An Improved Solar Heating Process

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ABSTRACT

Because of the rapidly rising cost of energy in recent years, considerable attention is being given to alternative energy sources. In many locations the utilization of solar energy should become an attractive possibility, but primarily because of the expense of the solar collectors, commercial solar heat or power generation to date has been very limited. To help overcome this problem a number of investigators have proposed that various types of simple solar ponds might be employed as the collectors.

A new solar collecting pond design that is relatively inexpensive in construction, and simple and stable in its operation will be reported in the following paper. Its thermal efficiency is high, thus making it smaller and more cost effective for either water heating or power generation. Its design employs conventional solar ponds with a thin oil or plastic film to inhibit evaporation, an insulating cover to reduce heat loss to the air, and dyes to increase the radiation absorption. For larger installations with power generation, direct contact heat exchange with organic low boiling fluids should be employed for greater efficiency, along with "cooling water" ponds. The initial capital cost for this pond "collector" system is not high, perhaps about $200/kw, but the total power installation would be about $2,200/kw. However, the power production cost could be as low as $.01/kw hr. Most of the individual components of the concept have been proven in detailed tests or industrial operations, but no commercial plants have yet been built. The system should be ideally suited for solar salt producers who are already skilled in solar pond operation.

LITERATURE AND PRIOR WORK

Considerable literature exists on solar ponds, solar heat and power generation, and related activities. A detailed review of the design and operation of solar salt ponds has been given in a series of four articles (Garrett, 1962) that provides a comprehensive description of the construction of solar ponds and their operation. The average modern facility of this type employs from 10,000 to 70,000 acres of ponds, which if used for power production could hypothetically generate the equivalent net solar thermal power (after subtracting the energy consumed in the process) of 1,000 to 7,000 megawatts.

Many articles on solar ponds detail their energy balance, cyclic behavior under a variety of design conditions, and present computer models for their design and operation (Laborde, 1983). The inhibition of water evaporation from pond surfaces has likewise been studied (La Mer, 1965 and White, 1976). It was found that even monomolecular films of organics with both a polar and non-polar component can effectively reduce evaporation, as can thicker films. Such agents have been tested on various reservoirs and water bodies with excellent success under non-windy conditions. Similarly, the solar absorption characteristics of water, brine and various dyes have been studied, and there are several excellent review articles (Keyes, 1967, etc.). Dyes are available that absorb essentially the entire spectrum of solar radiation, and several are currently being employed in commercial solar pond operations.

Many references exist on solar thermal power production (Duffie and Beckman, 1974, etc.), and several methods have been proposed for constructing solar pond collectors. The most pertinent is a U.S. patent (Garrett, 1977) which is similar to that discussed in this article. As noted previously, many investigators have also discussed salt gradient ponds (Battelle, 1974; Bechtel, 1975; Rabi and Nielson, 1975; Schaffer, 1977; Zangrando and Bryant, 1977; Mauch, 1982; Wilkins, 1982; Multer, 1982; French, 1981; etc.). These ponds are currently being tested extensively. Experimental stratified solar ponds have been reported to reach temperatures of over 100°C with both saturated salt (NaCl) and magnesium chloride solutions.

These ponds have clearly demonstrated that solar energy can be effectively gathered in large solar ponds for useful heating or power generation purposes. They are very simple and effective solar collectors and for many specific locations and purposes are almost certain to find a useful application. However, they do have a number of problems, as follows:

1. Instability. It is difficult to prevent the lower saturated solution from mixing with the upper layer of water because of wave action, convection currents, boiling, brine withdrawal and injection, etc. In the small ponds tested to date there is only occasional complete mixing, and usually careful control with the addition of water and strong brine, plus removal of weak brine has kept them fairly stable. However, in larger ponds this becomes increasingly difficult. The geological subject of limnology (study of natural stratification in water bodies) shows that: a) most ponds or lakes do mix, and b) that many stratified lakes "turn over" or mix at least annually unless very deep. Thus it may not be possible to maintain large ponds without extensive pond diking, baffling and salinity adjustment.

2. Low thermal efficiency. The salt gradient ponds still evaporate a great deal of water, and also lose radiant and conduction heat from their surface. Their efficiency in recovering solar energy is only 15–20% at best. This requires a much larger pond area than should be necessary, which is quite expensive.

3. Large inventory. Because of their great depth and brine volume, the salt gradient ponds require several years to come to their steady state working temperature. This large "inventory" of heat may be an advantage, but it is not very controllable, it is expensive, and if the ponds mix, a considerable recovery time and loss is experienced.

4. Auxiliary problems. There are numerous ones that may or may not be serious, depending upon the location:

a) They require a large amount of salt. Unless there is a cheap concentrated brine source available this could be their greatest cost factor.
b) Their depth aggravates soil leakage problems. Double liners are usually required, with leakage detection devices.
c) They cannot tolerate excess light absorption in the upper layer, potentially caused by dust, leaves, algae, fungi, turbidity or water coloration resulting from soil leaching, corrosion, contamination, etc.
d) Additional facilities are required to process the withdrawn diluted lower salt layer.
e) Considerable make-up water is necessary to make up for evaporation and dilute brine withdrawal.
f) There is possible environmental contamination from the strong brines.

In an attempt to overcome the de-stratification problems noted above, the use of a membrane between the strong and weak brine has been suggested, or the use of a gel or viscous solution for the top layer. These construction methods, of course, would be very expensive. Lawrence Livermore Laboratory (LLL) has also proposed a different type of solar pond system with an "enclosed bag," producing hot water and possibly solar thermal power. They report achieving maximum temperatures of about 96°C with their sealed bag ponds, even though they generally design for a maximum of 60°C. These ponds respond quickly to the solar conditions, deliver predictable quantities of heated water and recover a fairly high percentage of the solar energy falling upon them. A fairly large commercial operation was built (Dickinson *et al.*, 1975), and a design manual prepared (Casamajor and Parsons, 1978).

A final aspect of solar power generation is the need to use "Rankine cycle" turbines or boilers to convert the heated brine or water into power. This involves heat exchange of the hot brine with Freon or some other low-boiling-point fluid, which is in turn vaporized, and this vapor drives a turbine. The low pressure vapor is condensed and the cycle repeated, as in a water boiler-turbine cycle with a condensate return. A number of companies make such Rankine cycle turbogenerators (Editor, 1981), but they are expensive. Ormat (Israel) estimates costs of 4–5$/kwh for a standard 300 kw unit and an initial price of $400,000 for the system. MTI (Latham, N.Y.) estimates the purchase price at $2000/kw installed, for a variety of sizes. These unit prices would be less for larger systems and should come down as more units are sold.

PRINCIPLES OF THE NEW SOLAR POND CONCEPT

In considering of how to improve the current solar pond design as a solar collector the objective was to achieve the favorable results of the other systems, eliminate their problems and hopefully improve their efficiency. Cost, simplicity and reliability are the principal factors of importance for any commercial operation and conventional "salt type" solar ponds have these virtues. This should make them good candidates for solar collectors if they could be adapted for heat and power production.

The new collector design is similar to a normal solar pond as utilized throughout the world for sea water salt, potash, and other chemical production. However, the ponds are designed to be operated with a very shallow brine or water level (2 to 8 inches depth) so that they can heat up rapidly and to a high temperature. The ponds have a film of plastic or oil covering the brine surface to minimize evaporation and an insulating plastic cover over them. The design allows for a comparatively rapid brine flow through the system. A process flow sheet is shown in Figure 1.

The ponds brine depth would be variable, with the inlet and outlet ends capable of being maintained at what-

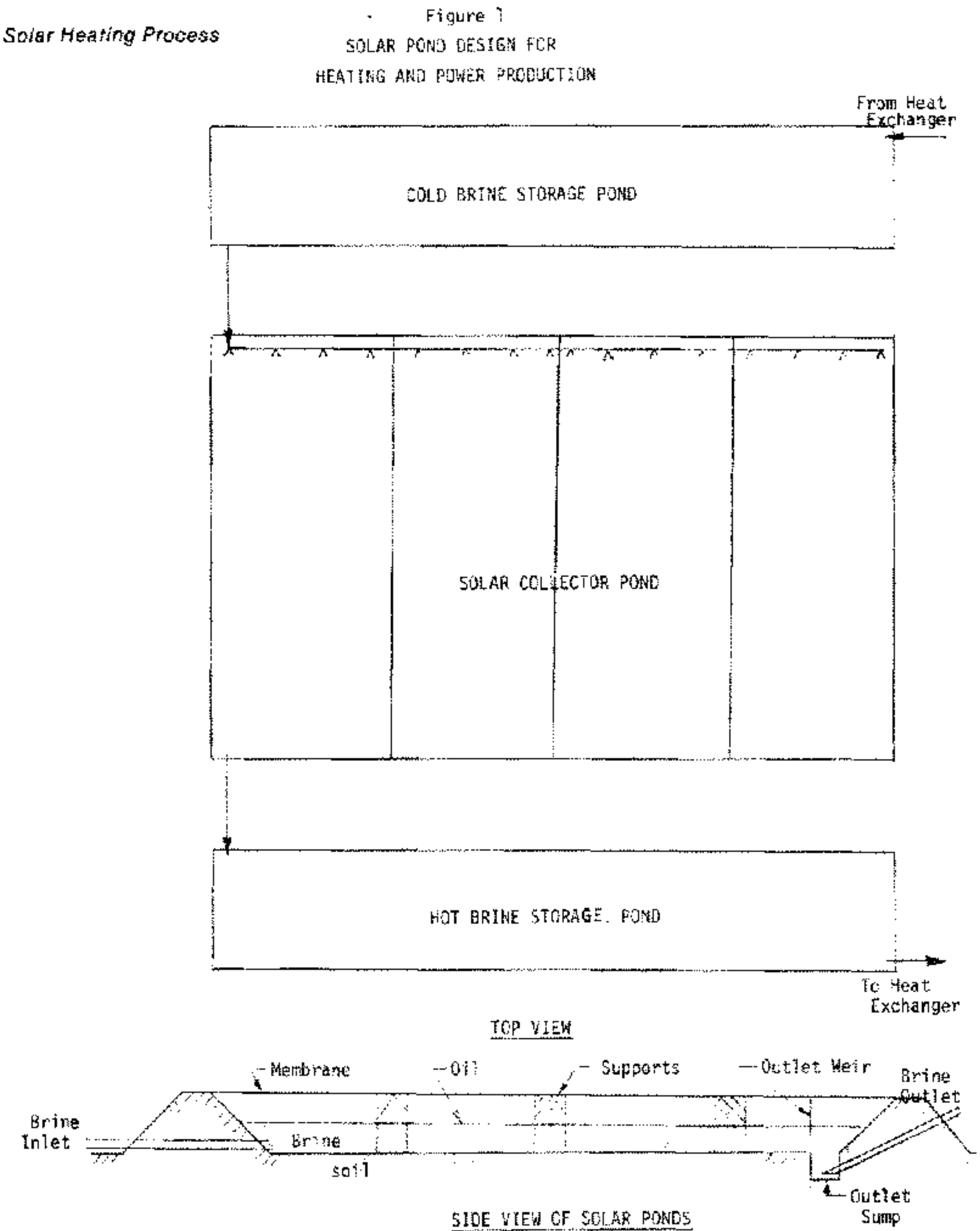

Figure 1. Solar pond design for heating and power production.

ever height was required for the appropriate hydraulic gradient to provide the desired flow through the pond at the time of maximum output. Oil would be placed on the brine in a sufficient thickness to prevent evaporation, or alternatively, a floating clear plastic membrane would be used, depending upon which was less expensive. Normally this would be oil, and a reasonably clear, acid-treated product that would not darken or polymerize when exposed to ultraviolet radiation and brine would be used. Small-scale tests have indicated that very thin films are effective, but thicker ones provide more evaporation protection and have less likelihood of congregating near the down-flow barriers. To further prevent oil flow, spaced baffles would be required to prevent flow from depleting part of the surface cover.

The top membrane would allow about 2 to 6 inches of insulating air space above the brine and be supported by blocks of polyurethane or other plastic that would be fastened to the pond bottom, and in turn have the membrane fastened to it. The membrane would be of the thin film type used in greenhouses for its clarity and ability to withstand ultraviolet radiation. Standard production dimensions, such as 30′ × 100′, or the largest size available would be used, with the edges fastened securely to the dykes and baffles to minimize wind damage. The film would be reinforced, preferably with polypropylene filaments for added strength and longer life. Fiberglass greenhouse paneling could also be used for much longer resistance to sunlight if the added capital expenditure was warranted. It might be considered for second generation installations, or to replace the first membrane when the project economics was more fully established.

Return pond water from the Rankine fluid heat exchanger could go directly to the collector ponds for small installations or be stored in large, deep earthen reservoirs with a floating insulation layer on top. When the sun heated the water in the collector pond to the desired temperature, flow would start into the pond system from the feed reservoir at such a rate as to maintain a predetermined exit temperature, or to allow it to slowly increase on a given time cycle. This flow would continue until the late afternoon, when slightly declining temperatures would perhaps again be allowed, and the flow would finally stop at a computer-estimated optimum value. The hot water would be used directly (for small operations) or stored during the day, with a constant withdrawal sent to the Rankine turbine system. Water could be used in the pond system, but a strong brine with a low vapor pressure would be preferred.

As an optional feature to provide slightly colder cooling water during the evening, the process would be repeated in other ponds to cool the condenser water to the greatest extent possible. When the pond temperature reached the desired low level, the water would be withdrawn to storage. As it warmed up in the morning, flow would be stopped. The cold water would then be withdrawn as needed for condensing the Rankine fluid. A cooling tower would be used alternately for smaller installations, when it could lower the cold water temperature (in very low humidity areas), or when the cold water storage supply was exhausted. The two pond system is shown in Figure 2.

Power production would depend upon the temperature differential between the high temperature brine from the collector pond and the Freon condensing temperature obtained by the cooling water produced from ponds in the evening or from cooling towers. The hot pond brine would be heat exchanged with a Rankine fluid (i.e., Freon) as an intermediate turbine-driving material. The comparatively low pond temperatures would not allow a high thermal efficiency for the turbine (i.e., 8–14%), but because of free sunlight and low operating costs the Btu or kwh costs should be reasonable and the potential volumes of heated water or power very large.

Also, because of this comparatively low temperature differential available for the Rankine Cycle (estimated to vary from 40° to 75°F), depending upon the time of day and the time of year, the added thermal efficiency of a direct contact heat exchange with the Rankine fluid would be desirable (as shown in Figure 2). However, this would be more complex and costly and only warranted for larger installations.

Modern day microprocessor control would greatly as-

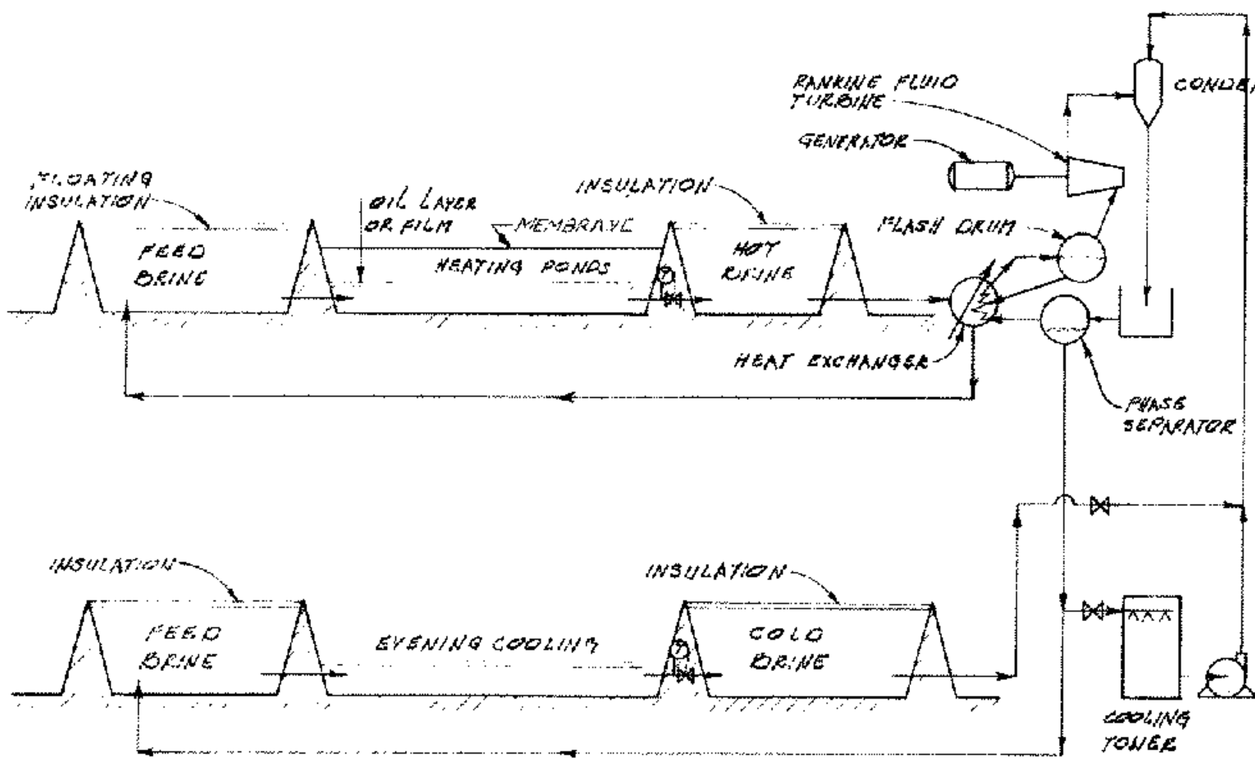

Figure 2. Solar pond process for power production.

sist in obtaining the maximum performance from the system. Temperature probes in the exiting hot brine could control the brine flow to the heat exchangers or the amount going to storage in the normal manner. The microprocessors would be programmed to anticipate the remaining daily thermal input in the early afternoon and reduce or increase the preset temperature to make sure that the hot reservoir was filled each day. It could likewise consider in its control of the brine flow to the heat exchanger the optimum power output, for example, by reducing the flow to obtain a higher temperature that would result in higher efficiencies for the turbine, or by higher flows and lower temperatures for greater efficiency in the ponds. In a similar manner, there could be several solar pond pumps and, depending upon the flow required, they could be switched on or off as needed, thus saving power.

In summary, for optimum solar thermal energy production, the brine temperatures need to be as high as possible, and thus the ponds should be shallow and the brine volume comparatively small. Also, a number of changes must be made in the normal salt pond design. Exit flows should travel under a weir, with the discharge going to a deeper sump for ease in withdrawal. A surface production on the weir would be employed to prevent the oil film from leaving the solar pond with the heated brine. A thin, clear plastic film would be laid on supporting blocks of polyurethane or other material to provide an insulating cover. The blocks could be fastened to the pond bottom and the membrane to support it above the pond, to prevent wind damage. Edge supports and tie-downs would be used to further help prevent the wind from blowing the cover. The function of this membrane is as an insulator to improve the thermal collection efficiency and prevent the oil film from blowing to one side of the pond.

Technical Basis for the Approach

As solar energy falls upon a pond, experience has shown that a small amount (0-15%) is usually reflected from the surface, depending upon the time of day (the sun's angle), the pond size and the condition of the surface resulting from the wind. Usually about 70-80% of the light entering the pond is absorbed in the water or brine, and the remainder is absorbed on the pond bottom, or reflected back from it, particularly if there are salt crystals. Normally, most of the solar energy is utilized in evaporating water, although some brine, soil and air heating occurs. The brine heating is a function of the time of day and the depth of the pond, as shown in Figure 3. As would be expected, when the ponds are shallower they become warmer in the daytime and colder in the evening. The very smooth, symmetrical curves shown in Figure 3 are based primarily on energy balances for the heating cycle and convective heat transfer for the cooling period. In actual practice the curves are neither smooth nor perfectly symmetrical, and the heating of open ponds depends a great deal upon the evaporation taking place, which is largely controlled by the wind, and the concentration of the brine, which determines its vapor pressure.

For solar thermal power generation the salt gradient pond system suffers the normal surface reflection loss (0-15%), the top water layer absorption and evaporation loss (which could be as much as 50%, depending upon the water depth, color, and turbidity) and thermal conduction loss from the lower, hot brine to the water layer and the soil (10-20%). The lower, concentrated solution layer has only slightly better solar absorption properties than the water above it, unless it contains natural coloring impurities (humic acids, etc.) or dyes have been added. It will, however, receive most of the heat absorbed on the pond bottom. Such ponds are thus thermally very inefficient, generally converting only 15-20% of the solar radiation into heat in the lower reservoir brine. This type of pond is an interesting example of solar ponds' ability to heat brine to a high temperature, but its low efficiency, high cost and instability result in many problems as a commercial solar energy collector.

In contrast to the complex stratified pond system, the same result can be accomplished if a film is placed on the water surface, because it reduces the reflection and reradiation loss and retards evaporation. Then, if a dye is placed in the brine or the pond bottom is dark, essentially all of the solar radiation striking the pond is utilized in heating the water, except for the soil and air heating and re-radiation to the sky. The closest analogy to this proposed system that has been tested extensively is the sealed bag solar pond construction, or perhaps the gel cover on the "salt gradient" pond (where the thermal efficiency was doubled). If open pond waters are solar heated, convection heat transfer losses rise, and some form of insulation is usually justified to maintain a high thermal efficiency, as shown in Figure 4. This can be done in the proposed open pond system by laying a clear plastic film on insulating blocks fastened to the bottom. Two layers, such as pleated, air-filled membranes could be employed if desired for further insulation. The use of dyes or ponds with dark bottoms will allow the shallower, higher temperature ponds to be used with good absorption efficiency because water or brine depth will then not be required for light absorption. Evening cooling would automatically occur in the ponds, both from convection heat transfer with the cool evening air, and on clear evenings, black body radiation to the sky. Flow through a pond system at night should produce Rankine fluid condensing waters colder and/or less expensively than cooling towers, if this added efficiency factor were desired.

COST EFFECTIVENESS

The proposed Solar Pond Process is based upon two premises: 1) it should be more practical and economical

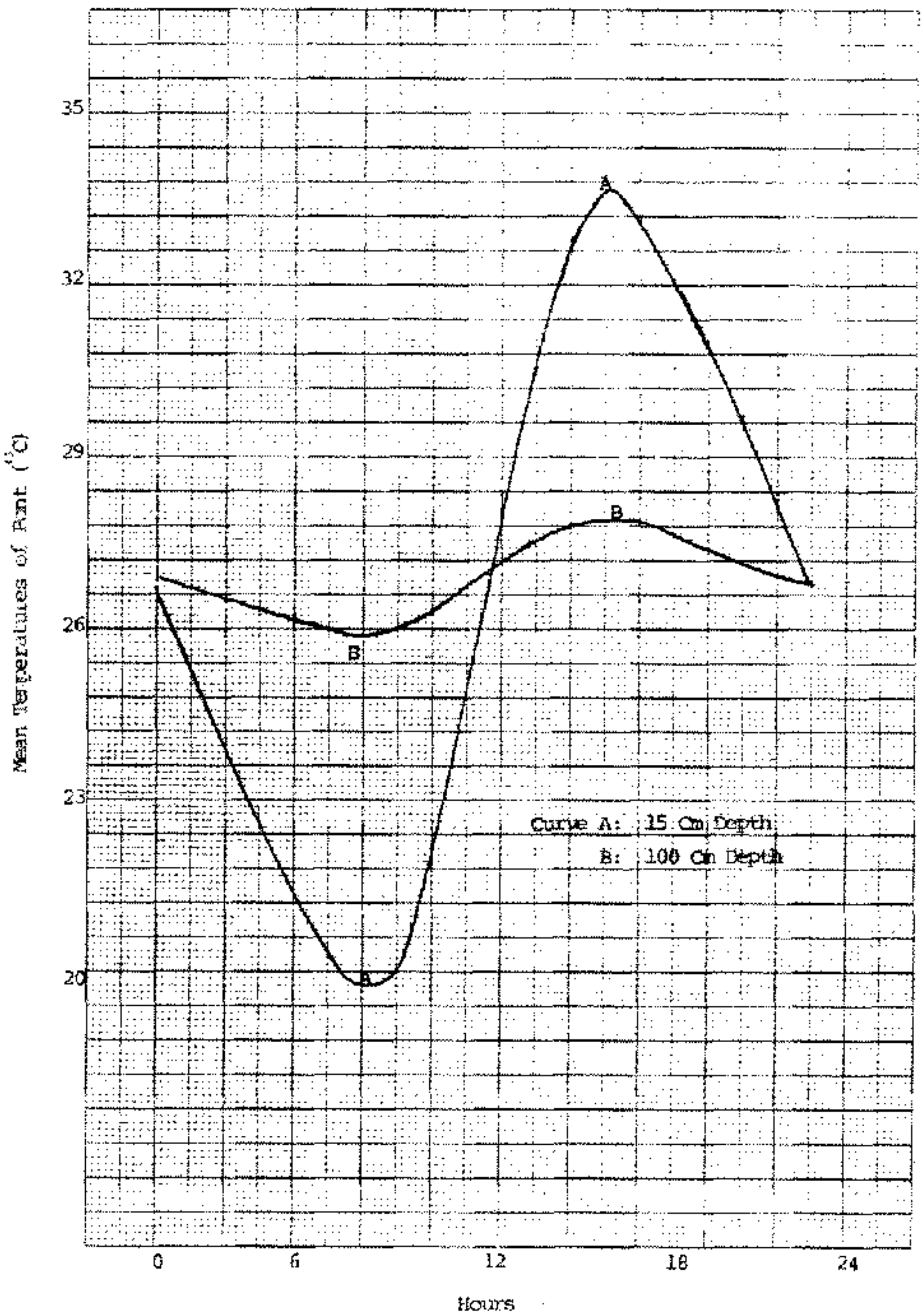

Figure 3. Typical variation in mean pond temperatures with various solution depths.

to have a large, inexpensive solar collector that produces a moderately high temperature fluid and requires somewhat more expensive power generating equipment than a complex, costly, size-limited mirror array, bag, or stratified pond system, and 2) that simple solar ponds could fill this requirement (along with direct contact two-fluid heat exchange), if a high solar absorption could be effected, and evaporation and heat loss reduced to a low value. The extent that this has been accomplished is estimated in the following cost calculations.

Design Data

In an attempt to calculate the operating cost of such a pond system it has been assumed that the ponds are 1000 m square (200 acres); the solar energy absorption is 85%; heat loss from the system, 20%; maximum brine temperature to the plant, 180°F; winter temperature, 150°F; turbine driving fluid, Freon 11; approach to pond and cooling tower temperatures for turbine vapor and condensate, 8°F each; wet bulb temperature, 70°F summer,

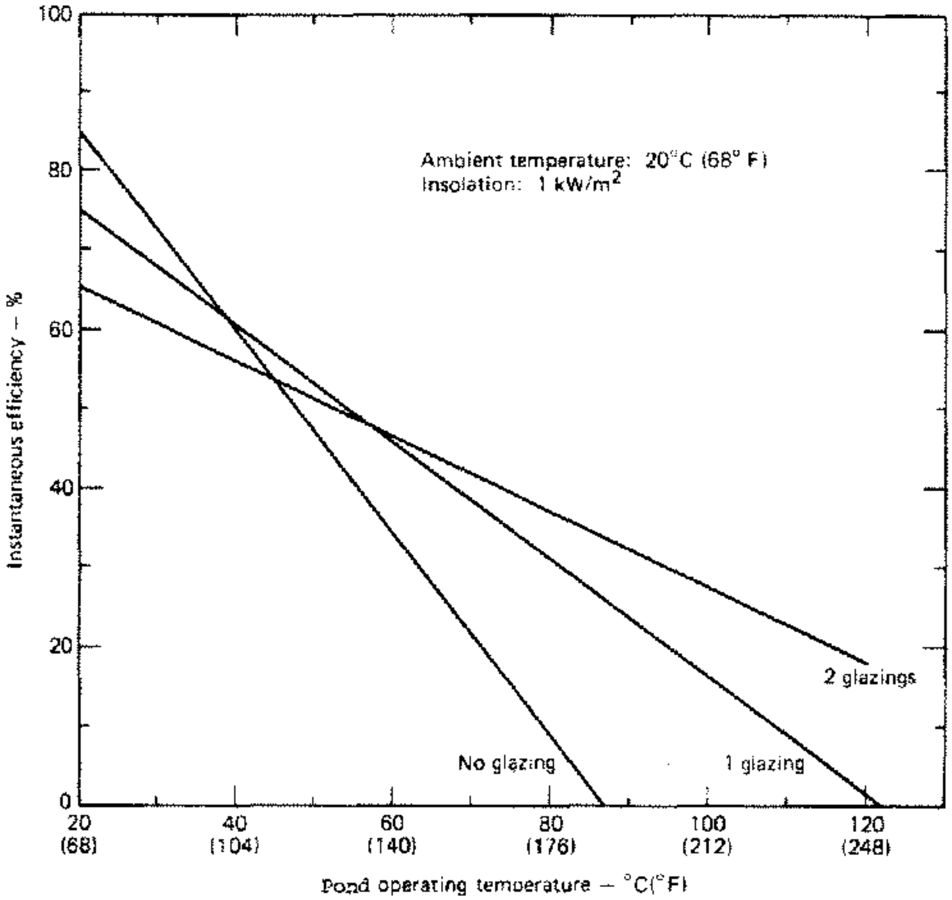

Figure 4.

50°F winter; and 8°F rise for cooling tower water. The energy absorption is:

Summer: (770 × 3.64 Btu/ft² × day) (.85 efficiency) × (1,000² M² × ft²/.0929M = 29.055 × 10⁹ Btu/day, summer

Winter: 10.566 × 10⁹ Btu/day, winter

Brine flow rate:

$$\frac{29.055 \times 10^9 \text{ Btu/day}}{(172\text{–}78)\,(8.34)\,24 \times 60} = 18{,}300 \text{ gpm, summer}$$

8,800 gpm, winter

Power output: 29.05510⁹ × .8 (heat losses) × .8 turbine efficiency) × .293018 × .148 (therm. eff.) × 10⁶ × 24 (Kw-hr) = 40 MW, maximum

Turbine (thermodynamic) efficiency: Winter, 145 to 58°F 109–20 = 89 Btu/lb; 109–99 = 10; 10/89 = 11.2% Summer, 172° − 78°F, 115–101.5 = 13.5 Btu/lb., 115 − 24 = 91 13.5/91 = 14.8% efficiency (Actual plant experience is about 8.5%).

Power requirements: brine pumps, assume a 15′ lift plus friction loss, 85% pump efficiency:

18,300 × 8.33 × 1.2 (lb/min) × 15/33,000 × .85 = 97.8 HP, × 745.7 = .073 MW; Cooling Tower: 30′ lift plus friction: 234,000 gpm = 2500 HP = 1.86 MW

Power Summary (summer)

Gross power produced	40 MW
Less cooling water pumps	1.86
Less cooling tower fans	2.55
Less Freon pumping	.56
Less brine pumping	.15
Less misc. losses (5% gross)	2.00
Total	7.12

Net power production	Ideal Case	Conservative, Practical
	32.88 summer	20 MW
	12.0 winter	7 MW

Cost Data

Solar ponds: (1000 m² Dikes 18′ high × 18′ wide at top, 45° slope: 1.5 × 1.5 × 2 × 4 × 3.281 × 1000/27

= 2,187 cu. yds. @ \$2/cu. yd. = \$4,374; × 20 for interior baffles, roads, riprap, etc. = \$90,000. Weirs, pump pits, etc. = \$110,000. Pond piping, pumps, canals, electrical, etc. = \$200,000.

COST SUMMARY

Ponds, Civil Work		\$ 400,000
Dikes, weirs, roads, etc.	\$ 200,000	
Piping, pumps, etc.	200,000	
Power Generation		4,000,000
Turbines	2,000,000	
Heat transfer	1,000,000	
Cooling towers	500,000	
Balance of plant	500,000	
Total		\$4,400,000

Cost per Kw, \$2220

Electric Power Costs

Annual costs (amortization, interest, taxes, etc.) 17% = \$748,000

Salaries, materials, misc. expenses = \$130,000

Dye, evap. retardant, isobutane loss = \$100,000

Total = \$978,000/yr.

Average power = (20 − 7)/2 = 13.5 MW

@ 95% on stream time = 12.8 net MW

$$\text{Cost}\ \frac{\$987{,}000 \times 1000\ (\text{mils/yr})}{12.8 \times 1000\ (\text{Kw})\ 365 \times 24} = 8.8\ \text{mils/Kwh}$$

SUMMARY

The technical feasibility of constructing low operating cost, inexpensive solar ponds is well demonstrated by the world's large commercial salt pond operations. Evaporation retardant films have also been utilized, as have insulating covers on solar collectors. Rankine cycle engines for power production from low temperature heat sources are likewise in commercial operation. Thus, the technical feasibility of this proposed new solar energy process would appear to rest upon the ability of the various components to fit together into a practical, economical and efficient process. It should be a unique and promising method for solar thermal power production having many improvements over other means of collecting solar energy (a patent has been granted on the process [Garrett, 1977]). Compared to salt gradient ponds it has the advantages of being available for commercial operation immediately after construction, it has higher peak temperatures, is less expensive to construct, is much more stable, requires less operator attention, requires less water make-up, has greater thermal efficiency, does not need the expensive salt loading or auxiliary evaporation area, does not need pond linings and poses few environmental problems. However, it has disadvantages for equally uniform power production of requiring small hot and cold storage ponds; it needs variable flow pumps for the ponds; it has a somewhat more complex membrane structure; it requires oil for the evaporative retarding film; needs more pond subdivisions and is not yet as well demonstrated.

In general, however, the new method has the potential of: 1) allowing small or large-scale heating or solar thermal power to be generated, and 2) producing heat or power on any scale more cheaply than currently studied methods. The utilization of solar energy for heat or power generation appears to have significant potential to improve the economics of plants where solar ponds can be employed. Both this new method and the salt gradient ponds should find a wide application in the future.

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