Salt Gradient Solar Ponds: Research Progress in Ohio and Future Prospects

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ABSTRACT

Since 1975, four salt gradient solar ponds have been designed, built and operated in Ohio by Ohio State University researchers in Columbus and Wooster, Ohio. Two solar ponds were built in Columbus for physical studies, one solar pond was built at the Ohio Agriculture Research and Development Center at Wooster to heat a greenhouse, and one solar pond was built in Miamisburg to heat a community swimming pool and recreational building.

From these research efforts, data and recommendations have been developed on site selection, linear selection, salt gradient establishment and maintainance, heat extraction and environmental protection. Sodium chloride was used as the stabilizing salt for all ponds, but the salt profile of each pond was different. Actual applications of these four solar ponds were detailed, together with the mechanics of heat extraction from the solar pond storage zone.

The costs of building a solar pond were shown to vary from $38 per square meter to $60 per square meter. Future prospects for solar ponds depend upon the realistic recycling of salt from the surface layer of the solar pond to the lower convective, or storage zone, of the pond.

INTRODUCTION TO SOLAR PONDS

Solar ponds for space heating and crop drying have been extensively researched and tested at Ohio State University (OSU) in the Department of Physics in Columbus and in the Department of Agricultural Engineering at the Ohio Agricultural Research and Development Center (OARDC) in Wooster, Ohio.

Research on salt stabilized solar ponds at Ohio State University commenced in 1975 with the building of a solar pond at the Farm Science Review fairgrounds in Columbus for grain drying, and the building of a solar pond at OARDC in Wooster to heat an adjacent greenhouse. In 1978, a solar pond was built by the City of Miamisburg in Ohio in consultation with Dr. Carl Nielsen of OSU. A solar pond was built at the dairy center at OSU in Columbus and was completed in 1979. This pond has been designed to study stability and heat loss phenomena that have been questioned in other ponds.

DESCRIPTION OF OHIO PONDS

OARDC Solar Pond

The solar pond at OARDC (Figure 1) was a box shape 18.3 meters (60 ft) long, 8.5 meters (28 ft) wide and 3 meters (10 ft) deep, with verticle side walls and a flat bottom (Short et al., 1979, 1977, 1976). Soil was excavated from the bottom of the pond and bermed up against the outside of the solar pond walls. The OARDC solar pond contained 1555 cubic meters (120,000 gal) of brine, had a surface area of 155 square meters (1680 sq ft) and a salt content of 100 tons. The profile configuration had a storage zone depth of 1.8 meters (6 ft), a salt gradient zone depth of 0.9 meters (3 ft) and a surface zone depth of 0.3 meters (1 ft). These depths were varied during the years of pond research.

The OARDC solar pond has been used for supplying heat to a greenhouse during the winters since 1977. The heat from the pond has been used in three different modes for heating the greenhouse: heating of the air in the greenhouse using standard greenhouse equipment, heating of the soil using buried heating pipes, and heating the greenhouse using a heat pump in order to extract heat from the solar pond to heat the greenhouse for the entire winter.

Farm Science Review Solar Pond

The solar pond at the Farm Science review site in Columbus, Ohio was circular in design with sloping side walls,

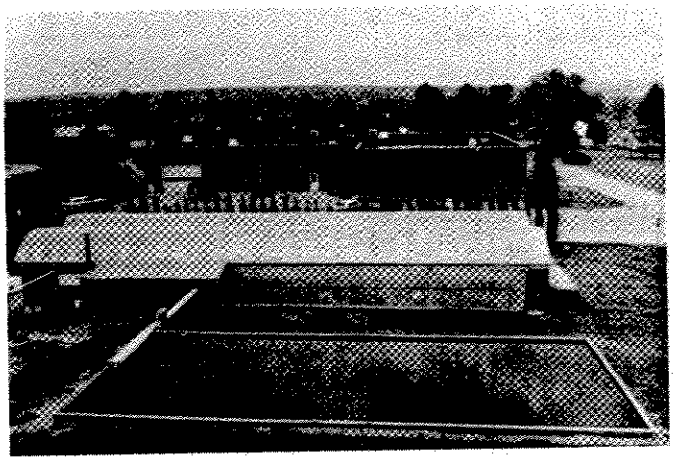

Figure 1. The OARDC Solar Pond.

and a depth of approximately three and a half meters. It had a surface area of 156 square meters and a salt concentration of 20% in the lower convective zone. This solar pond has been used to provide heating for air that was circulated to a grain bin for grain drying in the fall.

Miamisburg Solar Pond

The Miamisburg solar pond was rectangular in design, measuring 54.5 m by 36.4 m (180 ft × 120 ft) at the top with sides sloping at 1:1 to a depth of approximately 3.0 m (10 ft). The pond had a surface area of 2020 square meters and contained approximately 1100 tons of sodium chloride. The salt concentration in the lower convective zone of the pond was approximately 18.5% (Bryant et al., 1979).

The Miamisburg solar pond has been used to heat the city swimming pool since the summer of 1978. The heat is extracted from the solar pond by use of a heat exchanger, which transfers the pond heat directly to the swimming pool water.

OSU Dairy Solar Pond

The solar pond built at the dairy facility at Ohio State University was circular in design with a diameter of 22.8 m and a surface area of 408 square meters (Nielsen, 1981,1980). The bottom of the pond was dish-shaped with a maximum depth of 4.5 meters at the center and 1.3 meters at the perimeter. The perimeter walls were verticle with insulating panels between the liner and the wall timbers. The salt concentration was approximately 24%. The pond was built with some specific measurements in mind, and it has been very carefully instrumented so as to study ground heat losses and pond perimeter losses.

Solar Pond Liners

All the solar ponds mentioned have membrane liners to contain the brine solution. The liner in the Farm Science pond is a chlorinated polyethylene liner and is similar to the liner used in the OARDC solar pond that failed. All other ponds have Shelter-Rite XR-5® liners. The selection of an appropriate liner for a solar pond is vital to the success of that pond (Fynn et al., 1981).

What is a Salt Stabilized Solar Pond?

A salt stabilized solar pond is a body of liquid that collects solar energy and stores it as heat. This type of solar pond relies on a salt solution (usually sodium chloride) of increasing concentration with depth to suppress natural convection. Warm concentrated brine at the bottom of such a pond is prevented from rising to the surface and losing its stored heat because the upper portion of the pond contains less salt and is, therefore, less dense than the lower portion. The pond relies on the salt gradient zone in its upper part to act as a transparent insulator that allows radiation from the sun to penetrate the pond and heat the storage zone in the lower part of the pond. This gradient zone insulates the storage zone from the ambient air temperature above to reduce pond heat loss to the atmosphere. A typical solar and pond salt profile is shown in Figure 2.

SALT GRADIENT ESTABLISHMENT

The two main functional zones of a salt stabilized solar pond are the storage zone and the salt gradient zone. a salt gradient is an essential feature in a solar pond, and much research effort has been spent studying the effects of salt concentration, heat flow, heat extraction and diurnal heating and cooling on the salt gradient (Fynn and Short, 1983).

The heat loss upward from the storage zone of the pond to the atmosphere is dictated by the depth of the gradient zone. However, the solar radiation penetration into the storage zone is also influenced by the depth and clarity of the gradient zone. As the gradient zone depth is increased, the upward heat loss will be reduced according to the equation $Q = KdT/D$, where Q is heat flow in watts per square meter, K is the thermal conductivity in watts per meter degree calcium, dT is temperature difference in degrees celcius, and D is gradient zone depth in meters.

However, radiation input will also be reduced accordingly to the equation $T = 55.4e ** -0.28(D + S)$, where T is the radiation transmission efficiency in percent, D is the gradient zone depth in meters as before, and S is the depth of the surface convective zone in meters.

The salt gradient zone has an approximate thermal

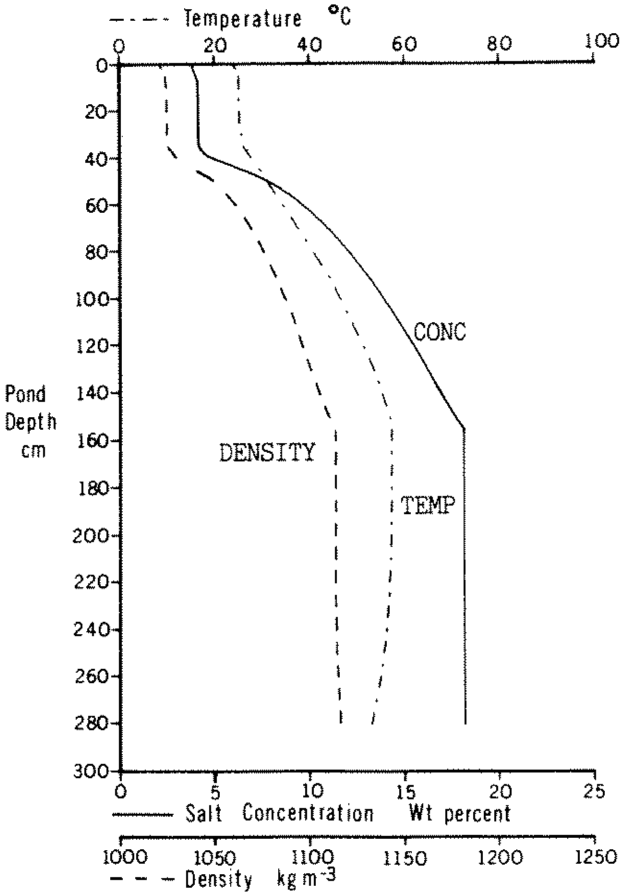

Figure 2. Solar pond profile.

conductivity (K) of 0.6 watts per meter degree centigrade. It is imperative that this salt gradient be established and maintained properly.

Salt Quantities

To calculate the quantity of salt required in a solar pond it is necessary to calculate the weight of water in the storage zone and half of the salt gradient zone. The volume of water in the storage zone is added to half the volume of water in the salt gradient zone. The weight of this volume of water is then multiplied by 0.2 and this will give the total weight of salt required for a solar pond with a storage zone having a twenty percent salt concentration.

A solar pond with a gradient zone depth of one meter (3 ft) and a storage zone depth of two meters (6 ft) has a salt requirement of 500 kg per square meter of pond surface area. At a cost of salt of $35 per ton delivered, that gives a price of $17.50 per square meter of pond surface area ($1.50 per square foot of pond surface area).

Gradient Establishment

The gradient can be established a number of ways and three methods are discussed below. The first method is to fill the pond with fresh water to a depth equal to the sum of the storage zone depth and half of the salt gradient zone depth. All the salt is then dissolved in this water and the solution mixed up to make a homogeneous brine. Fresh water is then floated onto the surface of the brine so that the pond is filled to the full operational level. This fresh water is subsequently pumped from the surface of the pond into a brine diffuser and injected into the high density brine solution. While the injection process is proceeding, the diffuser is raised from its position within the brine solution to the surface of the pond. The salt gradient can be established in one pass using this method.

Alternatively, the pond can be filled with concentrated brine as before, but fresh water is *not* floated onto the pond surface. The diffuser is placed at the top of the required storage zone and fixed in position. Fresh water is pumped into the center of the diffuser until the pond surface has risen by 5 cm. The diffuser is now moved up 10 cm, refixed in position, and more fresh water introduced until the pond surface has risen a further 5 cm. The diffuser is moved up another 10 cm and fixed. This cycle is repeated until the diffuser reaches the surface of the solar pond. The step-by-step gradient so formed will diffuse to establish an even salt gradient in time.

Multiple Use Equipment

The pumping concepts described above will work perfectly well for any size solar pond. However, the larger the pond, the more pumping is required, and the equipment may become unwieldy and impractical. If the heat extraction method used for the pond is one which pumps the brine to an external heat exchanger using diffusers, then this same equipment can also be used to establish the gradient initially and to modify it, if necessary, at a later date. The advantage is that the same capital equipment can be used to perform three functions—establishing the gradient, heat extraction from the storage zone, and profile modification and maintenance.

Monitoring the Vertical Profile

While the vertical concentration profile of the pond is being established, salt concentration measurements need to be taken at various depths to evaluate progress. This can be done either by gravimetric sampling or by temperature and electrical conductivity measurements at selected points over the entire depth. Almost any horizontal location in the pond is acceptable for sampling since the concentration zones quickly become stabilized across the pond.

Conductivity Measurements

An electrical conductivity cell and thermocouple system can be used to measure the vertical salt concentration, density and temperature profiles in a solar pond. Such a system, developed at the OARDC, measures and records electrical conductivity and temperature of the solution at preselected points while the sensing head is being moved from the bottom to the top of the solar pond (Fynn et al., 1980). From these measurements, a salt concentration, density and temperature plot against the pond depth can be made using equations derived from salinity tables. Researchers at OARDC have developed such an instrument, and a profile of the OARDC solar pond is shown in Figure 2.

Gravimetric Measurements

A second way of measuring the salt concentrations is the gravimetric method used in the laboratory. Samples of brine are removed from the pond at specified depths and allowed to cool in sealed containers. Once cool, the brine is transferred to specific gravity bottles and weighed. The density of the brine at room temperature is now known, and the salt concentration can be read from tables available from the Office of Saline Water.

SALT GRADIENT MAINTENANCE

Gradient maintenance is essential to the long term operation of a solar pond (Fynn, Short and Shah, 1980). There are two requirements for gradient maintenance. The first requirement is to recycle, or replace, salt that is continuously diffusing from the high salinity storage zone in the bottom of the pond to the low salinity surface convective zone. The second requirement is to monitor the salt gradient zone densities and to correct any instabilities that may occur within the salt gradient zone.

Salt Diffusion

Salt slowly diffuses upward through the solar pond gradient at an approximate annual rate of about 20 kg/sq m (Nielsen, 1982). This rate varies and is dependent upon ambient conditions and the salt and temperature gradients in the solar pond at any one time. During this diffusion process the surface zone slowly becomes more salty and the storage zone loses salt. Most solar pond operators to date have maintained the convective zone concentration by disposing of some of the surface zone brine, replacing it with fresh water and adding new salt to the storage zone of the pond. Ideally, the brine from the surface zone should be reconcentrated and then injected into the storage zone. This procedure would alleviate two problems: no salt would have to be discarded to the environment and the operating expense of purchasing new salt would be eliminated. However, the cost of the concentration procedure has to be taken into account. In the newer research ponds, the surface zone brine is being fed to evaporating ponds where it is concentrated and eventually returned to the storage zone of the solar pond.

Gradient Zone Instabilities

During pond heating, and particularly at higher temperatures, small, unstable convective zones may develop within the stable gradient zone. If these zones are left unattended they will increase in thickness, depriving the pond of insulation. The increase in thickness, depriving the pond of insulation. The increase in thickness of these zones can be halted and even reversed in various ways. The first way is to withdraw heat from the pond faster than it is accumulating. This may occur as a natural part of the pond cycle. For example, an instability may develop at the end of summer when the pond is at its hottest, as the space heating or crop drying season is about to begin. Withdrawal of heat and cooling of the pond during this season will probably restabilize the convective zones.

Concentrated brine solution may be injected into the unstable zone in order to stabilize it. Enough brine must be introduced to increase the salinity of the pond below the unstable zone. The best way to ensure against instabilities within the salt gradient zone is to have a storage zone with a high salinity. If the storage zone is maintained with sufficient salt concentration, then instabilities will not occur within the gradient zone.

Some gradient maintenance occurs naturally, depending on the geographic location. A unique natural phenomenon is the formation of surface ice during cold winter periods. Freezing is a desalting process that tends to reverse the salt flow and purify the surface. The ice also protects the pond from wind mixing, but very little light transmission into the pond occurs because the ice is often covered with snow.

MAINTENANCE OF BRINE CLARITY

Importance of Brine Clarity

Brine clarity in a solar pond is important because the radiation falling on the pond must be able to penetrate through the pond gradient zone to the storage zone. The more radiation that can penetrate to this storage zone the higher will be the collection efficiency of the solar pond. It is imperative that the salt gradient zone be kept as clear as possible within reasonable economic limits. The salt stabilized solar pond is unique because, once established, the storage zone and most of the salt gradient zone will not come into contact with air unless the pond is disturbed in some way. Thus, chlorine, introduced into the pond as "free chlorine" for algae control, will be present in the pond for a considerable length of time. Copper salts, once introduced, will also remain in the solution. This means that the continued dosage of chemicals such as required for swimming pools, is not necessary for solar ponds, and much smaller amounts of chemicals can be used at larger time intervals.

Bacteria Control

Bacteria can and will grow in even the highest concentrations of brine if the temperature is less than 50–60°C

(120–140°F). Chemical control for clarity in high temperature shallow ponds may be necessary only to get the pond above the sterilization temperature.

Chlorine is the chemical most commonly used to control bacteria. The effectiveness of chlorine varies with pH, and it is more effective in an acidic solution than a basic solution. If the pH is maintained at approximately six, then the chlorine will have a high sterilization efficiency.

pH Control

Control of brine pH is necessary to minimize electrochemical corrosion and to activate chemical treatment. An operating range between 5.5 and 6.5 is desirable. Adding chemicals to the brine for various treatments will often change the pH and must be compensated for accordingly. Alum, for instance, produces an acid when it reacts with water and it is desirable that brine pH be slightly high before adding alum. At a higher or lower pH, the alum floc in the water will begin to dissolve and result in ineffective treatment.

Algae Control

Algae growth in solar ponds will also inhibit solar transmissibility. Effective control can be difficult because there are many different algae species that can be introduced from rainwater or dust and debris. The best way to control algae is to prevent it from getting started through regular use of a commercial algaecide. Again, since human safety is not a factor, some overdosage may be desirable for control assurance.

Iron Oxide Control

Depending on the locality and water source, dissolved iron in the water is usually one of the first problems encountered that requires chemical treatment. Any aeration will oxidize the iron and cause a rust-colored iron oxide suspension to form. This suspension will greatly reduce the brine transmissibility until it has settled onto the bottom. The dissolved iron may also contribute to scaling problems if exposed to metallic surface in the heat extraction system. To accelerate the settling rate, alum (aluminum sulfate) is sprinkled over the pond surface to floculate the iron. This treatment may be used anytime, even if the pond salt gradient has already been established.

Surface Skimmers

Wind-borne debris such as leaves will contaminate the surface of a pond. The best method of cleaning has been found to be skimming the surface. Floating surface skimmers for swimming pools can take off leaves and dust rapidly. If a skimmer is located at the down wind end of a solar pond the wind will help carry the dirt to it.

Sand Filtering

A sand filter has been found to be most effective in filtering out suspended solids in the storage zone of the OARDC solar pond. Most dirt will fall to the bottom of the pond and will remain there. The filter is only required for any contamination that remains suspended in the solution and reduces the clarity of the pond. It is imperative that the filter has a bypass valve and that it can be backwashed with fresh water. Most of the time the brine will bypass the filter.

Chemical Addition

If the brine from the storage zone is pumped to an outside heat exchanger, then this brine can be used to transport chemicals back to the pond. These chemicals, in liquid form, can be introduced to the return line to the bottom of the pond. However, the chemicals will be effective only in the storage zone of the pond. Treatment of the salt gradient zone has to be done from the top of the pond.

HEAT EXTRACTION

Basic Principles

It is a common misconception that salt is added to a solar pond to improve its thermal capacity. Salt is used only to create liquid stability with concentration density gradients that are stronger than thermal density gradients. Since thermal energy is then stored as sensible heat in the high concentration storage zone, it is desirable to know the thermal properties of the specific brine being used. The addition of most salts to water actually *reduces* the specific heat of the solution. Figure 3 shows the reduction of heat capacity of sodium chloride brine as the salt content is increased.

The heat from a solar pond is usually extracted one of two ways. The first is to pump the hot brine from the storage zone of the pond to a heat exchanger located near the pond. The second is to pump a heat exchange fluid, usually fresh water, through a heat exchanger located within the convective zone of the pond. Both have advantages, but pumping the hot brine to an out-of-pond heat exchanger tends to be the most cost effective and trouble free system. Both systems have been researched at Ohio State University (Badger et al., 1979).

Pumping Brine

Pumping the hot brine from the pond storage zone to an out-of-pond heat exchanger is the most common heat extraction system in use on solar ponds today. The pump and related pipes are sized to the anticipated heat demand and the predicted temperature of the solar pond during that demand. To determine pipe sizes, the brine velocity must be kept below two meters per second. Head losses become unacceptable above this velocity. Hot brine

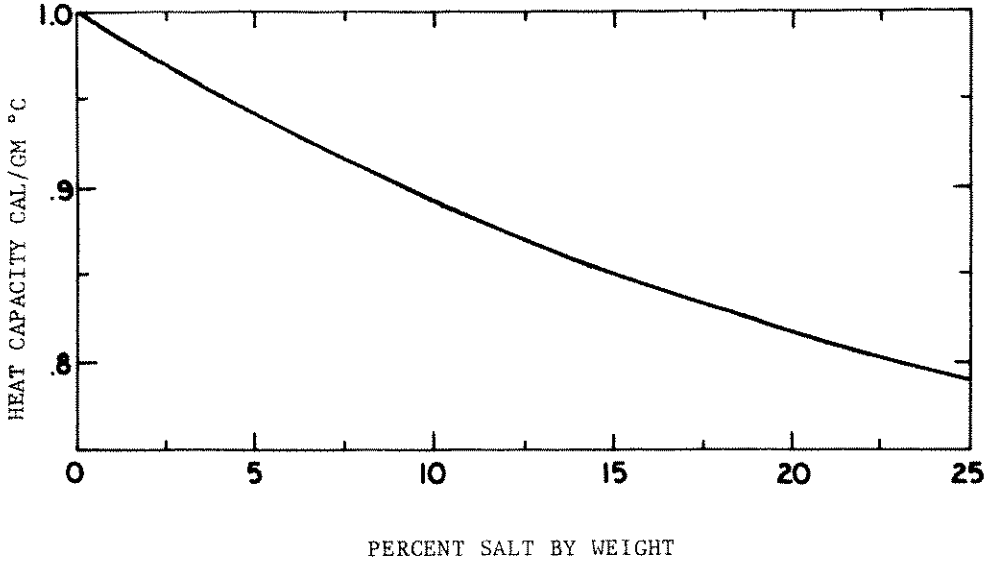

Figure 3. Graph showing the relationship between heat capacity and brine concentration for a solution of sodium chloride in water.

is taken from the upper portion of the storage zone, passed through a heat exchanger and returned to the bottom of the storage zone. Heat extraction by brine pumping requires that a pump and heat exchanger be incorporated into the circuit to circulate the brine and exchange its heat to some other medium. This medium may be fresh water, a heat pump refrigerant, air, concrete or soil. If the brine is pumped to any metal heat exchanger, compatability of materials is essential to avoid corrosion.

A filtration system can also be incorporated into the plumbing circuit and a leaf trap should be used. Plastic components seem to give satisfactory service with brines. All outside pipe runs need to be heavily insulated and protected from the weather. Concentrated brine, 18%, will freeze at temperatures below −9°F (−23°C) if it is not being pumped to the heat extraction circuit.

Materials and Corrosion

Materials used to transfer the hot brine should be nonmetallic where possible to minimize corrosion. One feature of a solar pond is that the storage zone normally contains little dissolved oxygen. As long as it not aerated, corrosion is minimized. However, any air leaking into the pipe and pump seals can add oxygen to the storage zone.

The plumbing for brine pumping can be effectively done in high temperature plastics. In all cases, glued joints seem to be preferable to threaded joints to prevent leaks. All plumbing should be adequately insulated thermally and supported at frequent intervals to prevent sagging to ensure joint integrity.

Pumps used for pumping brine have ranged from expensive fiber reinforced resin pumps to standard off-the-shelf cast iron units. They all can be made to work, but the following points need to be considered for solar pond applications:

- Pumps must have good seals to prevent air from being sucked into the system. Significant amounts of air discharged into the storage zone will rise to the pond surface, upsetting or even destroying the salt gradient.
- Salt solution will seep through most mechanical seals when the pump is not working. In direct coupled pumps, brine will creep along the drive shaft into the motor unless the shaft is fitted with a good, tight fitting flinger ring.
- Some means of providing variable liquid flow is necessary. This can be done by throttling flow or by varying pump speed. Pump speed can be varied by using a belt drive or variable speed motor and is the preferred way of controlling liquid flow. Another advantage of a belt drive is that brine coming through the pump seal will not contaminate the motor.
- Different metals within the pump are to be avoided. For example a cast iron pump body with a mild steel drive shaft driving a bronze impeller will corrode. If the body of the pump is cast iron, the impeller should be cast iron and the drive shaft should be stainless steel. Generally, it has been found that, whatever the pump body and impeller are made of, a stainless steel drive shaft performs best.

Filtration systems also need to be plastic with few metal parts. The same criteria for selecting pumps apply to any valves used with the equipment, such as backwash, bypass and recirculating valves. High temperatures pvc ball valves have been found to give good service with brine.

Brine heat exchangers external to the pond should be specified with copper-nickel tubing. Copper-nickel tubes also reduce the scale that can accumulate in heat exchangers because of their high thermal expansion coefficient. Hot brine has been pumped between the cast iron shell and copper-nickel tubes of a shell and tube heat exchanger at OARDC for six years with no detrimental effects. All-brass heat exchangers can also be used, and one such heat exchanger has been in use at the Miamisburg solar pond in Ohio for two years.

Heat Loss to the Ground

Recently, much emphasis has been put on the measurement of the heat loss to the ground underneath a solar pond. It used to be thought that the ground under and around a solar pond would act as a heat storage in conjuction with the pond storage zone. The disappointing performance in practice of the solar pond at the OARDC (maximum temperature 65°C) when compared with the predicted performance (maximum temperature 80°C) has been almost entirely attributed to unforeseen heat loss from the bottom of the pond to the ground. The thermal conductivity of soil changes appreciably with moisture content (sellers, 1965). The soil underneath the OARDC pond has a thermal conductivity of from 0.6 watts/m°C to 2.6 watts/m°C or more when wet. Thus, heat from a pond can be transmitted downward at a high rate, particularly in conditions of a wet subsoil and a high water table. Dr. Nielsen at OSU has done a considerable amount of measurement and research of temperatures underneath the solar pond at the OSU dairy center and has consistently shown thermal conductivities as high as 2.4 watts/m°C under that solar pond.

COSTS

The main objectives at OSU and OARDC on solar pond research were those of understanding the engineering and physical phenomena that combine to make a viable solar pond operation. costs incurred in the building and operating of such research projects can be totally misleading. However, detailed costs were kept of the construction phase of the Miamisburg solar pond, and they are presented below together with the cost incurred by Coreco of Canada in the building of their solar pond in Quebec, Canada (Crevier, 1982; Harris et al., 1982).

It can be seen that the advantage of building a large pond is a lower cost per unit area; so, larger ponds will produce cheaper energy. The estimate of the cost of energy produced by the Miamisburg solar pond is $ 9.40 per gigajoule (US$ 9.90 per million BTU).

TABLE 1

Owning and Operating Costs for Two Solar Ponds

Item of Cost	Miamisburg Pond 2020 sq m	Coreco Pond 700 sq m
Liner	22000	16400
Excavation	10000	10190
Salt	19400	4050
Heat Extraction	14270	4476
Miscellaneous	11800	6125
Totals	77470	41241
Cost per Square Meter	38.35	58.92
Annual Operating Cost		
Capital Recovery		3711
Salt		164
Labour		9100
Total		12975

FUTURE PROSPECTS

A large factor in the future of solar pond operation will be the implementation of an acceptable means of salt recycling. This is a major point in the minds of those consumers who are interested in the use of a solar pond, particularly when considered on a farm or private land. It is likely that on-farm use will predominate in the more northerly latitudes, simply because of the availability of land, machinery and labor. That is not to say that other industries will not make use of solar pond technology. The great advantage of the solar pond is that it has built-in long term thermal storage, which no other solar collection device can match. Many of the initial engineering bugs have been sorted out of solar ponds and performance can be predicted much more accurately today than could be done five years ago. In the lower latitudes and the tropics, solar ponds may well be used for electricity production, as they are in Israel today.

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