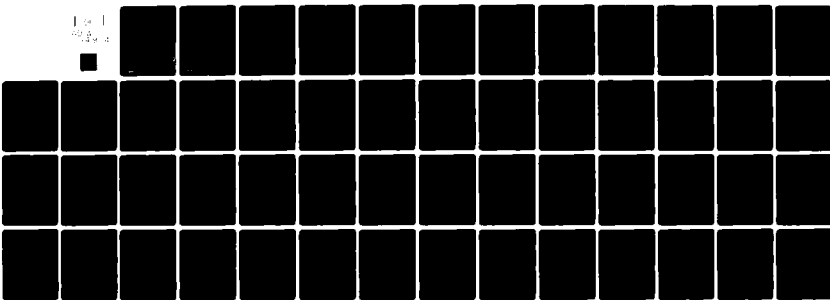


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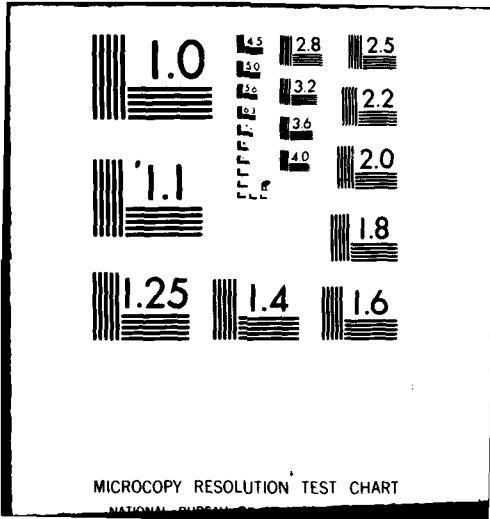
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# JASON

Technical Report  
JSR-81-26

October 1981

## ASSESSMENT OF SOME ENERGY TECHNOLOGIES ASSOCIATED WITH SOLAR ENERGY

H. D. Abarbanel  
K. M. Case  
S. M. Flatté  
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K. M. Watson

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H. D. Abarbanel  
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## 1.0 OVERVIEW AND RECOMMENDATIONS

In this report we present our study of three alternative energy generation concepts which employ solar energy in some part of the system. We will discuss these subjects: Salinity Gradient Solar Ponds, Osmotic Membrane Power Generation, and Thermochemical Storage and Transport. Our treatment of these items is not uniform. Our report will emphasize the ponds, briefly dwell on Osmotic Membranes and only touch on the third topic. This, in fact, reflects our assessment of the potential of the three concepts.

We have concluded that in specialized applications and in some special geographical circumstances (inexpensive local salt and land) the salinity gradient solar pond can be an economically attractive way of producing 80°C-90°C hot water or of generating electricity. Under most circumstances the costs of salt, land, and pond liner will make the solar pond not competitive commercially at today's fuel prices. As fossil fuel costs rise, the solar pond is sure to be a viable economic competitor in more markets.

Large scale power plants utilizing salinity gradient solar ponds are not going to be a wide spread source of thermal or electrical energy. Ponds do, however, appear to us to have a high potential for small-local and neighborhood-demand applications: heating of a block of buildings, crop drying, heating swimming pools, and the like. So we see

ponds as having a role as one of many resources we should have in our arsenal of methods to utilize the renewable solar resource.

Much is not known about the use of ponds over periods longer than a few years and, in this country anyway, there is only a tiny program directed toward understanding more of the basic phenomena of ponds with an eye toward improved efficiency and reliability. We can, if we choose, rely on the Israeli developments and purchase ponds from ORMAT, the Israeli company building ponds and turbines. We do not recommend that the U.S. adopt this posture, and are, instead, of the view that the Department of Energy should be involved in the development of this technology in two active modes:

- (1) Participate in and encourage the installation of large ponds at locations like the Salton Sea or the Army Corps of Engineers salinity control project in Texas. These are projects for the generation of many-megawatts of electrical power. Participation should be in the form of moral encouragement, of financial support of engineering development, and of monitoring systems.
- (2) Support a research program on scientific questions associated with ponds (gradient stability, maintenance of optical transmission quality, heat extraction methodologies, etc.). The program should support the building and maintenance over a multi-year period of a moderate size pond (perhaps as big

as  $10^4 \text{ m}^2$ ). The pond should be well instrumented for accurate measurement of salinity, temperature, density, and possibly fluid flow profiles. There should be a modest theoretical effort associated with this experimental program. There are several sites in the U.S. where pond research is presently underway (SERI, Argonne, Ohio State, and others). One or several of these locations seems an appropriate place to direct additional research support. An overall effort of 4 to 5 full time research physicists would provide a strong core. To the support of these people would be added the cost of building and instrumenting a medium sized research pond (perhaps as large as  $10^4 \text{ m}^2$ ) if that seemed a fruitful project to undertake.

It is our conclusion that power generation using osmotic membranes is not likely to be economically viable because of the high cost of membranes. Membranes have been extensively employed in the past few years in desalinization operations, and it is possible that membrane costs will in the future be such that for some specialized applications the concept may be quite attractive. We do not see any substantial research questions in this arena which should command the resources of the DoE. Since membrane development is proceeding in the commercial world without further encouragement appearing to be required, we conclude that DoE support is not presently called for here.

In the matter of Thermochemical Storage and Transport we have little to add to the reports of other investigators. The new information available to us consists of data from the experiments conducted by the Naval Research Laboratory--New Mexico State University collaboration last winter at the White Sands Solar Furnace. These experiments appear sensible and well executed. We see no reason to make a major increase in the DoE support of this work. It appears premature to pour major funding into this technology at this time, but it is enticing enough that experimentation at the present level ought to be continued. This should be carried out with the involvement and scientific support of the research staff at SERI. Again this is an idea that is not likely to be economically competitive for large scale power generation, but may be appropriate for specialized applications.

## 2.0 SALINITY GRADIENT SOLAR PONDS

### 2.1 Introduction

In 1901 Kalecsinsky discovered a lake (Medve Lake) near Zovata, Transylvania, with the remarkable property that in the summer the temperature at a depth of 1.65 m reached 71°C. Other such lakes have since been discovered. In 1958 one was found near Oroville, Washington, on Mt. Kruger. There the temperature was greater than 49°C at 2 meters. There are also such lakes near Eilat, Israel, in the Venezuelan Antilles, and the Antarctic (Lake Vanda). This last is most interesting since it is permanently under 3 to 4 meters of ice.

The explanation for these (meromictic) lakes is that they consist of fresh water lying over heavily salinated water. Normally, when the interior of a lake is heated by sunlight, convective instability leads to mixing and isothermalization. However, the salinization stabilizes the fluid.

It is an obvious idea to try to collect energy by means of artificial salt gradient stabilized ponds. It is this class of Solar Ponds that we consider here.

### 2.2 The Generic Pond

As seen in Fig. 2.1 the general idea is that there are three regions:

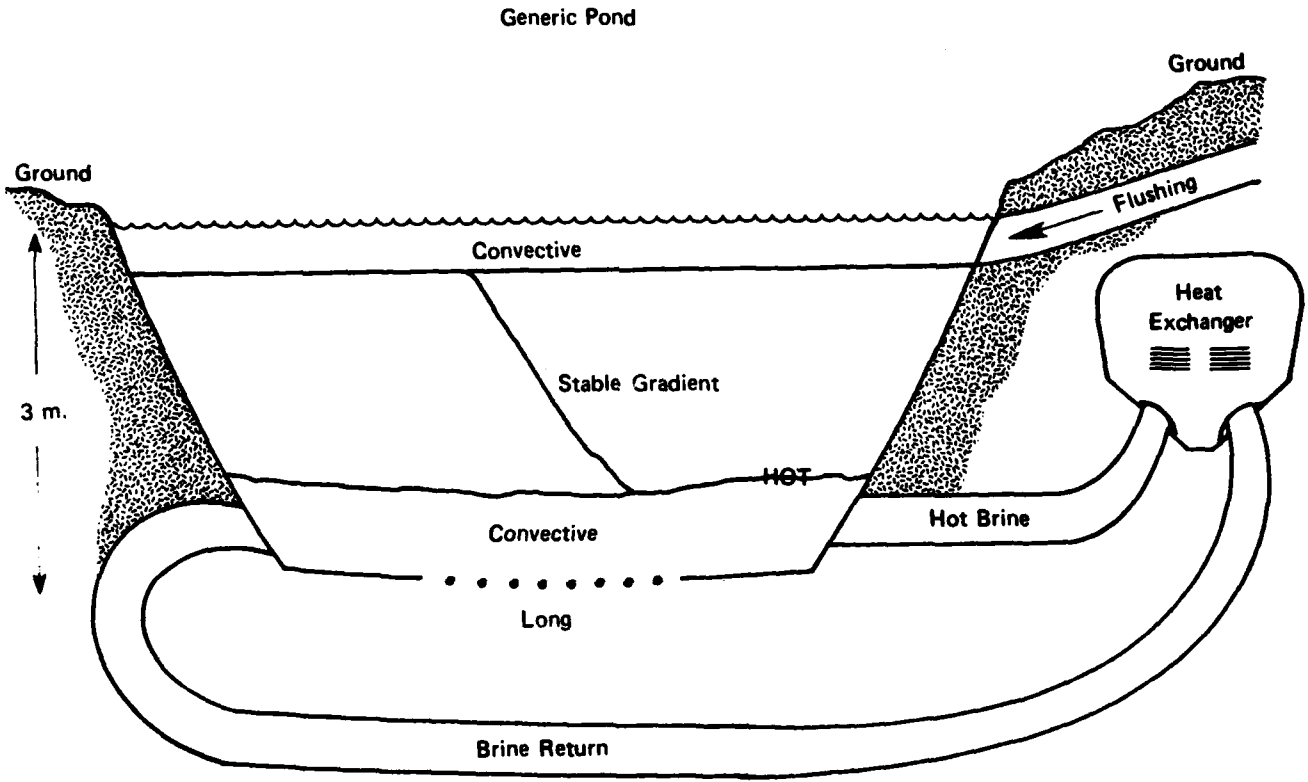


Figure 2.1 A GENERIC POND

- (1) A (hopefully) thin mixed top layer at essentially ambient temperature;
- (2) A stable stratified insulating region; and
- (3) A mixed hot storage region from which brine can be brought to a heat exchanger.

For environmental and economical reasons one must line most ponds with a plastic which can withstand the very high temperature brines generated in the storage layer. The weakest part of the liner, in practice, appears to be the seams between large segments of the plastic. Leakage from the liner damages the environment by salt pollution of the local ground water and is quite expensive because of the loss of high cost salt. Interesting exceptions to this worry are found at the Dead Sea, Salton Sea, and Truscott, Texas, sites.

### 2.3 The Israeli Program

The Israelis have had the strongest program in the field. In the 1950s they developed the basic relevant theory. In the 1960s there were demonstration experiments. Work was then stopped until the 1973 war. From this point on they were very active.

Some landmarks in development:

1975 - An 1100 m<sup>2</sup> pond, T reached 103°C, and a heat efficiency of 15% was achieved.

1977 - A pond near Eilat, 1100 m<sup>2</sup>, T max = 87°C.

1977 - Yavne Pond - 1500 m<sup>2</sup>. This pond was connected to an Ormat Turbine and for the first time demonstrated an ability to generate power (6 kw) 24 hours a day.

1978 - Ein Bokek Pond (near the Dead Sea). 7500 m<sup>2</sup>, depth 2.6 m, T ~ 93°C. This pond normally generates 15 kW<sub>e</sub> in the winter and 35 kW<sub>e</sub> in summer. However, in a peak load mode it can reach 150 kW<sub>e</sub>.

Future plans for electrical power generation:

5 MW Pond,	1/4 km <sup>2</sup>	1982
20 MW	1 km <sup>2</sup>	1983
20 MW	1 km <sup>2</sup>	1984
50 MW	2 1/2 km <sup>2</sup>	1985

The goal is to produce 50-100 MW<sub>e</sub> modules until there are 2000 MW<sub>e</sub> produced by ponds by the end of the century. This would then represent 20% of Israeli capacity. It is estimated that the cost will be between 5 and 15¢/kwh.

Note: There are some significant reasons for the relatively low cost estimate.

- (1) The Ormat turbine was designed to work at low temperature;
- (2) The salt and water (the Dead Sea) are essentially free;
- (3) The land is essentially useless--and therefore can be counted as free;
- (4) Leakage will not cause significant damage and so no liner is needed.

#### 2.4 The U.S. Program

There have been a number of small experimental ponds built.

The most useful for gaining information have been the following:

- (1) A pond at the University of New Mexico. This was 167 m<sup>2</sup>, 2.5 m deep and reached 108°C.
- (2) Two ponds at Ohio State University. These were both 2.5 m deep and had areas 200 m<sup>2</sup> and 450 m<sup>2</sup>, respectively.

The most interesting (for our purposes) is a pond built at Miamisburg, Ohio. It is the only one built to be useful--namely to heat a municipal swimming pool. It is 2020 m<sup>2</sup> in area and 3 m deep. The design goal is 10<sup>3</sup> MBTU per year at \$5-10/MBTU.

Cost Breakdown (1977 dollars)

Salt, 1100 tons at \$17.60/ton	= \$19,400
Liner and Installation	= \$22,000
Heat Exchanger	= \$ 6,800
Misc. Supplies	= \$11,800
Labor, excavation, etc.	= \$10,000
Total	= \$70,000

There are a number of omissions.

- (1) Land cost-taken as zero.
- (2) Salt replacement. This could be small ~ \$400/yr.
- (3) Water cost; taken as zero. Probably cheap in Ohio.
- (4) Brine disposal. No mention of this is made. Do they send it down the sewer system?

The important point to note is that the salt and liner were more than 1/2 the total cost. Rule of thumb general estimates are that the salt is about 1/3 and the liner about 1/4 of pond costs. These partial costs can, of course, vary since at some sites salt is essentially free and no liner may be necessary. The pond did develop some problems from which some important things can be learned.

- (1) The pond leaked. This occurred at the seams which bound together the plastic strips which made up the liner. Clearly considerable care must be taken to insure the seams are well bonded.

- (2) The heat exchanger was located within the hot brine. The tin-antimony joints corroded. It was found that other materials would not. Alternatively the heat exchanger could be placed outside the pond.

## 2.5 The Salton Sea Project

This is the most ambitious project currently being studied in the U.S. Support is from the State of California, Southern California Edison, and DOE. The initial pond is planned to be 1 km<sup>2</sup> in area, 3 m deep and generate 5 MWe. It is proposed eventually to use 20-50 MWe modules to build up to a 600 MWe capacity.

The advantages here are that the salt, the water, and the land are essentially free. There is a possible problem with leakage. Unless the ground can contain the brine a liner would be needed so as not to undo the desalinization of the Salton Sea which is also a goal of the project. If a liner is needed costs will probably be unacceptably high.

## 2.6 Lessons

- (1) From Miamisburg: It appears the small ponds can be competitive with oil.
- (2) From Israel: Cheap land, free salt and water, free disposal and no liner are necessary for large electricity producing plants.

2.7 Advantages Claimed

Modular Construction is possible. There is good storage. It is an inexpensive technology. There is peak power capacity.

It is also claimed to be an ecologically clean technology. This is only correct if one can insure containment of the brine. If the ground itself cannot do this, suitable confidence in liners will be needed.

2.8 Problems for the Ponds

- (1) The surface: since salt diffuses upward (slowly) the surface must be flushed with fresher water. This and the effects of winds tend to increase the surface layer thickness. This is bad and must be controlled, for the major absorption of solar energy occurs within the first few tens of centimeters below the surface.
- (2) The volume: this must be kept clean so that sunlight can penetrate.
- (3) Wall and bottom: heat losses through these should be minimized.
  - (a) for thermal efficiency,
  - (b) to avoid convective instability.
- (4) Overall: one must worry about the stability of the profile.

Conclusions

- (1) Small ponds: subject to clarification of some technical problems, small ponds seem feasible for industrial heating, agricultural drying, and heating small groups of houses.
- (2) Large ponds: these would be used for electricity production. There are two problems.
  - (a) scale effects are unknown,
  - (b) the applicability is very site-dependent. The Israelis seem to have a fine situation. For a Salton Sea plant detailed ground tests are needed. It is probable that there are not enough suitable sites to build enough plants to have significant impact on the U.S. energy supply.
- (3) Recommendations:
  - (a) we support the idea that at one or more sites in the U.S. the Department of Energy support long term research devoted to understanding the significant physical processes and the continued operation of a salt gradient pond. This latter task will require the construction, maintenance and operation of a research pond or ponds at selected U.S. facilities.
  - (b) proper instrumentation of such a pond is essential. Temperature should be measured to about 1 cm resolution. Salinity measurements should have a few cm resolution (for example, the University of

Washington needle probe-contact shown to us by Dr. Mike Gregg). Fine scale current measurements are needed. A current meter would probably be best (for example, the Jim Smith meter developed at the University of Washington).

(4) Specific research is needed to understand the following:

- (a) development of the upper convective layer and entrainment of the fluid from the gradient layer.
- (b) evolution and stability of the gradient layer.
- (c) horizontal transport in the gradient layer--wall effects.
- (d) the extent of internal wave activity and any resulting effect on the evolution of the gradient layer.

#### 2.10 Economics of the Solar Pond

The three principal costs in the construction of a solar pond appear to be for the salt itself, for the plastic liner for preventing leakage of the salt out of the system, and for the excavation of the site. We were briefed by Dr. G. D. Mehta of Science Applications, Inc. on these costs and report here the approximate magnitudes which should be useful for "back of the envelope" estimates of the expenses in pond construction. A useful rule of thumb is that when a pond is to be built from scratch, requires a liner, and needs salt brought to the site, more or less 1/3 of the cost will be for the salt, more or less 1/4 for the

liner, and less, about 1/10 for excavation. Clearly there is a wide range to be expected in these costs, but the mnemonic is as accurate as one needs to begin thinking of the expenses of a pond. A more detailed estimate in dollars per square meter, according to Dr. Mehta, is as follows:

Land	\$1/m <sup>2</sup> or \$4000/acre
Water	≤ \$1/m <sup>2</sup>
Excavation	\$4/m <sup>2</sup>
Liner (Installed)	\$10/m <sup>2</sup>
Salt	\$0-25/m <sup>2</sup>

For a minimum cost pond which has free land, free salt, and requires no liner one might achieve the pond construction for ~ \$5/m<sup>2</sup>. Paying for all of these will send the price as high as \$30/m<sup>2</sup>.

Taking the pond efficiency to be 2% overall (20% efficiency in conversion of sunlight to heat; 20% efficiency in the heat exchanger; 50% efficiency in the power plant) and taking 200 W/m<sup>2</sup> to be a good figure for the insolation, we expect about 4 We/m<sup>2</sup> of pond. The costs above then lead to \$1.25/We to \$7.50/We from a solar pond. These costs are arrived at without consideration of the cost of the power plant, so at best should be thought of as optimistic.

A more up-to-date idea of the actual cost of an installed solar pond comes from the estimates made by Marquess Engineering Company of

Springfield, Oregon, for a 4-acre pond at Clark College in Vancouver, Washington. For  $\$2.065 \times 10^6$  this pond with back-up heat pumps will provide 60% of the campus heating requirements. This pond-heat pump system costs  $\sim \$128/\text{m}^2$ . If the output were electric, that would come to  $\$32/\text{We}$ , which is 10-15 times the going installation rate for electrical energy. These costs include extensive new plumbing for bringing the heat from the pond to the buildings, so it clearly paints a pessimistic picture of pond economics alone. Nevertheless, it should stand as a reminder that real world uses of ponds will often require extra capital expenditures for hooking the pond into the system.

So there is a lesson here: if one has a small application and must purchase salt and liner, use your pond for local heating rather than for generating electricity. If no liner is needed and salt is free, electrical power generation may make sense for specialized application, but the ball-park figures above certainly indicate it won't really be competitive with present-day large scale coal or oil-fired or fission plants.

## 2.11 The Dynamics of the Salinity Profile

### 2.11.1 Introduction

A Salt-Gradient Solar Pond, whose temperature gradient alone would be unstable against convection, maintains a one-meter-deep non-convecting section by means of a stabilizing salt gradient. As a result of the gradients of temperature and salt concentration, there is

a motion (flux) of both heat and salt through the system. The conditions at the top and bottom of the non-convecting section are determined by convecting (mixed) layers, controlled at the top by winds and the supplying of fresh water, and at the bottom by the solar heating at the pond bottom and by the heat extraction process.

Theoretical analysis of the behavior of the non-convecting layer has been based on molecular diffusion of heat and salt, plus the possibility of catastrophic local breakdown of gradients due to double-diffusive convection. It is the purpose of this note to point out that experimental data on temperature and salt-concentration profiles in an operating solar pond require the existence of some other vertical mixing processes. The most likely possibility for this other process is dynamic motion on the boundaries (side-walls) of the pond, whose effects rapidly spread horizontally through the pond. Very small scale vertical convection processes are only a remote possibility. Internal-waves generated at the mixed layer interfaces and travelling into the non-convecting zone are a possibility, but such processes have not been directly observed experimentally nor calculated theoretically (since the internal waves must break to create mixing). On the other hand, side-wall induced processes have been observed many times in stratified-fluid experiments and have been theoretically analyzed in a number of cases.

The practical consequence of this conclusion is important. At present, considerable operator intervention is required to maintain the salt-concentration gradient in the non-convecting layer. A system to

measure the gradient accurately is combined with a system to add or subtract salt at any level, requiring accurate control of temperature and salt-concentration of the introduced fluid. The amounts of salt and fluid that must be added are significant, and the time required for the operation is costly. It is concluded that the proper design (and perhaps control) of the side-walls is likely to be the primary tool for maintaining the desired salt-concentration profile, thus reducing the necessity for dynamic intervention.

#### 2.11.2 The Constant-Flux Salinity Profile

A layer of water with a depth-independent vertical flux of salt satisfies the equation

$$\frac{\partial}{\partial z} \left[ K_s \frac{\partial S}{\partial z} \right] = 0$$

where  $S$  is the salinity and  $K_s$  is the effective diffusivity of salt. If  $K_s$  were a constant then the salinity gradient would be independent of depth.

The molecular diffusivity is a function of temperature (see Fig. 2.2). To a good approximation

$$K_s = K_o [1 + \alpha(T - T_o)] \quad K_o(20^\circ\text{C}) = 1.39 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$$

$$\alpha = 0.028$$

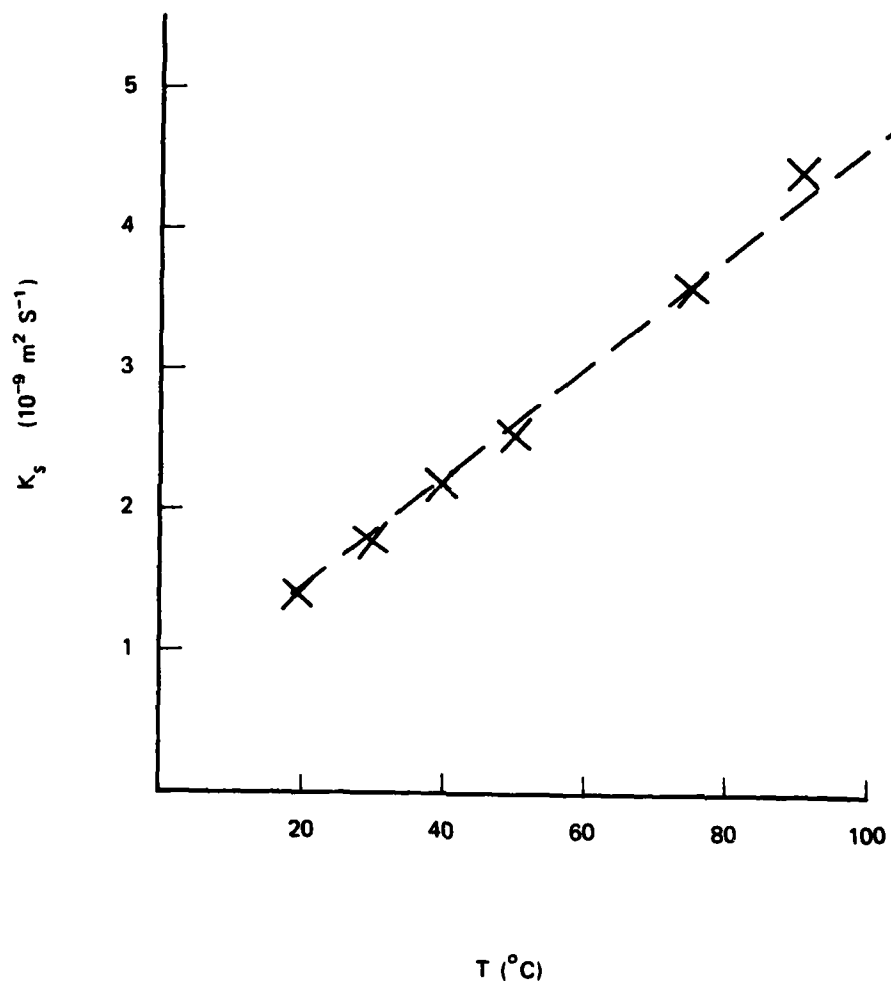


Figure 2.2 SALT DIFFUSIVITY

So that

$$\frac{K_s(90^{\circ}\text{C})}{K_s(20^{\circ}\text{C})} \approx 3$$

The treatment in this section assumes that the temperature profile is given (usually from measurements), thus avoiding all discussion of the dynamics of the temperature profile, which is complicated by solar-insolation and water-clarity issues.

In a solar pond whose non-convecting layer has temperatures of 20°C and 90°C at top and bottom, we would expect the salinity gradient to differ by a factor of three from top to bottom (larger at the top), if a steady-state (constant flux) had been reached by molecular diffusion. The gradient profile in between would be simply determined once the temperature profile was known. Figs. 2.3.a, b, c, show temperature and salinity profiles at two separate times for the solar pond at the University of New Mexico. The predicted profiles of salinity, based on molecular diffusion and the known temperature profile, with the observed salinities at 10 cm and 90 cm depths taken as boundary conditions, are also shown. In both cases the ratio of salinity gradient from 10 cm to 90 cm substantially exceeds the prediction (see Fig. 2.4). In addition, the amount of salt in the nonconvecting layer is substantially above the amount that resided there with a linear gradient (and appropriate boundary conditions). These observations require that the effective diffusivity of salt near the

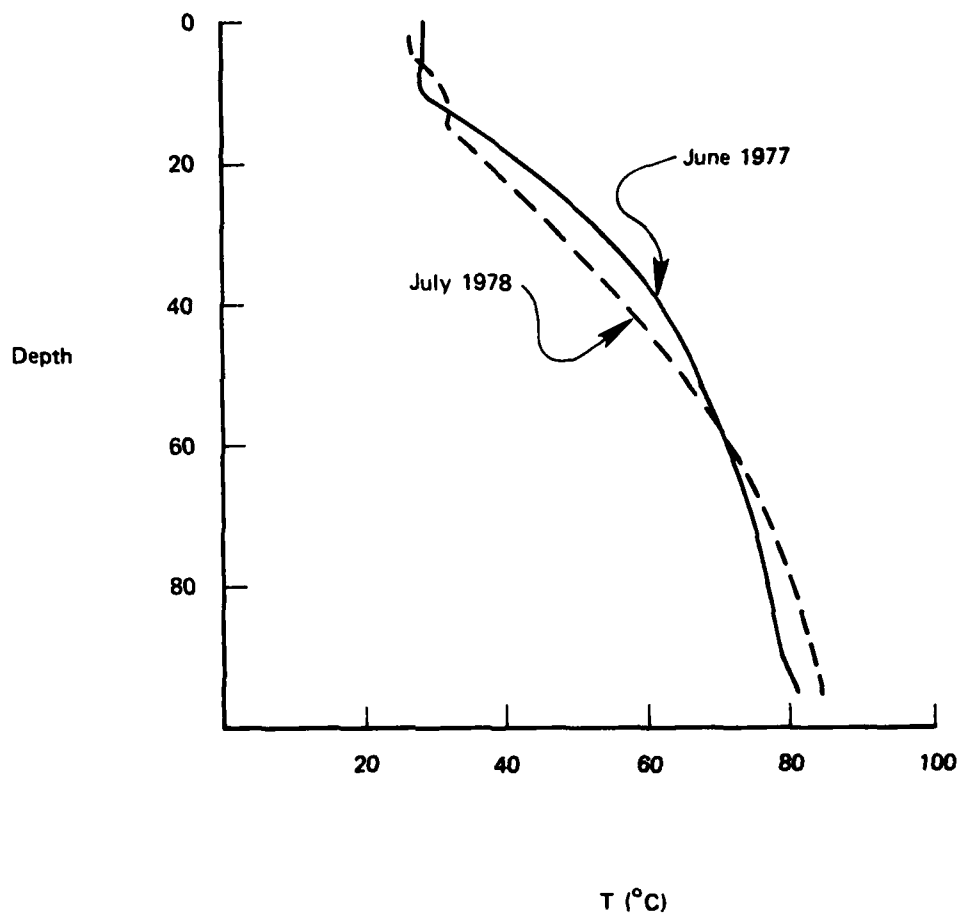


Figure 2.3a U. NEW MEXICO TEMPERATURE PROFILES

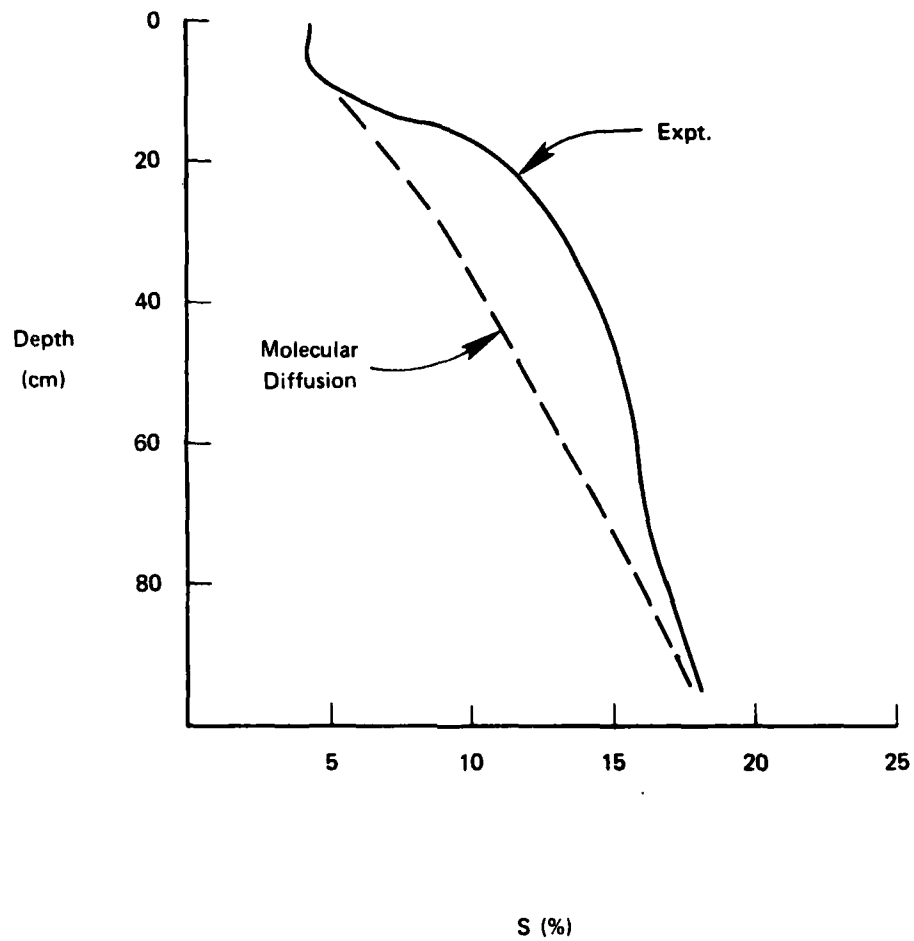


Figure 2.3b JUNE 1977 SALINITY PROFILE

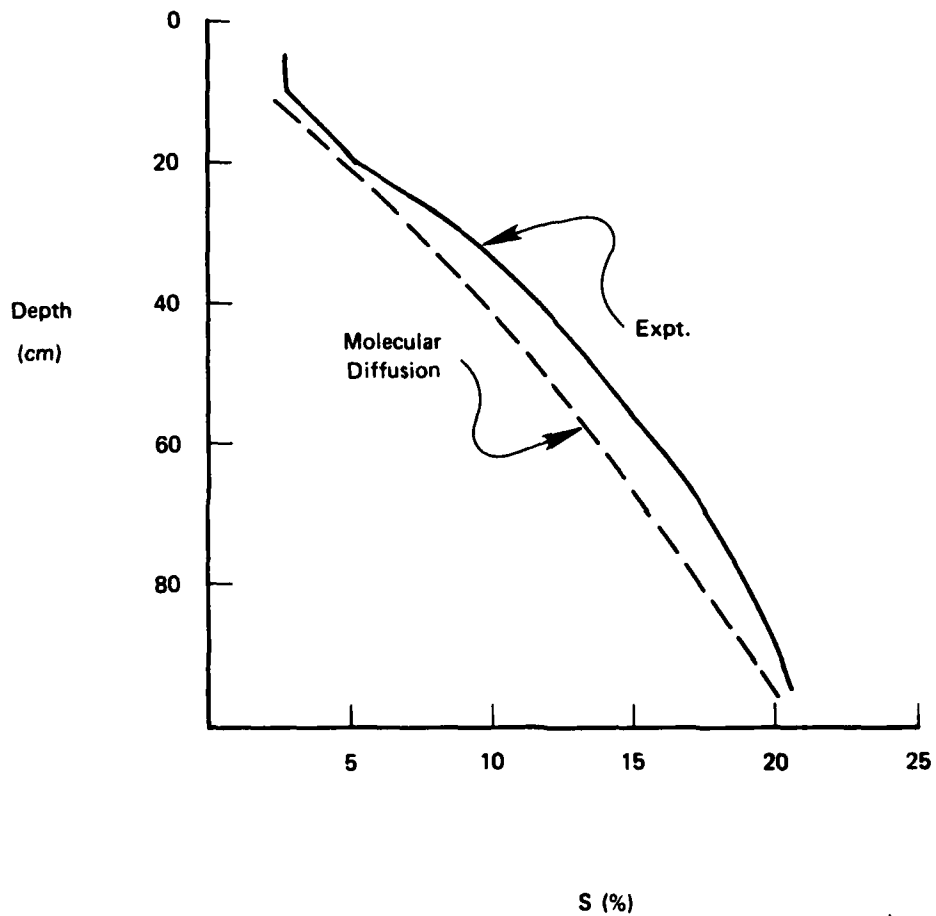


Figure 2.3c JULY 1978 SALINITY PROFILE

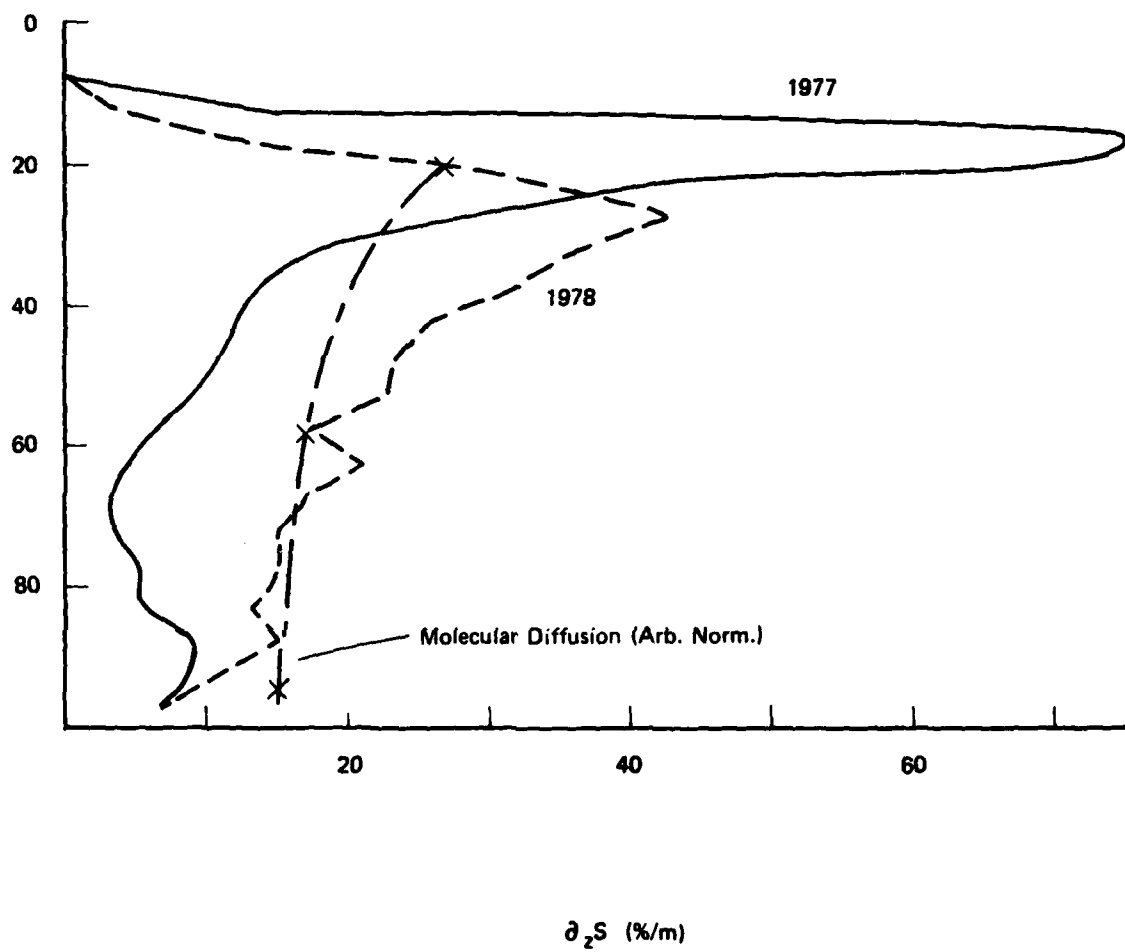


Figure 2.4 SALINITY GRADIENTS

bottom be very much larger than the molecular diffusivity--that is, some new vertical mixing process must exist, and preferentially near the bottom of the "non-convecting" layer. We may estimate the effective diffusivity as a function of depth by assuming a constant flux condition on the observed salinity profile. Fig. 2.5 shows the derived diffusivity. If the state is not constant flux, but is in the process of building up the bulge in salinity at intermediate depths, then the diffusivity curve would have to lie above the drawn curve.

### 2.11.3 Double-Diffusive Convection in the "Non-Convecting" Layer

After molecular diffusion, double-diffusive convection (DDC) has been the most studied process. The Rayleigh numbers are very large in solar pond situations, making the analysis simpler. It is clear that overturning may occur in layers whose density gradient is statically unstable ( $\beta\Delta S/\alpha\Delta T < 1$ ). Here  $\alpha$  is the rate of variation of density with temperature and  $\beta$  is the rate of variation of density with salinity.  $\Delta T$  and  $\Delta S$  are temperature and salinity increments over the same layer. Actually such layers might still be stable if the Rayleigh number were small enough (stabilized by viscosity), but this is not the solar pond case. For high Rayleigh number a statically stable situation may be unstable to oscillatory modes (DDC), but for instability one still requires ( $\beta\Delta S/\alpha\Delta T < 1.14$ ), a not too different requirement.

There is confusion and controversy in the literature about double-diffusive convection. The controversy arises from the following situation: Suppose a stable salinity gradient is heated from below. As

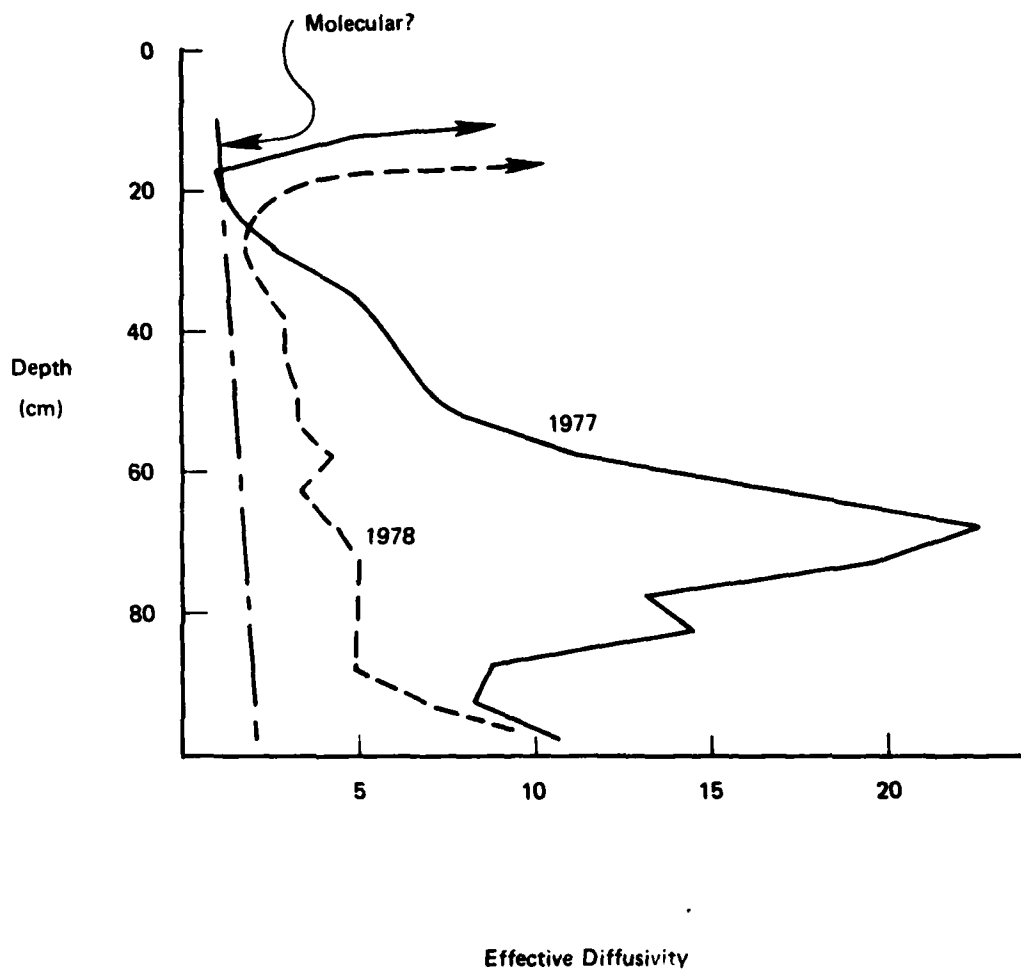


Figure 2.5 VERTICAL FLUX INDEPENDENT OF DEPTH

the system develops a temperature gradient, it remains stable until the temperature gradient satisfies the condition  $\alpha \frac{\partial T}{\partial z} / \beta \frac{\partial S}{\partial z} \approx 1$ . However, if the temperature gradient ever crosses the instability threshold, even due to a transient phenomenon, DDC sets in, increasing the effective diffusivity dramatically. The temperature gradient then can drop precipitously, and could reach a new and different steady state with a very reduced temperature gradient (reduced, in fact, by a factor of  $(Ra)^{1/3}$  where  $Ra$  is the original Rayleigh number). Whether this actually happens under a condition of nearly constant heat flux is not clear, however, because as soon as DDC sets in, the temperature gradient drops below the first stability criterion, but the heat flux is completely inadequate to sustain the second steady state until the temperature gradient has dropped by a huge factor. In solar ponds this factor is near  $10^5$ , so the layering should either quickly subside, or grow only very slowly. Experimentally, this prediction is borne out.

Therefore, the possibility that strong vertical mixing can be generated in a profile which is stable in the large scale is exceedingly remote. On the other hand, suppose we have a gross profile that is unstable to DDC over a region of, say, 15 cm. Then DDC predicts that the breakdown will result in one large layer of  $\sim 15$  cm depth, if no other factors are controlling. This follows from the fact that in the modal analysis, the most unstable mode is always that which has the largest vertical wavelength.

Often, however, several layers are seen to form simultaneously. In this case, horizontal gradients are controlling. The layers form with  $\beta\Delta S \approx$  horizontal difference in density from one end of the layer to another. (Note that if we are close to the stability boundary then we also have  $\alpha\Delta T \approx \beta\Delta S$ .) If the sides of the pond differ by  $1^\circ\text{C}$  from the water next to them, then a layer of a depth corresponding to a  $1^\circ\text{C}$  vertical variation will appear, if the gradients of salinity and temperature lie in the unstable region. In Fig. 2.6 the stability criterion as a function of depth for the profiles of Figs. 2.3.a, b, c, are shown. It is seen that the region around 60 cm depth in the June 1977 profile is substantially more unstable than the rest of the pond. The next day, layers  $\sim 5$  cm thick formed in that profile, as shown in Fig. 2.7.

If the pond walls are controlled to a smaller temperature difference, the layers will still form, though with smaller thickness, until the Rayleigh number drops below  $\sim 10^3$ . This will occur at a thickness given by

$$d_c = \left( \frac{g\alpha\partial_z T}{K\nu} \right)^{-\frac{1}{4}},$$

with  $K$  the thermal conductivity,  $g$  the gravitational constant, and  $\nu$  the kinematic viscosity.

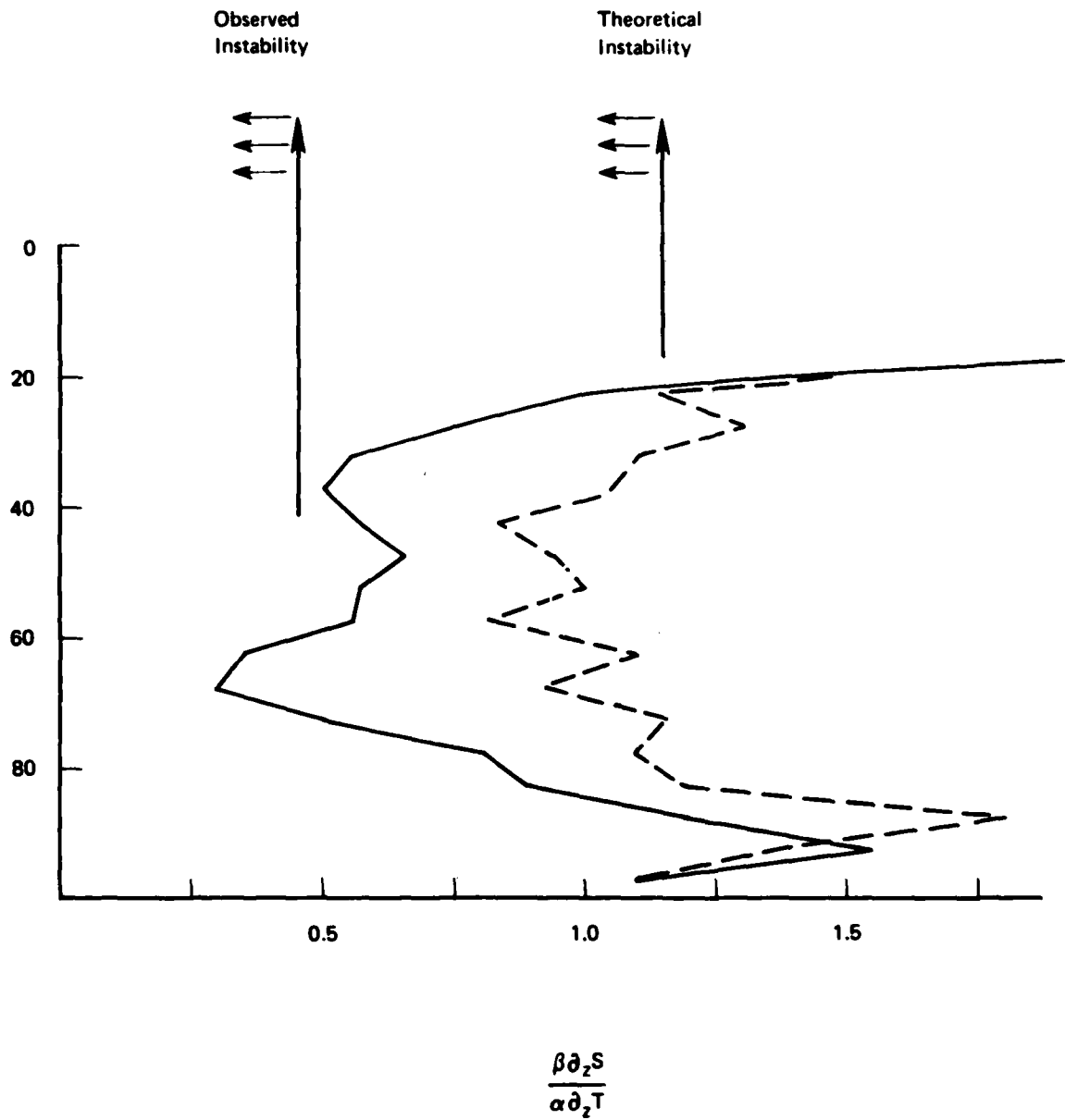


Figure 2.6 STABILITY CRITERION AS A FUNCTION OF DEPTH

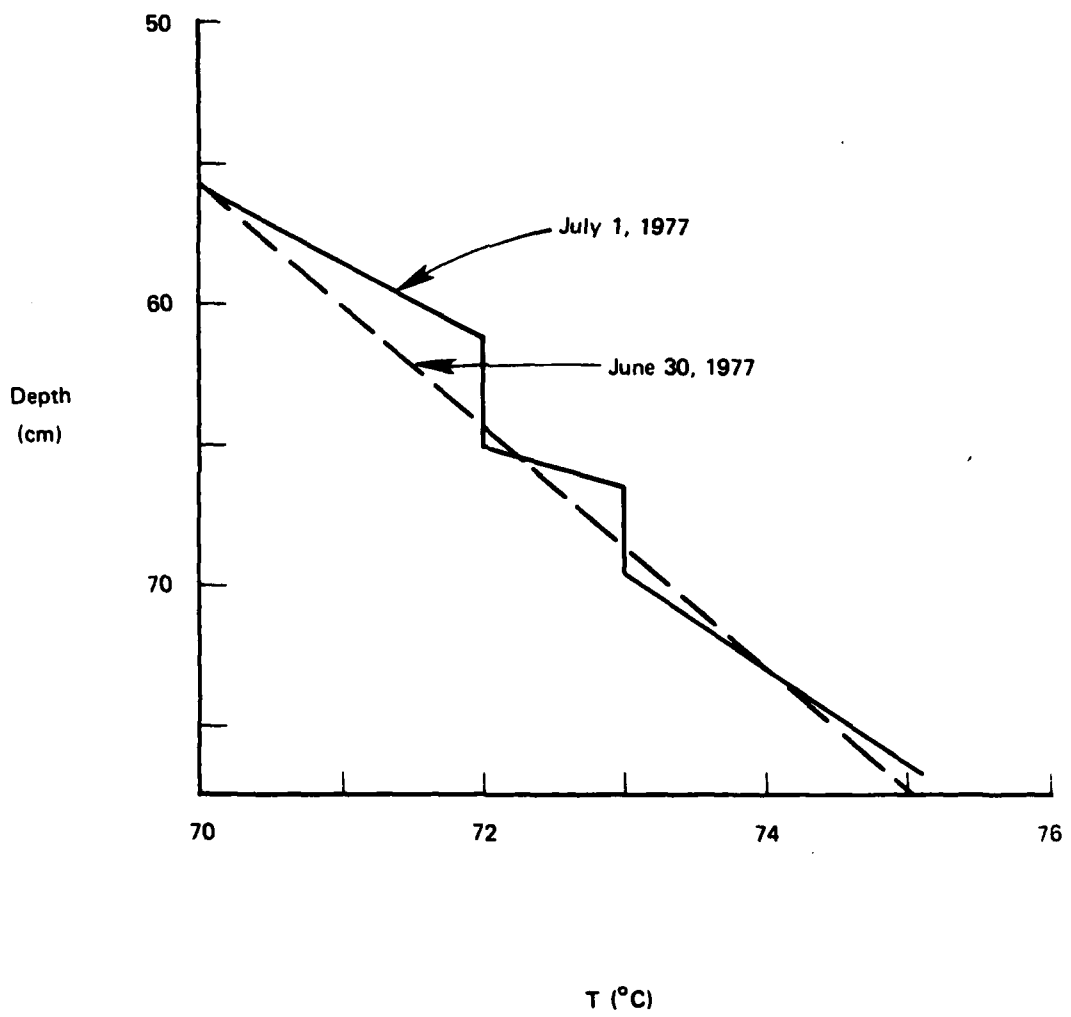


Figure 2.7 NEXT-DAY PROFILE (JUNE 30, 1977, JULY 1, 1977)

For a temperature gradient of  $20^{\circ}\text{C}/\text{m}$  (see Fig. 2.2) this would imply  $d_c \approx 0.25 \text{ mm}$  so that a difference in temperature between the side-wall and the fluid of  $0.005^{\circ}\text{C}$  could be withstood with no layering. This is hopeless, so we are left knowing that if the T,S gradients are in an unstable region there will be layering, and that the thickness of the layers is determined by the side-wall conditions.

The overriding conclusion of this section is that the profiles of salinity that are observed and that have long-term stability (months) cannot be explained on the basis of molecular diffusivity and DDC alone. Other vertical mixing processes are required.

#### 2.11.4 Side-Wall Effects

It was observed that a pond whose gradients are driven into the unstable region often develops several layers simultaneously. This is strong evidence that side-wall effects are operative, and the layer thickness is a direct measure of the density (probably temperature) difference between the wall and the central pond water at the same depth.

It is therefore almost certain that fluid motion is occurring near the side-walls when the vertical gradients in the pond are still in the stable region. These dynamic motions are the most likely candidate for vertically mixing the pond, and hence provide a source for the excessive diffusivities observed.

Experience with side-wall effects, for both instabilities and stable motion, has indicated that sloping side-walls are vastly more unstable, even without the introduction of gradients or fluxes of heat or salt at the boundary. (See, for example, Turner's book, p. 243 and plate XIX). Even vertical walls can be effective in producing layering with a substantial temperature difference (Ibid, plate XX).

The theoretical analysis of these effects is quite complex and probably sensitive to the assumed wall configuration and assumed boundary conditions. An important question is the size of a solar pond beyond which other processes for mixing will be dominant. Measurement of horizontal diffusion times in small ponds have yielded typical time scales of a few minutes; therefore even the largest contemplated solar ponds will probably be side-wall dominated. An experimental program to minimize the enhanced diffusivity due to the side-walls will do more than just avoid DDC instability; it will reduce the considerable salt-flux handling requirement and probably improve the heat-storage capacity of the ponds. Such a program should concentrate on the walls near the bottom of the non-convecting zone, and could involve varying the wall slope with artificially added (non-structural) walls, and perhaps horizontally corrugated walls.

The main thrust of the discussion in this section has been to point out the sensitive role played by side wall effects in producing layering and enhanced diffusion of heat and salt in the crucial gradient layer of a pond. The experimental evidence backing up our work is

clearly slim. It comes entirely from observations on the University of New Mexico pond. Those pioneering observations need confirmation and expansion. From the data available now and the analysis presented here one might imagine a remedy in the form of separators which isolate the side walls from the main volume of the pond. We are not able to conclude with any certainty that this will work, nor that it will not. Given the desirability of maintaining minimum thermal and saline transport, we instead wish to point out the necessity of actually running a properly instrumented research pond to answer crucial questions such as this one. Theoretical considerations in this type of project can only be suggestive guidance, not conclusive pronouncements.

#### 2.12 Recommendations

Our sense now is that though the basic physics of the solar pond is not complete, especially with regard to stability of the gradient layer and growth of the upper convective layer, one has a sufficient base to build and operate ponds of modest size, say  $\leq 10^4 \text{ m}^2$ . Clearly the Israelis are proceeding apace with their pond program, and their announced future goals are quite ambitious.

As we have emphasized several times in this section, the economics of ponds are not presently such that they pose a wide spread challenge to conventional forms of electrical power generation. In specialized circumstances they are an excellent alternative to conventional sources. One of these special circumstances is at Truscott Pond in North Central Texas where the Army Corps of Engineers plans to

generate ~ 2.2 MW<sub>e</sub> with solar ponds to run the pumps on a Salinity Control Project. The catch basins for the saline water will be the evaporation ponds for providing salt. Land is "free," i.e., already paid for, no liners are needed, and salt is plentiful--hence the project in the first place.

For generation of hot water (85-95°C) solar ponds seem like an excellent idea. The experiences of the Miamisburg, Ohio, municipal swimming pool, the Clark College (Vancouver, WA) heating system, and the possible Air Force Academy heating system should be closely watched. Other opportunities like these should be encouraged by the DoE.

Perhaps the best way to encourage the use of ponds in local heating, for low grade industrial process heat, and for agricultural applications such as crop drying, pig shed warming and the like, as well as meeting the need for research into stability issues, is to build and maintain a moderate size research pond at some site in the U.S. and to support a small theoretical program to interact with the experimental work. Basic research on ponds should be the primary goal of this program. A secondary but important task of the work should be a strong interaction with large scale projects such as the Salton Sea program and the Army Corps of Engineers' Truscott Pond work.

Important research topics to be addressed by a research pond program include the following:

- (1) Detailed temperature and salinity measurements in the gradient layer to determine the origins of and structure of local instabilities. Side wall effects as mentioned in Section 2.11 may be especially important in determining the most efficient modes of pond operation.
- (2) Materials questions especially connected with the lifetime of liners and heat exchangers.
- (3) Maintenance of optical transmission quality in long term open air operation.
- (4) Growth and stability of the upper mixed layer.
- (5) Stability of the pond under various heat extraction schemes.
- (6) Saturated Solar Ponds vs. Salt Gradient Ponds.

### 3.0 POWER GENERATION USING OSMOTIC MEMBRANES

#### 3.1 Basic Idea

If we separate two salty solutions of different concentrations by a membrane permeable to water but not to the salt, then a flow of water,  $J$  in  $\text{m}^3/\text{m}^2\text{-sec}$ , will occur from the solution of lower concentration to the solution of higher concentration. An osmotic pressure,  $\pi$ , which can be taken to drive the flow, is defined by imposing a back pressure  $P$  on the more concentrated solution and writing  $J = A_{os}(\pi - P)$ . By observing the variation in  $J$  with  $P$  we measure  $A_{os}$  and by finding the  $P$  for which  $J = 0$ , gives  $\pi$ . For a NaCl brine solution of 3% concentration--approximately that of sea water--  $\pi \approx 25$  atmospheres, and for commercially available membranes  $A_{os} \approx 4 \times 10^{-7} \text{ m}^3/\text{m}^2\text{-sec-atm}$ .

Now suppose we pressurize to pressure  $P$  a very briny solution and flow it by one side of a membrane while flowing on the other side of the membrane a less salty solution (see Fig. 3.1). During the passage of the flows through the membrane, the volume of the briny solution will increase by  $\Delta V$  due to water passing from the dilute solution into the briny one. Work  $\sim P\Delta V$  will be done which can then be extracted by a turbine. The volume change will be proportional to  $\pi - P$ ; that is, to the flow rate  $J$ . The power extractable will thus be

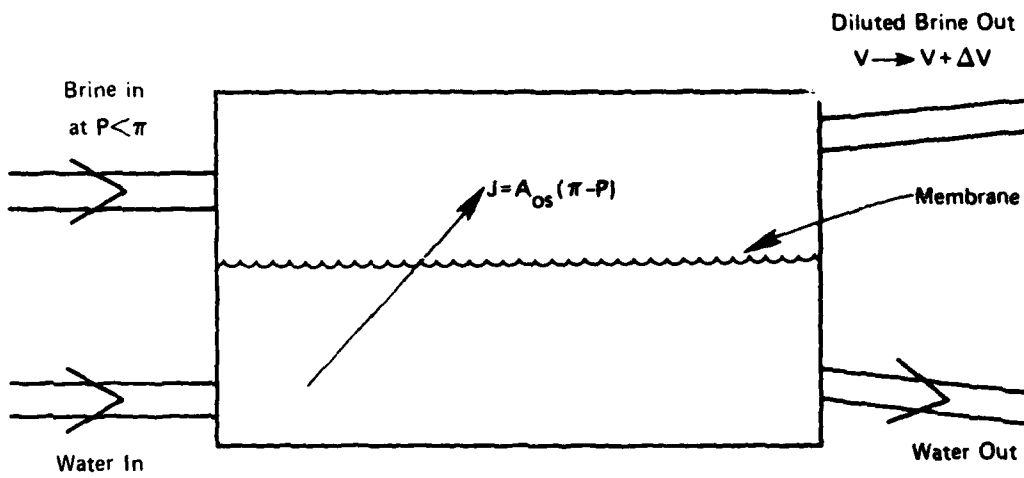


Figure 3.1 FLOWS OF BRINY SOLUTION AND LESS SALTY SOLUTION THROUGH A MEMBRANE

$$\text{Power} \sim P(-P)$$

which is maximized at  $P = \frac{\pi}{2}$ .

A more precise estimate can be made. If  $a$  is the area of membrane used, then the change in volume is given by

$$\frac{\Delta V}{V} = \frac{Ja}{F} \quad (3.1)$$

where  $F$  = flow rate in  $\text{m}^3/\text{sec}$ . Since the brine is diluted by the influx of water, the effective osmotic pressure is  $\pi/(1 + \Delta V/V)$ .

Using our expression for  $J$  we have

$$\frac{\Delta V}{V} = \frac{aA_{os}\pi}{F} \left( \frac{1}{1 + \frac{\Delta V}{V}} - \frac{P}{\pi} \right) \quad (3.2)$$

or

$$\frac{\Delta V}{V} = -\left(1 + \frac{\gamma P}{\pi}\right) + \sqrt{\left(1 + \frac{\gamma P}{\pi}\right)^2 + 4\gamma\left(1 - \frac{P}{\pi}\right)} \quad (3.3)$$

with

$$\gamma = \frac{aA_{os}\pi}{F} \quad (3.4)$$

We want  $\Delta V/V$  to be as large as possible to produce as much power as we can for a given  $\gamma$ , i.e., a given set of operating

parameters. From (3.3) we see that  $\Delta V/V$  grows slowly with  $\gamma$  and saturates at

$$\frac{\Delta V}{V} \approx 2(\pi - P)/P \quad (3.5)$$

for large  $\gamma$  :  $\gamma P/\pi \gg 1$  . So there is a limitation to the amount of power one can extract in this technology. In the next section we will use (3.3) to estimate how well one can actually do with such a system.

Once one has passed the two solutions past the membrane, the concentrated solution will be less concentrated and the dilute solution will be less dilute (unless it is fresh water). At some point one will have to concentrate the concentrated solution back to its original level and acquire more dilute solution. One can imagine several ways to do this: (1) simply add salt to the now diluted concentrate. If salt is inexpensive, and water is also, this may work just fine. (2) Take the diluted brine and run it into an evaporation pond thus using the sun to provide the potential energy lost during dilution. This requires the pressure head  $P$  to be lost and then to be recovered after concentrating the brine. So one begins with brine at 1 atm, pumps it to  $P \approx 10 - 12$  atm , runs it through the membrane manifold, and extracts work  $P\Delta V$  bringing it back to 1 atm. This is likely to be quite inefficient. There are also sizeable land costs for the evaporation ponds. (3) Use as a salt a material whose saturation density increases with temperature (  $KNO_3$  is an example). After passing through the membranes put the diluted brine into a solar pond (Section 2 above).

Because of the temperature gradient in the pond, the solution will be more concentrated at the bottom than the top and the brine will have been unmixed.

Dr. G. D. Mehta of Science Applications, Inc. suggested yet another method for using membranes for power generation which uses the changing miscibility of certain mixtures as a function of temperature to unmix a solution. The idea is to unmix the diluted "brine" after passage through the membrane manifold by changing the temperature of the high pressure brine. Then a physical separation of components is effected. The real advantage of this clever idea is that the high pressure of the working brine need not be lost and regained constantly. Unfortunately, no clear cut techniques for the separation of concentrated brine after the change in miscibility yet exist. Membranes for this purpose appear undeveloped at this time.

### 3.2 Economics

This is a very rough order-of-magnitude cost estimate section for osmotic membrane power. It does not replace the much more detailed analysis by G. Backus, "Technical and Economic Assessment of Salinity Power Concepts", available in preprint form from Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755; December 20, 1978. It also does not disagree with that analysis where they overlap.

If one puts aside the cost of land for evaporating ponds needed to reconcentrate the brine used in osmotic membrane power, then a major component of the cost is for membranes.

In order to extract work from the osmotic membrane power plant we must deal with the inefficiencies in the turbine which produces work  $P(V+\Delta V)\eta_t$ , with  $\eta_t$  the turbine efficiency, and in the pump which brings the brine up to pressure  $P$ . The latter requires work of  $PV/\eta_p$ ;  $\eta_p$  is the pump efficiency.

For the net work to be positive we require

$$\frac{\Delta V}{V} > \frac{1}{\eta_t \eta_p} - 1 \quad (3.6)$$

For  $\eta_t \approx \eta_p \approx 80\%$ , this means  $\Delta V/V \approx 1/2$ . This volume change requires  $\gamma = aA_{os} \pi/F \approx 4$ . Suppose we take  $\gamma = 9$ , a flow rate of 100 gallons/minute  $\approx 10^{-2} \text{ m}^3/\text{sec}$ ,  $A_{os} = 4 \times 10^{-7} \frac{\text{m}^3}{\text{m}^2 \text{-sec-atm}}$ , and  $\pi \approx 25 \text{ atm}$ . This means we will need  $a = 9000 \text{ m}^2$  of membrane surface. For these values  $\Delta V/V \approx 1$ , and the net power output

$$PF \left[ \left( 1 + \frac{\Delta V}{V} \right) \eta_t - \frac{1}{\eta_p} \right] \quad (3.7)$$

for this configuration is about  $50 \text{ kW}_e$ . To purchase membranes off the shelf from Universal Oil Products of San Diego costs  $\approx \$50/\text{m}^2$ , including the pressure housing. This means a cost of  $\$9/\text{Watt}$  for the

membranes alone. Roughly estimating the membrane to be 60% of an osmotic power plant, we arrive at ~ \$12/Watt for capital costs. Scaling the membrane prices estimated by Backus up to our \$9/Watt and adding his other costs (Backus, pp. 144-145) we arrive at \$14/Watt which is much the same as the estimates here.

### 3.3 Recommendations

The very rough cost calculation just done shows that osmotic membrane power is not a serious competitor to present day large scale commercial plants. It seems inappropriate, however, to dismiss it out of hand for specialized applications. For example, an isolated field station near the ocean or briny pool and a fresh water source might find it useful, indeed, to have a few kW power supply available even at \$10/watt installation cost. Since one can get about  $10^4 \text{ m}^2$  of membrane area for  $1 \text{ m}^3$  of physical volume, the size of such a unit is dictated by pump and turbine dimensions. Membranes which appear acceptable are off-the-shelf items.

Our recommendation then is to put some funds into the development and demonstration of a few kW osmotic membrane power plant. If the costs of \$10/watt are low by a factor of two, a 5kW pilot project would be \$100 K and given a few man-years over two or three years, a DoE investment of \$250-300 K could be an acceptable funding level.

#### 4.0 THERMOCHEMICAL STORAGE AND TRANSPORT

The basic idea here is to run an endothermic chemical reaction (for example,  $\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2$ ) using solar heat. The reaction products are then transported to another location or stored locally, and, when desired, the reaction is run in reverse to release the stored energy. The sun enters the cycle as the heat source; it is especially convenient because the temperatures needed to run the endothermic reaction require quite high temperatures (600 ~ 1000°C). Other sources of these high temperatures would work but probably be less efficient in the overall generation and storage scheme.

The reaction  $\text{CO}_2 + \text{CH}_4 \rightarrow 2\text{CO} + \text{H}_2$  has been extensively studied in the Solchem project by a team from the Naval Research Laboratory and New Mexico State University. In tests run in December, 1980, and January, 1981, at the White Sands Solar Furnace the reaction was run at efficiencies of 55-65% for conversion of solar power to chemical heat of reaction. Negligible side reactions occurred.

Writing in the Solar Energy Technology Handbook, Part A, Engineering Fundamentals (W. C. Dickinson and P. N. Cheremisinoff, ed.; Marcel Dekker, 1980), R. M. Mar and T. T. Bramlette write: "Since thermochemical energy-storage technologies are presently at an embryonic stage of development, one cannot seriously consider such systems for current use." We are inclined to concur, but not to be so pessimistic as these authors.

There are several detailed questions which must be addressed before serious consideration can be given to the application of this technology. Among them are (1) a detailed experimental study of reaction chemistry, (2) catalyst lifetime and eventual cost, and (3) study of heat exchangers and heat transfer in the proposed systems.

We are optimistic that continuation of the high quality, but moderate level, research program presently underway via Solchem and at the University of Houston is the correct route to follow, and it will lead to eventual specialized applications for the technology.

Using solar energy may be the wrong focus for this program. We understand that in Germany the  $\text{CH}_4$  + steam reaction is being used in conjunction with fission or fossil fuel plants for co-generation. It is reported that General Electric is much involved in this program. We urge the DoE to join its efforts with GE to explore the various ways in which thermochemical technology may be exploited. It seems premature to attach reality to grander schemes associated with solar initiated thermochemical reactions.

## 5.0 ACKNOWLEDGMENTS

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