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TITLE SALT-GRADIENT SOLAR PONDS

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SALT-GRADIENT SOLAR PONDS

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INTRODUCTION

Salt-gradient solar ponds are large-area devices for collection and storage of solar energy at temperatures up to 90 C. Ponds may be useful because of their low cost and because of the large amount of thermal energy storage that they provide.

A salt-gradient pond is usually two to three meters deep. Salt (usually NaCl) is dissolved in the pond in such a way that the salinity varies from 20% at the bottom to nearly 0% at the top. This causes the density to increase with depth, so that convection is prevented when the water at the bottom is warmer than water at the top. Sunlight penetrating the pond warms the water at the bottom of the pond, and the nonconvecting water above acts as a transparent insulator to retain the heat. Approximately 400 kg of salt are required for each square meter of pond area.

The pond has three layers (Figure 1). The bottom layer is about 1 meter deep. Density and temperature are constant throughout this layer because it is convective. The convection is indicated by circular arrows on the diagram. This layer serves as the thermal storage of the pond. The middle layer does not convect. It is stratified, and is about one meter thick. In this layer, the salinity and temperature both decrease upward. This is called the "gradient" layer of the pond because both the salinity and the temperature form continuous gradients. The top layer of the pond is convective, and is often about 0.4 meters thick. In the top layer the temperature is close to the temperature of the air, and the salinity is kept as low as possible. The variation of salinity and temperature with depth are shown in Figure 2.

Salt continuously diffuses upward through the gradient. If the gradient were to end at an impenetrable boundary

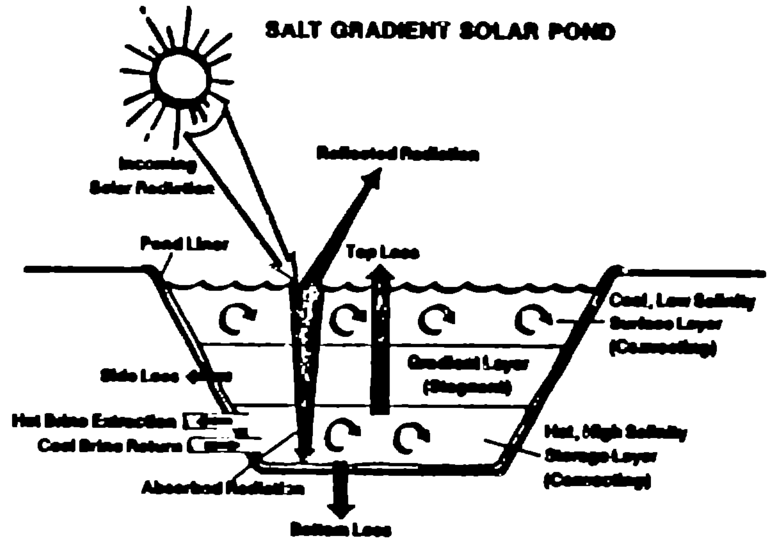

Fig. 1. Diagram of a solar pond.

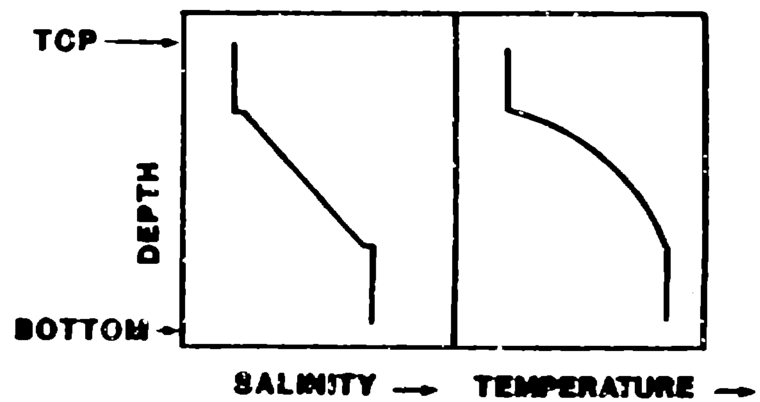

Fig. 2. Variation of salinity and temperature with depth.

(such as the air-water interface), salt could not diffuse through the boundary, and salt would accumulate at the boundary. Thus, we see that a salt gradient cannot end at either the bottom or the top of the pond. Therefore, convecting layers must exist at the top and bottom of the pond to bring salt to the end of the gradient at the bottom and to carry salt away at the top. The bottom convective layer is useful because it provides the thermal storage. However, the top convective layer serves no useful purpose. Any solar energy absorbed in this layer is simply lost to the air. Therefore, we wish to keep this layer as thin as possible. In practice, the upward transport of salt and the mixing due to wind make it difficult to maintain this layer less than 0.3 meters thick.

Diffusion through the gradient, which is about 1 meter thick, causes an upward salt transport of about 10 kg per square meter per year. As I shall explain later, other processes can cause the total upward transport of salt to be as large as 35 kg per square meter per year. The accumulation of salt at the top layer must be removed by flushing with fresh water or with water of low salinity, such as sea water. Salt must be added to the bottom layer of the pond about once per year.

The infrared portion is about one-third of the total incident solar energy. This portion is absorbed in the first few millimeters of the pond and the energy is lost to the air. Approximately one-third of the sunlight is absorbed in the gradient layer, and serves to maintain the temperature gradient in that layer. About one-third of the incident energy reaches the bottom of the pond. The theoretical efficiency of the pond is about 20%. In practice, 10%-18% of the incident solar energy may become useful thermal energy. Energy is usually removed from the pond by pumping hot salt water from the bottom layer through a heat exchanger located near the pond. However, a heat exchanger could be placed in the pond near the top of the lower convective layer.

CONSTRUCTION AND MAINTENANCE OF THE POND

Solar ponds are usually constructed with sloping side walls because it is difficult to construct vertical walls. Because there can be no diffusion of salt into a wall, the salt gradient near a wall must be parallel to the wall. If a wall is not vertical, a line of constant salinity will not be horizontal near the wall (Figure 3). This effect will cause convection cells to occur near the wall, with an added upward loss of salt and heat. These added losses are proportional to the length of the perimeter of the pond while other gains and losses are proportional to the area of the pond. These convective losses due to sloping walls have not been measured, but they are believed to be insignificant for ponds larger than a few thousand square meters.

All ponds built in the U.S. have used a plastic or rubber membrane to prevent the loss of water and salt into the soil. Workers in both the U.S. and Israel have studied the use of natural clay for the bottom of the pond, but there is little practical experience to tell us if this will be successful.

The gradient can be easily formed if the pond is first filled to the level of the mid point of the gradient with concentrated salt solution. An inlet diffuser (Figure 4) is then lowered into the pond to the position where the top of the lower convective layer will be. Fresh water is injected through the diffuser while it is pulled upward at twice the rate that the top surface of the water rises. The fresh water entering the pond from the diffuser will mix upward, and a salt gradient will be formed that approaches zero salinity at the point where the diffuser reaches the top surface of the water.

Organic growth can be prevented by dissolving a small amount of copper sulfate in the salt water before the gradient is formed, and by periodically injecting hydrochloric acid into the pond so as to keep the pond slightly acidic. Most windblown dirt will settle to the bottom of the pond. Leaves from trees and large pieces of debris should be kept out of the pond because they will settle to some depth in the gradient and possibly color the water. The pond should be sufficiently clear that you can see the print on a newspaper lying on the bottom.

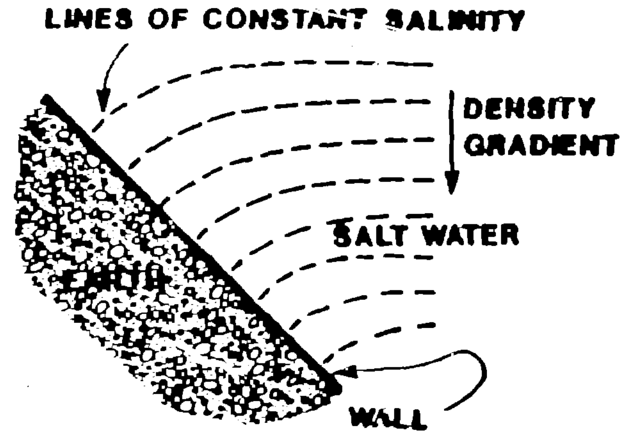

Fig. 3. Lines of constant salinity near an impermeable sloping wall.

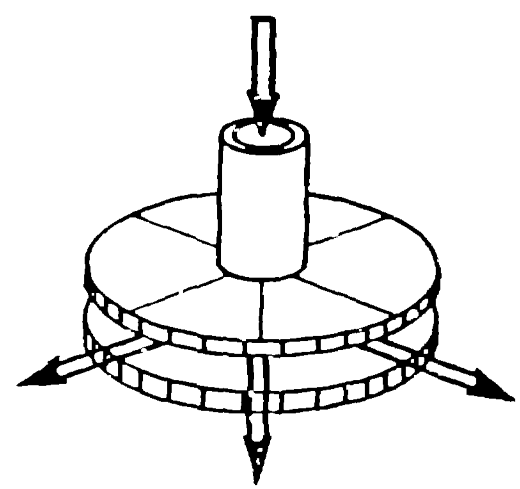

Fig. 4. Diffuser to spread incoming flow horizontally.

MIGRATION OF LAYERS

A salt gradient of 20% (by weight) salt per meter will not convect with a temperature gradient of 100 C per meter, and will not be greatly harmed even by divers going to the bottom. Thus, convective stability of the gradient can be assured. However, at high temperature gradients, the boundaries between the layers migrate in such a way as to erode the gradient layer from above and from below, thus enlarging the convecting layers. If the temperature gradient is sufficiently small, the boundaries of the gradient layer may move outward, enlarging the gradient layer. Figure 5 shows data from a pond that was operated with a weak salt gradient, which caused rapid boundary migration. The dots on the graph show the measured positions of the boundaries of the gradient layer.

At our laboratory, we have studied layer migration with a computer model, with experiments in laboratory tanks, and with an outdoor pond. We find that the heat flux across a boundary is determined by the temperature gradient near the boundary. The salt flux across the boundary appears to be a unique function of the heat flux. If the salt flux across the boundary is greater than that which can be removed or supplied by the salt gradient, mixing will occur at the boundary. The rate of mixing, and consequent destruction of the gradient layer, is reduced if the salt gradient is as large as possible. In Figure 5 the solid lines show the predictions of our computer model, which included entrainment of turbulence due to wind. Although the wind had a significant effect on the top layer, the dominant cause of the layer migration was due to the relationship of salt and heat fluxes at the boundaries.

Carl Nielsen of Ohio State University is attempting to control boundary migration by injecting small amounts of concentrated solution just below the upper boundary of the gradient layer while injecting small amounts of dilute solution just above the lower boundary, thus changing the gradient near the boundary to match the salt transport across the boundary. Other workers repair the gradient layer when necessary by injection of brine from the lower convective layer or dilute solution from the top layer while moving the diffuser up or down. Either method of gradient control transports salt and heat toward the top of the pond.

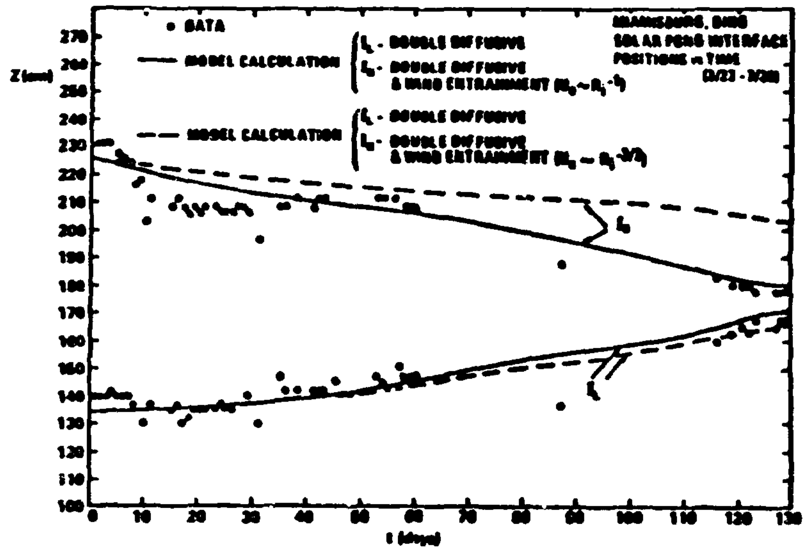

Fig. 5. Position of the measured and calculated positions of the upper and lower boundaries of the convective layer.

STATUS OF SOLAR PONDS

Solar ponds with area of 250 000 square meters are being tested in Israel for production of electric power. In the U.S., research has been done with the intent of using large ponds for electric power and smaller ponds for industrial process heat or heating and cooling of large buildings. However, in the U.S. no ponds larger than 2000 square meters have been tested. I now believe that ponds will be most economical in locations near salt lakes or the ocean, where salt has very little cost and where the discharge from flushing the top surface of the pond can safely be released without danger to the environment. Any pond will require monitoring of the gradient and maintenance to keep the gradient in place. A large pond may require no more effort for maintenance than a small pond. Construction costs, loss of heat through the sides, and convective losses due to the walls all become smaller, per unit area of the pond, as the pond becomes large. Thus, I feel that ponds smaller than several thousand square meters will not be useful. Because the losses of energy in conversion to electricity are so large, the net solar efficiency for conversion to electricity is about 1%. At a latitude of 30 degrees, four megawatts of electric power can be obtained per square kilometer of pond area. This can be economical if a naturally salty lake can be converted to a solar pond. Unlike other solar devices, a pond can deliver its energy at night, and a pond is not greatly affected by several days of cloudy weather. This is because a pond has a very large amount of thermal storage. I am therefore hopeful that ponds will be used, but I expect that they will be limited to large applications in naturally salty locations. At one time I had hoped that small ponds (2000-5000 square meters) could be used for heating buildings or for providing hot water, but I now believe that the maintenance required by layer migration may make small ponds too costly to operate unless we develop simple methods for controlling the gradient.

Workers in Israel have had some success with large ponds, but their work has not been published. I must regard any solar pond as a research project, and I caution you not to construct a pond with the intent of obtaining useful heat before you do experiments.

PHOTOGRAPHS OF PONDS (figures not printed in text)

I will show some photographs of ponds.

Figure 6 shows construction of a 2,000 square meter pond for heating a swimming pool. Figure 7 shows the finished pond. This pond has successfully heated a swimming pool, but the pond operators had several bad experiences with leaks and mixing of layers.

Figure 8 shows a small research pond to which a grain dryer was connected as a demonstration. This pond did not attain temperatures above 60 C because leaves from trees blew into the pond and stained the water.

Figure 9 shows a small research pond in a sunny climate with very dry soil. As an experiment, this pond was allowed to boil. The boiling of the lower convective layer stirred dirt from the bottom up into the water, and caused some mixing of layers, but did not otherwise harm the pond.

Figure 10 shows details of the sandbags and trench used to anchor the rubber membrane liner of the pond at our laboratory. Our pond was built by digging vertical side walls into soft volcanic rock. For research purposes, we wanted a small pond with vertical side walls so that it would simulate the operation of a large pond by avoiding the convection at sloping side walls. Figure 11 shows the side walls after foam insulation was applied. For research purposes, we wanted insulated side walls, so that the mixing of layers would not be influenced by loss of heat through the walls. The vertical side walls caused some stress in the membrane liner that eventually caused it to tear and leak. Figure 12 shows the installation of the membrane liner. The bottom of the pond under the liner was covered with sand to provide a smooth surface for the liner. Figure 13 shows the completed pond before salt and water were added. It is 15 meters square and 4 meters deep. Figure 14 shows the dumping of salt into the pond, and the instrumentation rack. Some rain water is in the bottom of the pond. Figure 15 shows the completed pond. The gradient was formed in one day and the bottom layer immediately began warming at the rate of 1 C per day.

Figure 16 shows a 7000 square meter pond at Ein Bokek, Israel. Experimental meshes are floating on top of the pond to prevent wind-driven waves. Workers in Israel have demonstrated generation of several hundred kilowatts of electricity from other ponds.

APPENDIX: FLUX RELATIONSHIPS

We find that the relationship between heat flux and salt flux at a boundary can be expressed as:

$$\frac{\rho C_p \beta F_s}{\alpha F_H} = 0.1455 F_H^{-0.13},$$

in which the left side of the equation is dimensionless but FH on the right side is in W/cm2. Data from other workers indicate values for the dimensionless ratio as low as one-third of our value. This relationship implies, for example, that with a temperature of 60 C and a temperature gradient of 0.5 C/cm, the salinity gradient must be 6.9x10-3 g/cm4 (0.54%/cm). For a smaller salinity gradient, the gradient layer will slowly shrink as the boundary moves into it. The rate of encroachment depends on the gradients, but is at most a few mm per day.

ρ = fluid density (g/cm^3)

C_p = heat capacity (J/g°C)

$\beta = \frac{1}{\rho}\left(\frac{\partial\rho}{\partial S}\right)_T$ = salinity expansion coefficient

F_s = salt flux (g/cm^2s)

F_H = heat flux (W/cm^2)

$\alpha = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_S$ = coefficient of thermal expansion (C^{-1})