy used in the plant (supplied by natural gas at $1.93/GJ) is required for can drying. However, approximately 22% of the total energy input goes to a water heater that supplies 60°C (140°F) water to the can washer. Water is heated via steam. The total annual energy requirement for can washing on one process line is 2.3×10^{12} joules (2185 MBtu).

Table 9. REQUIRED SOLAR POND SURFACE AREAS AND DEPTHS AT VARIOUS LOCATIONS IN THE UNITED STATES

Region	Location	Latitude (°)	Insolation (W/m^2) Avg./Min.	Ambient Temp. (°C) Avg./Min.	Pond Temp. (°C) Avg./Min	Pond Sizes for 50 kW_{th} Avg./70 kW_{th} Max. Load[a]			
						Winter Peaking		Summer Peaking	
						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	0.30	4.2	0.30	2.7
Mountain	Denver	39	203/96	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	2.3
East N. Central	Chicago	41	169/53	10.3/-4.3	75/50	1.37	3.6	1.37	3.1
	Chicago	41	169/53	10.3/-4.3	60/40	0.76	4.2	0.76	3.4
East S. Central	Jackson, MS	32	186/93	18.3/3.4	75/50	0.63	3.4	0.63	2.7
	Jackson, MS	32	186/93	18.3/3.4	60/40	0.45	4.1	0.45	3.3
New England	Boston	42	163/53	10.7/-1.0	75/50	2.07	3.2	2.07	2.9
	Boston	42	163/53	10.7/-1.0	60/40	0.93	3.8	0.93	3.2
Middle Atlantic	Philadelphia	40	154/62	12.0/0.2	75/50	1.42	3.3	1.42	2.9
	Philadelphia	40	154/62	12.0/0.2	60/40	0.77	3.9	0.77	3.1
South Atlantic	Miami	25	194/134	24.2/19.3	75/50	0.59	2.9	0.59	1.0
	Miami	25	194/134	24.2/19.3	60/40	0.37	3.6	0.37	1.9

[a]Approximately the demand of 25 to 50 households.

The second application is for hot water used in washing in a large Colorado commercial laundry. Water is heated via steam and effluent heat exchangers. Steam is primarily used in the ironing machines (the largest load in the plant) so that it is conceivable that the required hot water at 82°C (180°F) could be alternatively supplied directly by a solar system. The hot water load constitutes only 8% of the total plant energy demand. The laundry normally operates for one daytime shift, 8 h each day, 6 days per week. Total annual energy to be supplied is 4.3×10^{12} joules (4085 MBtu). Energy is supplied via natural gas at $1.85/GJ.

Solar pond systems were sized to assist the IPH needs of the metal can manufacturer and the commercial laundry. In theory, a pond could have been sized to provide 82°C continuous output, as required for the commercial laundry. The incremental surface area and depth required, however, to increase the pond's minimum output temperature from 80°C to 82°C is considerably greater than that required to increase it from 60°C to 62°C. Therefore, there is likely to be an optimal size at which the marginal cost of increasing the pond's area is equal to the cost of backup energy. Hence, the optimal solar pond may use backup, even though it may be feasible to size a solar pond large enough to require no backup.

For the metal can washing application, a solar pond was sized to achieve an annual average temperature of 55°C, with an annual high of 65°C, and an annual low of 45°C. It was assumed that a 5°C loss would be suffered in exchanging heat from the pond. Hence, at its peak temperature of 65°C, the pond will just satisfy without backup the application's requirement for 60°C water. At all other times, it will require backup to boost the temperature. The pond is 5143 m^2 (1.27 acres) in surface area and 4.9-m deep. The capital cost of the pond alone is $128,000 if salt is free, $173,000 if salt costs $10 per ton, and $218,000 if salt costs $20 per ton. The costs of the heat exchanger and piping were conservatively assumed to be $8/$m^2$ of pond surface area.

For the laundry application, a solar pond was sized to achieve an annual average temperature of 65°C, with an annual high of 80°C, and an annual low of 50°C. This pond is 3552 m^2 (0.88 acre) in surface area and 3.2-m deep. Its capital cost is $76,000 with free salt, $94,000 at a salt cost of $10/ton, and $112,000 at a salt cost of $20/ton. Again, heat exchanger and piping costs were assumed to be $8/$m^2$.

The simulation codes PROSYS and ECONMAT (Brown, 1979) were used in SERI case studies of the two applications to assess annual performance and costs of alternative "conventional" solar IPH systems. Approximately 20 different collectors were analyzed and the most cost effective collector and system were chosen for each application. Table 10 shows the cost and performance characteristics of each conventional solar system and of the comparable solar pond system for three assumed salt costs. The annual energy outputs of the solar ponds for the two applications were calculated using the method described in Section 3.3. Note that the configured systems will annually deliver different amounts of energy. A comparison is possible, therefore, only on the basis of annualized energy costs or projected rates of return. It is useful, however, to compare the relative amounts of capital investment required for unit annual energy delivery. The capital capacity cost of the conventional systems (total

Table 10. COMPARATIVE COST AND PERFORMANCE OF CONVENTIONAL SOLAR SYSTEMS VERSUS A SOLAR POND SYSTEM

System Type	Area Land Required	Annual Energy Delivered	Collector Subsystem Cost	Balance of Plant[a]	Total Capital Cost	Estimated Annual OMPI
Metal Can Washing						
Parabolic Trough Collector Heat Exchange System	1273 m^2 (13,695 ft^2)	2.3×10^{12} J (2,260 MBtu)	$190,000	$167,000	$360,000	$ 7,500
Salt Gradient Pond at $20/Ton For Salt	5143 m^2 (55,339 ft^2)	5.6×10^{12} J (5,320 MBtu)	$210,000	$186,000	$414,000	$ 8,000
Salt Gradient Pond at $10/Ton For Salt	5143 m^2 (55,339 ft^2)	5.6×10^{12} J (5,320 MBtu)	$175,000	$103,000	$330,000	$ 6,000
Salt Gradient Pond at 0/Ton For Salt	5143 m^2 (55,339 ft^2)	5.6×10^{12} J (5,320 MBtu)	$120,000	$103,000	$324,000	$ 4,000

Laundry Hot Water

System Type	Area Required	Annual Energy Delivered	Collector Subsystem Cost	Balance of Plant[a]	Total Capital Cost	Estimated Annual OMPI
Parabolic Trough Collector, Heat Exchange System	2207 m^2 (23,480 ft^2)	2.83×10^{12} J (3,780 MBtu)	[illegible]	$210,000	$332,000	$18,000
Salt Gradient Pond at $20/Ton For Salt	3552 m^2 (38,220 ft^2)	3.03×10^{12} J (2,867 MBtu)	$110,000	$112,700	$224,700	$ 4,000
Salt Gradient Pond at $10/Ton For Salt	3552 m^2 (38,220 ft^2)	3.03×10^{12} J (2,867 MBtu)	$ 90,000	$112,700	$203,700	$ 3,700
Salt Gradient Pond at $0/Ton For Salt	3552 m^2 (38,220 ft^2)	3.03×10^{12} J (2,867 MBtu)	$ 70,000	$112,700	$183,700	$ 3,000

[a]Includes materials and labor for installation of auxiliary equipment items, such as heat exchangers, plus 60% of direct field costs for indirects, contingency, and fee.

capital cost divided by annual energy delivered) is approximately $165 per GJ/yr ($173/MBtu/yr). The capital capacity costs of solar pond IPH systems vary between $74 per GJ/yr for expensive salt and $60 per GJ/yr for free salt ($77/MBtu/yr to $62/MBtu/yr). However, approximately twice as much land area is required for the pond as for the conventional trough collectors to deliver the same annual energy.

Installation of a retrofit solar IPH system (no storage is assumed for these systems and full conventional backup is available) is a "service" investment whose costs are offset by savings accrued from reduced fuel consumption. To compare the economic viability of the parabolic trough with the solar pond, a rate of return calculation was performed for each application using the method identified in Dickinson (1979).

Equity financing was assumed, with a 20-yr service life, 7-yr depreciation, 50% tax rate, and 20% investment tax credit. No salvage value was taken. Therefore, a multiplier may be determined for various rates of return and the levelized cost of solar energy plotted against rate of return. On the same graph, the levelized cost of the fuel displaced may be plotted for various discount rates. The rate of return from the given project is then found at the intersection of the two curves. Figure 8 shows the rate of return calculation for the metal can washing application and the calculation for the commercial laundry. Two levelized fuel prices are assumed in each case: (1) current quoted price of fuel with an 8% rate of escalation and (2) fuel price of $5.00/GJ ($5.27/MBtu) escalating at 10% per annum. An efficiency of conversion to delivered heat of 85% in metal can washing and 75% in the laundry is assumed.

As can be seen in the charts, installation of any sort of solar IPH system in either application does not offer adequate return on investment when compared to costs of natural gas and a fuel price escalation rate of 8%. However, when compared to natural gas at $5.00/GJ escalating at 10%, the solar pond systems usually provide a rate of return in excess of 15%, which is generally sufficient to warrant commitment of funds in general service investments. The alternative conventional parabolic trough systems offer less than half of this rate for the same fuel price scenario. Hence, solar ponds justify serious consideration as economic alternatives for low-temperature IPH. In addition, it appears that the return from solar pond systems is not highly sensitive to salt cost.

4.4 ELECTRIC POWER GENERATOR - In combination with organic Rankine cycle engines or thermoelectric devices, solar ponds may be used for the generation of electric power. Conversion efficiency is low--on the order of 1% to 2% from insolation to electric output--but costs are so low that solar pond-electric applications may be economical in many cases. Much work is being done in Israel on solar pond-organic Rankine cycle engine generation of electricity (Sargent, 1979). It has been proposed that thermoelectric devices in comparison with solar ponds would provide an even more cost-effective means of generating electricity (Jayadev, August 1979). It should be noted that solar pond-electric generation has a significant advantage over other solar-electric systems in that, because of the inherent solar pond storage, electricity is available on demand, rather than only intermittently.

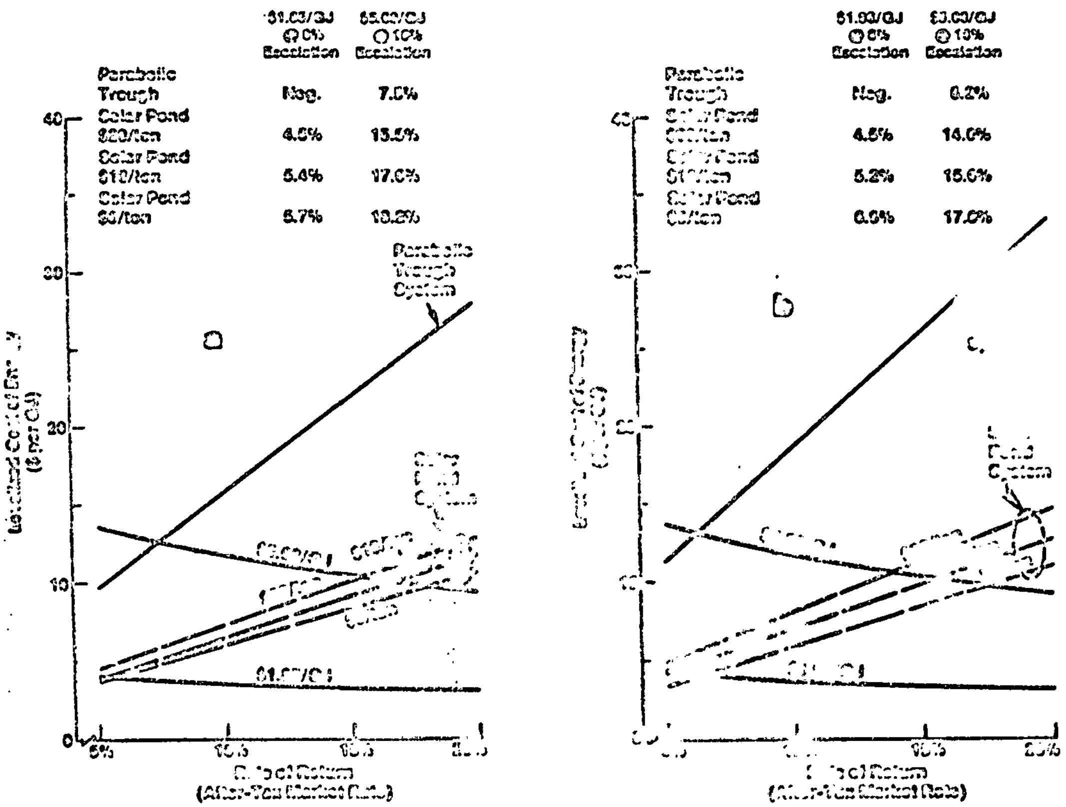

Figure 8. Exam[illegible] for
(a) A [illegible]
(b) A [illegible]

5.0 CONCLUSION

Solar ponds have considerable potential for economically providing district heating for residential and commercial areas, industrial process heat, and electric power. There has as yet, unfortunately, been little research, development, and demonstration of solar ponds in the United States, although there has been a major effort undertaken in Israel. Work is needed to research inexpensive salts for salt gradient ponds and surface glazings and night insulation for saltless ponds. An accumulation of experience with demonstration ponds and commercial ponds in the United States would provide needed lessons in design and maintenance techniques. With a little effort applied to their development, solar ponds are one of the most promising near-term solar technologies.

6.0 ACKNOWLEDGEMENTS

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