1.0 OVERVIEW:

Solar Pond is a large area solar collector and storage medium which is essentially a water pool with reduced heat losses. It can supply heat up to a temperature of about 95°C. The Solar pond involves simple technology and uses water as working material for:

1. Collection of solar radiant energy and its conversion to heat.
2. Storage of heat
3. Transport of thermal energy out of the system.

A solar pond represents a low cost option among other solar systems because it uses indigenous resources, such as land, salt and water (1). It possesses thermal storage capability spanning seasons. Solar ponds have received worldwide recognition, as an alternative means of energy for electric power generation and industrial process heating (2).
1.1. HISTORY OF SOLAR POND:

The first recorded use of solar energy for heating a water pool was made about 2500 years ago when great Roman baths were heated by the Sun. The phenomenon of natural solar ponds was discovered by Von Kalecsinsky in 1902 (3) who reported that Madve Lagoon in Transylvania, in summer, had the bottom temperature approaching 70°C at a depth of 1.32 m. In this lake salt concentration was observed to increase with depth. This downward increase in salt concentration prevents the convection and renders the upper region of lake a partially transparent insulator to trap solar heat in the bottom region.

In an ordinary lake, the loss of heat is large because each small element of water, when heated, rises to the surface and exchanges heat with the atmosphere. In contrast, in the non-convective or salt gradient lake only the upper layers of water at low temperature can exchange heat with the atmosphere. Surface heat loss is therefore low. Heat loss from the lower regions to the surface is low because non-convective water has a poor thermal conductivity of 0.5 W/mK. Thus the bottom region of lake attains a high temperature. The salt concentration gradient and temperature gradients are referred to as "halocline" and "thermocline" respectively.

Following the discovery of Madve Lagoon, similar solar lakes have been discovered in other parts of the world (4). A hot lake located near Oroville in Washington State discovered in 1958 has a temperature around 50°C at a depth of 2m during mid summer. Natural solar lakes also have been found near Elate, Israel (5) and in the Venezuelan Antilles (6). and Lake Mahega (7). A natural solar pond has been found even under a permanent ice cover of 3m to 4m in the Antarctic (Lake Vanda) (8) exhibiting a temperature of about 25°C in its deep regions.
1.2. TYPES OF SOLAR POND

The conceptual design of first artificial solar pond first proposed by Bloch in 1948, was developed by Tabor in 1958 (9). The system was an artificial pond, of 1m deep having black bottom and salt gradient generated by filling the pond with progressively less dense brine layers, with maximum concentration at the bottom. Today the term salinity solar pond has been applied to a variety of artificial water bodies which collect solar energy and store it as thermal energy. These may be broadly classified into two categories

I. Non-conveclive solar ponds. 2. Convective solar ponds

In non-convective solar ponds the basic approach has been that heat loss to the environment is reduced by the suppression of natural convection in the water collector cum storage medium. The most documented type of nonconvective solar pond is salt gradient solar pond and is referred to as unsaturated salt stabilized pond.

In convective ponds, heat loss to the environment is reduced by covering the pond surface. The cover is transparent and the pond is of shallow depth and is often referred to as shallow solar ponds. In practice it could even be a water filled plastic bag glazed at top and having a blackened bottom insulated by foam or other thermal insulating materials.

Another form of non-convective solar pond is the saturated solar pond. It uses salts like KNO3, NH4NO3, and MgCl2, whose solubility increases rapidly with temperature in the pond, saturation of the salt concentration is maintained at all depths. The pond is hottest at the bottom region and the temperature progressively decrease.
from the bottom to the top. So progressively larger amount of salt is dissolved towards
the bottom. Owing to saturation at each level, the vertical diffusion of salt is checked
and the density gradient is stable. This promises the possibility of a maintenance free
solar pond.

1.3. SALTLESS SOLAR PONDS

Some other methods of suppressing convection have also been
investigated and several non-salt type of solar pond systems have been proposed and
tested. It includes gel or viscosity stabilized pond, membrane pond, honeycomb
stabilized solar pond.

In the nonsalt type gel or viscosity stabilised solar pond, the non
convecting layer is composed of a viscous polymer solution (polymer gel) partitioned by
a number of transparent films. The polymer gel has low thermal conductivity and is
used at a near solid state so that it will not convert.

Membrane stratified solar pond which is a body of liquid utilizes closely
spaced transparent membranes. However, since the liquids in the nonconvecting layer of
this pond are such as sugar solution or ethanol, the membrane space for suppressing
convection should be very small and a large number of high transparent films are
required.

Based on the work on convection suppression in flat-plate collectors,
honeycomb stabilized solar ponds have been investigated as another saltless alternative.
Typically, a plastic structure of vertical walls of 10-30 cm height in the shape of a
honeycomb is floated on top of fresh water. The cell spacing is such that convection of
air within the honey-comb is suppressed and the top of the honey comb structure is covered with a horizontal membrane to prevent dust and debris and heat is collected in the pond water.

Even though saltless pond concept holds promise, they have several drawbacks compared to the salinity gradient solar pond. In saltless pond the removal of dirt and debris, algal and other biological infestations once developed cannot be done by in situ cleaning and hence the pond transparency will get adversely affected. Which in turn will adversely affect the performance of the pond. In order to undertake the cleaning work to improve the transparency the structure has to be dismantled, cleaning operations performed and structure re-established and for this entire period, the pond will be inoperative. Whereas in a salt gradient solar pond in situ cleaning of algal and other biological infestation are possible with the application of algicides.

Of all the different types of solar pond the most widely experimented solar pond is the salinity gradient solar pond or non-convecting solar pond. Many salt gradient solar ponds have been designed constructed and operated all over the world and the results of their operational experiences with achievements and problems have been reviewed in the following pages.

1.4. LITERATURE REVIEW

The suggestion made by Bloch in 1948, in Israel, that an effective solar collector could be created by developing a density gradient in a pond triggered the activities connected with the design and construction of artificial salt gradient solar ponds and their experimental and theoretical investigations.
Bloch’s idea was translated into reality by Tabor (10) in Israel by establishing the first artificial salinity gradient solar pond in 1960. The pond was of size 25X25 m with 0.8m depth. This solar pond was constructed to study the physics of the solar pond and its economic viability. The end brines of the Dead Sea Potash works, at Sdom, which is rich in MgCl2 was used to fill this pond. It operated during September 1959 to April 1960 and attained a maximum heat storage zone temperature of 92°C. Leakage of the pond and erosion of gradient zone due to wind mixing resulted in emptying the pond in August 1960. However, with this pond, Tabor studied the basic problems of the solar pond such as solar radiation transmission, rate of diffusion of salt, condition for stability, method of safe heat, extraction, wind induced mixing, clarity, effect of evaporation loss, and about the optimum operating conditions for the solar pond. His work showed that the development of a salt gradient solar pond is a possibility.

The solar pond possibility was theoretically substantiated by Weinberger (11) in 1964, who analysed the Physics of the solar pond. He predicted the performance of the solar pond by solving the heat conduction and salt diffusion equations analytically for the transient temperature distribution. In this theoretical model he assumed that

1. an one dimensional model with or without LCZ and neglecting edge losses is adequate.
2. the top surface temperature of the pond is the ambient temperature.
3. the UCZ-NCZ & LCZ-NCZ boundaries are fixed.

He also made discussion on several parameters which affect the performance of a solar pond. He predicted that the solar radiation can effect a considerable rise in non-convecting ponds of about a metre depth and salt water at temperatures near 100°C can be withdrawn for utilization from the bottom of a solar pond. He showed that the
efficiency of the pond as a collector of solar energy is then greater than 20 per cent. He also established that the solar pond is maintained non-convecting by means of a salt concentration gradient with downward increase of concentration.

A computer model for solar ponds, using the method of finite differences was first proposed by Tybout (12) as a simple alternative approach to Weinberger's model (11). Tybout has incorporated periodic observations of solar radiation, ambient temperature and other variables without explicitly describing them as functions of time. He has discretised the pond depth into many equal layers and applied the heat conduction and radiation absorption for each layer for a given duration. This results in a system of equations whose solution is the temperature distribution inside the pond.

Tabor and Matl., 1965 (13) reported the construction of two more experimental ponds-one in the same location Sdom very close to the first pond and the other one at Atlith Salt works near Haifa. The second pond at Sdom was operated between June and December 1962. During this period studies on radiation measurement and salt diffusion inside the pond were conducted. This pond had also used the endbrines of Dead Sea and was abandoned due to percolation of underground water into the solar pond. The third experimental pond constructed at Atlith was of 25X55m size and 1.5m deep and was built on clay compacted ground and with clay compacted walls so as to avoid percolation of ground water into the pond. The collection efficiency of this solar pond was 12.5%. Bubbles due to gassing from bottom seriously disturbed the gradient and lifted mud particles from the pond bottom thus affecting the clarity of the pond and the pond became inoperative. Despite these setbacks, the research team of Tabor established the potentialities of the solar pond for energy collection, storage and heat extraction.
This first phase of the Solar Pond research in Israel came to an end by 1967 and after a lull period it was resumed in 1975. During this period when the solar pond activities were suspended in Israel, some studies on small solar ponds were initiated in Chile during 1970 (14) by Hirschmann, in USSR by Eliseyev, Usmanov and Umarov et al. during 1971 to 1973, (15-18) and in India by Jain during 1973 (19). Hirschmann explored the possibility of making solar ponds on natural flats - to collect Solar Energy for electric power generation, industrial heat and desalination. The USSR work consisted mainly of theoretical studies and small laboratory experiments, with the emphasis on temperature attainable and collection efficiency, in very shallow ponds. Jain(19) has achieved heat extraction from the bottom layer of an experimental pond, at a storage zone temperature of 80°C. This pond was of 1210 m² area and of 1.0m depth, and bitterns was used to establish the pond. The pond operation was discontinued in 1972 after two years of operation.

During the same period, the solar pond work was initiated in the U.S.A. by Nielsen and his coworkers. Nielsen and Rabl, 1975, (20) have made reports about the 300 m² area and 2.5m depth solar pond built at Ohio State University, Columbus. It was constructed with the aim of conducting research to understand the physics of solar pond, behaviour of materials and to conduct heat extraction experiments. This pond was constructed employing an excavation and sloping wall embankment and lined a single factory secamed, flat sheet of 0.8mm thick chlorinated polyethylene (CPE) as an exposed membrane.

Rabl and Nielsen, 1975, (21) developed a simulation model for the performance of a solar pond for space heating applications. The pond model was considered to contained two zones only, namely the NCZ and LCZ. It was assumed that the top of the NCZ had temperature equal to the mean dry bulb temperature of the
and the thermal properties of water and sod earth were considered to be equal and all radiation reaching the bottom was found to get absorbed there. The steady state temperature at any point in the pond was assumed to be sinusoidal and a closed lor, solution was obtained to predict this performance of a solar pond.

The radiation reaching a depth $x$, is estimated by the following superposition of four exponentials given below

$$H(x) = \gamma H_s \eta_n e^{-\mu_n x}$$

Where $\gamma$ is the coefficient of transmission

$\mu$ is the absorption coefficient

$H_s$ is the full radiation incident upon the water surface and $\eta_n$ is the empirical constants used for the four different wave length regions.

Bryant and Colhcck 1977 (22, have used the Rabl- Ntelsen (21) model to estimate the temperature of a solar pond suited to the climatic condition of London. They have predicted that a solar pond of area equal to the floor area of a residential house is required for its space heating purposes with a cost comparable to the cost of using gas for heating. They have also developed relation for the fraction $h(x)$ of solar radiation reaching any depth $x$ of solar pond from 1 cm to 10 m and is given as

$$h(x) = a - b \ln(x)$$

This relation gives values close to the experimental values and closely matches the equation developed by Rabl & Nielson (21).
Zangrando, 1979, (23) has constructed and operated a salt gradient solar pond of 167 m² area and 2.5 m depth using NaCl Solution at the University of New Mexico, Albuquerque. It was built in 1975 and was successfully operated for conducting experiments on gradient maintenance, heat extraction and stability with NaCl. A thermal efficiency of H percent has been achieved and the storage zone temperature reached its boiling point.

Zangrando (24) has developed a very simple and the most expedient way to establish and modify salt gradient in the pond. It does not require any additional storage tanks and was found suitable for ponds of any size. This method is called the redistribution method, has been tested at the University of New Mexico (UNM) pond, and at Miamisburg, Ohio for the installation of 2000 m² pond and proved to be quite successful.

Tabor, 1981 (25) restarted his work and in collaboration with Ormat Turbines Company, Yavne, demonstrated the technical feasibility of generating electric power from salt gradient solar ponds. To achieve this Tabor constructed a solar pond of 1500 m² area of 2.0 m depth. The pond was operated during the year 1977 - 79 and the pond had supplied hot brine at 90°C to a 6 KW (e) Organic Rankine cycle (ORC) turbogenerator. This was the first small scale solar pond power plant installed. The pond was emptied due to leakage through the exposed membrane liner used in the pond.

Immediately after this, Tabor and Doron, 1986, (26) have installed the world's first commercial scale solar pond power plant at Ein Boqek, on the shores of the Dead Sea. The solar pond power plant was commissioned in December 1979. The salt gradient solar pond was of 6250 m² area and of depth 2.55 m. The end brines of Deadsea was used to establish this pond. Solar pond supplied hot brine at a temperature of 73.4°C.
to the ORC Engine. The solar collection efficiency, Carnot's efficiency and electric conversion efficiency were found to be 11.10%, 9.4% and 5.7% respectively. The diurnal temperature variation of less than 1°C was noticed. To reduce the mixing on the top zone due to surface waves, floating nets were used on the UCZ. "Dilution Shock", method was practiced to maintain clarity of the pond. Sheets of EPDM (Ethylene Propylene Diene Monomer) was used as submerged membrane to line the pond. The pond was successfully operated in peaking mode in order to generate 150 KW (e) power from the pond, for a period of more than 7 years during 1979 - 1986.

Wittenberg and Harris, 1981 (27) have developed a solar pond of 2020 m² area and with 3.0m depth at Miamisburg, Ohio in 1978, using NaCl of 18.5% concentration with the aim of providing heat to a city recreational building and a swimming pool. Zangrando's (24) redistribution technique of establishing the gradient zone was employed. After one year of operation this pond had leakage due to the failure in the liner used in the pond and the pond was emptied.

Leshuk et al. (28) have conducted solar pond stability experiments on the thermo-haline systems. Their studies indicated that

1. The gradient zone is fairly stable. Stable temperature gradients ranging from 150-300°C/m were observed.
2. The only failure mechanism is the steady growth of the bottom and top uniform mixing layers during irradiation and subsequent cooling.
3. External disturbances did not appear to trigger spontaneous instabilities.
4. The intermediate portions of the gradient are extremely stable.
5. The rate of instability growth can be controlled by increasing initial salinity gradient.
Viskanta and Toor (29) have made analysis to predict the local rate of lar ener°y absorption in a pond using the radiative transfer theory. The physical model insiders absorption and scattering by water and internal reflection of radiation from the r - water interface as well as the bottom. The effects of pond depth, bottom reflectance id meteorological conditions on the local deposition of solar radiation were determined. hey found that a) use of reflecting bottom for a pond increase the total reflection from e pond (water plus bottom) system but at the same time causes a more uniform sorption of solar radiation throughout the pond and particularly increase the ^sorptions near the bottom. The radiation characteristics of a pond bottom must, be losen with care for optimum absorption and distribution of the absorbed energy and b) npurities and additives to water, to increase absorption of solar radiation will result in a lore non uniform deposition of the absorbed energy.

Kooi (30) has presented a steady state three /one salt gradient solar pond model with the assumption that the UCZ temperature is equal to the wet bulb temperature if the ambient. Here the solar pond was considered as a flat-plate solar energy collector ind hence Hottel-Whiller-Bliss form of equitions could be applied for a solar pond. The resultant efficiency of solar pond has been compared with that of a flat-plate collector. 3e has shown that, for a given surface temperature, heat collection temperature and isolation, there is an optimum thickness of the non convective zone 1.2m for which the heat collection efficiency is maximum.

Akbarzadeh and Ahmadi (31) have developed a computer model of a solar pond to suit the conditions of the southern part of Iran. Several computer simulations have been carried out to optimize the performance of an actual solar pond. The temperature variation of the pond for different overall efficiencies of the pond under various conditions has been studied. The studies indicate that solar ponds are reliable
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collectors for production of hot water all year round. During summer heat can be extracted from the pond at a rate of 50% of the annual average solar insolation and in winter it could be 10% and even then the pond temperature would be above 80°C. The operation of the pond is not affected by the daily and weekly changes in climatic conditions and even if there is zero insolation for one month (one month cloud), the temperature drops only by 10°C while heat is removed. The losses due to evaporation are not significant.

Hull (32) has proposed a different approach to collect solar energy, eliminating the difficulty of maintaining a salt gradient in a solar pond, by suggesting a membrane stratified solar pond. The membrane stratified solar pond is a body of liquid utilising closely spaced transparent membranes to quench convective heat transfer in the top part of the pond. Membranes may be configured as horizontal sheets, vertical sheets or vertical tubes. The steady state thermal efficiency has been estimated and has been found to be comparable to a well maintained salt gradient solar pond. The thermal behaviour was found to be similar to that of salt gradient solar ponds.

Hawlader and Brinkworth (33) have analysed the thermal behaviour of nonconvecting solar pond using numerical solution of the dynamic equations, incorporating detailed representation of the losses from the surface and using hourly meteorological data for a site in southern England. Results resembling those of Bryant and Colbeck (22) have been obtained. Compared to the analytical treatment reported by Rabl and Nielsen (21), numerical solution method gives greater freedom to incorporate appropriate initial and boundary conditions and more realistic representation of climatic conditions and load variations of the site.
Tabor (25) has reviewed the status of solar ponds and this review provides the status of solar ponds as proven viable large area collectors capable of providing both low-cost thermal energy and mechanical or electrical energy using state-of the art low-temperature turbo generators. Suitability of NaCl and MgCl₂ salt for solar pond use has been confirmed. Realistic pond cost figures have been analysed and they indicate thermal energy costs equivalent to US$41 per ton of fuel for a sunny climate. The ability of solar pond for power production in peaking mode operation has been highlighted along with other applications.

A small 156 m² pond of depth 3.0m was operated by Shah et al.(34), at the Agricultural Research and Development Center, Wooster in USA. NaCl of 19% concentration was used in the pond and the heat from the pond was used for the greenhouse heating of 165 m² floor Area. A brine source electric power driven heat pump was incorporated with the heat extraction system. Computer simulation model for the heating system was developed and was utilized for the analysis of the pond. This pond was contained in a plywood-lined rectangular excavation with vertical walls. It was fitted with a liner made of scrim-reinforced chlorinated Polyethylene (CPE) and it gave variety of leakage problems and it failed due to delimitation and leakage problems. To generalize the design of a solar pond heated greenhouse a computer simulation model was developed. The results were validated with experimentally measured data from the full scale OARDC solar pond and greenhouse. The solar pond was of rectangular cross section of 18.3 m X 8.5 m and 3.0m deep. It has been found that deep solar ponds are more efficient and Gradient zone depth of 1.0m was found to be effective in increasing the coefficient of performance.
Patel and Gupta (35) have constructed an experimental circular solar pond of 100 m$^2$ area, and with a depth of 2.0 m at Pondicherry, India. This is the first of its kind in a hot humid climate. The main objectives of the work were to gain experience in solar pond operation, to evolve criteria for the materials to be used, to get an estimate of construction, to monitor thermal performance and to study the physical behaviour of the gradient zone and the objectives have been successfully realised. Gradient stabilization was achieved with the hot brine injection and algal control was made using a submerged chlorinator. When the pond reached 70°C the side wall developed vertical cracks and an LDPE was inserted to arrest the seepage without affecting the storage zone temperature much and after two years of operation it was abandoned. A maximum storage temperature of 70°C and a minimum temperature of 50°C was noticed in an annual cycle. Solar Pond cost has been estimated as Rs. 300/m$^2$ and the cost of heat delivery was of the order of Rs. 0.20 per Kwh thermal.

Wang and Akbarzadeh (36) have investigated the theory of "falling pond" and its stability requirements so as to find its feasibility. Falling pond concept was first presented by Tabor (37). Based on this the possible maximum temperature gradient curves determining the regions of operation of stable falling solar ponds have been presented. They could obtain a value for the diffusivity of NaCl as of 1.6XH.H mVday which matched the relation given by Tabor and Weinberger(38).

Akbarzadeh and Mac Donald (39) have suggested a passive method for the replenishment of salt in solar ponds, based on the natural circulation of water caused by density differences. Careful system design ensures that this circulation will transport enough salt to the bottom region of the pond to compensate for its upward diffusion in salt gradient solar ponds. In this method no pumping installation or maintenance are necessary. A small laboratory pond was used to make these studies at the University of Melbourne, but this technique lacks experimental investigations on larger size ponds.
Hull (40) has presented a calculational procedure to determine the thermal efficiency of a solar pond with a diffusely reflecting bottom. Results of the calculational method indicate that decreasing the bottom reflectivity from R=0.25 typical of dirt to R = 0.05, has significantly increased the pond total thermal efficiency from 11.5% to 16.8%. He has also suggested several possible methods for reducing bottom reflectivity. Thermal stratification developed near the bottom of the pond during heat extraction helps to agitate the dust and dirt gently at the bottom and the suspension forms a suitable optical cavity leading to low reflectivity.

Crevier, 1982, (41) has developed an experimental solar pond for industrial process heat to dry grain at Montreal, Canada. Solar Pond of 700 m² area and of depth 2.0m was built in 1981. This pond had used EPDM, 47 mil as primary liner and polyethylene 5 mil as hack up liner. The pond attained temperature of 70° C. to be utilized for process heat application and the pond was operated between 1981 - 1984.

Hull et al., 1982, (42) have developed an experimental solar pond at Argonne National Laboratory, Illinois, of 1080 m² area, with a depth of 4.0m and 45° slope angle for walls and have used NaCl to establish the pond. The pond was lined with XR-5 Plastic sheet. The pond was operated for 5 years between 1980 to 1985. The temperature of the HSZ cycled between 40 and 77°C on annual basis in a climate with winter temperature as low as - 30° C. Heat extraction using both submerged heat exchanger and brine withdrawal using extraction diffuser methods were employed to extract heat from the pond. They found that both systems are reliable and the choice of which option to use will be determined mainly by the application. For grain drying, the brine extraction method appears to be better because it provides a higher heat exchanger effectiveness and lower cost.
Wang and Akbarzadeh (43) have made steady state analysis on a salt gradient solar pond and have presented a linear relation between the efficiency of solar ponds and the difference between temperature of pond bottom and the ambient divided by the average insolation. In this work, parametric studies on solar ponds have been made regarding the thickness of UCZ and NCZ and ground loss. They found that when thickness of the UCZ was reduced from 0.2 to 0.1m, the efficiency increased from 18.5% to 19.7%; on the other hand when the UCZ thickness was increased to 0.5m, the efficiency decreased to 15.5%.

In Australia, the Solar Pond activity began with the strong motivation of providing electricity to isolated communities in remote regions.

Collins and Frederiksen, 1987, (44) have constructed a 2100m² solar Pond of depth 2.1m, using NaCl as pond solution. This experimental Pond was made in Alice Springs in Australia in order to study small scale power production for remote areas and to gain experience on large solar ponds. Since it had density gradient instability it was terminated in 1984. Later another solar pond of area 1600 m² with vertical wall was built in 1984. The pond attained a maximum temperature of 80°C and has been used to supply heat to run a developmental 20-KW organic vapour - screw expander Rankine cycle engine and generator. 2.5mm thick HDPE liner was used to line the pond.

Golding 1983, (45) has developed two 900 m² area sloping wall ponds with bitterns, one unlined, of depth 2.6m as research facility at Seetham Saltworks, Laverton near Melbourne in Australia. Studies have been conducted on the effect of floating ring wave suppressers to reduce wind induced gradient erosion. Low temperature industrial process heat applications have been investigated.
Kishore and Veena Joshi (46) have presented a practical collector efficiency equation for nonconvecting solar ponds, by developing a steady state model, taking into account the heat losses from the surface and bottom of the pond. In this model efficiency equation does not depend upon the surface zone temperature but depends only on the geo-climatic parameters. Their work has shown that, depending on geo-climatic conditions, the thermal efficiency of a solar pond can deviate substantially from the value predicted by Kooi’s (30) equation.

Rubin and Benedict (47) have developed a mathematical model, applying finite difference implicit method so as to investigate the interaction among physical variables represented by various dimensionless parameters. A complete simulation of the heating up and heat withdrawal phases of solar pond operation has been accomplished, by solving one dimensional heat transfer equation. In this model though no attempt has been made to optimize the heat withdrawal, which decides a balance between maximum heat use efficiency and the demands for thermal energy, this model can be used to conduct such optimization exercises.

Katli and Bansal (48) have theoretically investigated the performance of a 3-zone solar pond with a diffusely reflecting bottom under submerged and brine withdrawal modes of heat extraction. The study includes the effects of the absorption of solar radiation in pond water and the multiple reflection arising from the reflection of radiation at the bottom and the reflection of light at the surface of the pond system. For the case of heat extraction at constant temperature, optimal efficiencies obtained by considering multiple reflections are approximately 2% higher than those obtained for single reflection.
Akbarzadeh, Parker and Wong (49) have developed a simple instrument to measure densities of brine at different depths in a solar pond. The system showed a sensitivity of 0.15 Kg/mv for salt concentration measurement and has been found comparable to the measurements made with a Specific gravity bottle.

Lund and Keinonen (50) have measured transmission spectra and extinction coefficients for different salt solutions. The effect of pond transparency on the performance of a community solar pond has also been discussed. Measured extinction coefficients of different brines were found to be between 0.4 and 2.7 m$^{-1}$ and depending on the value of extinction coefficient, suitable salt has to be selected for the particular pond.

Cengel and Ozisik (51) have determined the local rate of absorption of the solar radiation in a solar pond, for the direct component at angles of incidence from 0° to 75° with 15° intervals as well as for the diffuse components by the exact treatment of the radiation problem. The fraction of the solar radiation absorbed within the first 10 cm of water has been determined and ranges from 40 to 43% for various conditions.

Velarde, Cohen and Yuste (52) have analysed the feasibility of a solar pond for central Spain, for various choices of insulating layer thickness, convecting layer thickness, and pond surface to supply for the required heating load. They found that Madrid and its environs are quite acceptable places for useful solar ponds and the ponds in these places will give sensibly higher temperature than those in the USA.

Atkinson, Munic and Harleman (53) have developed an algorithm and described a procedure by which the movement of a scanning diffuser can be determined in order to modify the existing stratification within a solar pond. Qualitative observations of the dye injection tests indicate the diffuser must not be moved too quickly.
Hull (54) has presented a one dimensional analytical solution for the heat loss from the bottom of a solar pond to the soil that contains a moving water table. Results have been presented relative to the heat loss to a water table with infinite flow. In this treatment, the edge effects and horizontal heat conduction have been ignored. It has been found that the thermal efficiency of a pond is strongly depended on the mass flow rate of the water table.

Hull (55) has examined the use of Ammonium salts for salt gradient solar pond application, with a view to eliminate the environmental problems associated with NaCl, by incorporating the salt discharge from the solar pond into the fertilizer cycle of an agricultural system. Thermophysical and optical properties of several ponds of Ammonium salts have been found to be very close to NaCl pond. Ammonia outgassing was observed to be minimal and out gassing was curtailed by precipitating soluble phosphates. For a solar pond dedicated to grain drying, there was a good match between the land area required to grow the grain and the land area the pond runoff can fertilize.

Tabor and Doron (26) have discussed the lessons learnt over a period of 6-8 years with the salt gradient solar pond of 6250 m² area, 2.55m depth, constructed at Ein Boqek on the shores of Dead sea in 1979, with the aim of generating 150 KW (e) of peaking power. Factors that affect the performance of a pond such as pond clarity and control of wind induced surface mixing have been elaborately considered. Annual heat efficiency of 11% has been achieved. Thermodynamic conversion efficiency; electricity/heat was found to be 5.7%. The technical viability of generation of electric power from salt gradient solar pond has been successfully demonstrated with this pond. Though in this pond they have used single liner of 1 mm thick sheet of EPDM (ethylene-propylene-diene-monomer), it has been suggested to use multilayer lining, instead of single layer lining for large area ponds. Instead of vertical walls sloping walls have been used, with a ratio of 1:3.
Anati (56) has studied the salinity profiles in steady state solar ponds. It has been observed that the slope of the walls in a non-convecting rising solar pond is found to affect its advective-diffusive salt flux and hence the steady state salinity profile. The idea of rising pond is that the unwanted but unavoidable diffusing salt flux in the pond is taken care of, by adding to it another (advective) salt flux in the pond and in the same sense, but in such a way that their sum can now be counterbalanced externally. The changes of a pond's horizontal area with depth are considered and salinity profile has been found to be independent of this parameter.

Swift, Reid and Boegli, 1987 (57) have constructed a solar pond of area 3355 m$^2$ and depth 3.0m, using NaCl as pond solution, with the aim of providing industrial process heat, to a nearby food industry, at the University of Texas, Elpaso, Texas in 1985. A maximum temperature of 87°C has been attained in August 1986 and a minimum temperature of 68°C has been observed in February 1987. This pond was also used to generate electric power of the order of 100 KW from September 1986 onwards. Shelter Rite XR-5 plastic material was used to line this pond.

Nielsen, 1988, (58) "developed a 4000 m$^2$, 3m deep NaCl pond for food processing industry at Tennesse Valley Authority, Chattanooga, in 1982. The pond was operated between 1982 - 1986. It was lined with Shelter Rite XR-5 plastic film and leak was detected from the salt inventory and was attributed to the insufficient compaction of earth underneath the liner.

Pacetti and Principi, 1987, (59) have constructed a 25,000 m$^2$ solar pond at Margherita di Savoia Salt works in Italy in 1986, of depth 4.0m with a NCZ depth of 1.5m. This pond was meant for the continuous production of 80 m$^3$ of fresh water per day from sea water. This pond was capable of producing 50 KW of electrical power with
8 Hrs/day mean working period. Polypropylene lining has been used in this solar pond. Cesini et al. 1987 (60) have developed a solar pond at the University of Ancona, Ancona, Italy, inorder to investigate the feasibility of using salt gradient solar ponds for greenhouse and other agricultural applications. This pond has an area of 625 m^2 and depth of 3.5 m with 2:1 slope on sides and lined with 1 mm thick EPDM liner.

Okamoto et al. 1987 (61) have constructed a solar pond at Hokkaido in Japan, which is situated in very cold climate at high latitude of 41°N. This pond was circular in shape of area 1500 m^2, with a depth of 3.0 m of which UCZ = 0.2 m, NCZ = 1.3m and LCZ = 1.5m. The pond supplied hot water at 65°C to a factory in addition to using it for experimental studies.

Venegas et al., 1987 (62) have constructed a solar pond of 1375 m^2 area, 3.5 m depth at Zacatepec, Mor, Mexico. Plastic/clay laminate lining system was practiced in this pond. The pond was built with CH-type clay. This pond was used to produce 10KW electric power and to provide thermal energy to remote areas.

Tsilingiris (63) has made an estimation of maximum transmission of solar radiation within a body of natural water, with special reference to salt gradient solar ponds. It is observed that the Rabl-Nielsen (18) four exponential term transmission function didn't represent the upper radiation transmission limit for the direct beam and a 19 term transmission function has been proposed here for a favourable AM = 1 solar spectrum.

Mehta et al. (64) have construed and analysed the performance of the bittern based solar pond of 1600 m^2 area located at Bhavnagar, India. Actual solar radiation transmission measurements have been made. Very low thermal efficiency of
4.69% has been achieved which has been attributed to the heavy heat losses through the ground, poor transparency, and small NCZ thickness. The maximum bottom storage zone temperature reported was only 65°C. High velocity wind which caused the gradient erosion resulting in a reduced NCZ depth. A 100 micron thick HDPE film was used to line the pond as a submerged membrane.

Akbarzadeh and Manins (65) have conducted a series of demonstrative laboratory experiments simulating the possible instabilities in density gradient solar ponds that can be induced by absorption of sunlight by the sloping wall of the pond. It was found that the salinity gradient generated horizontal convective layers of thickness 10 and 20 mm and that the fronts of these layers advance with 0.2 to 0.3 m/hour. Enhancement of vertical salt transport also has been caused by these convective layers.

Tsilingiris (66) has developed a simple one-dimensional computer model to investigate the effect of various zone geometries and operational parameters on the thermal performance of solar pond in Greece. It is a three zone model in which periphery and edge losses have been neglected. A clear distinction between the submerged and brine withdrawal modes of heat extraction has been made. It has reported repassed that fixed heat extraction levels may lead to appreciable variation of LCZ temperature and hence it was suggested to maintain the heat collection temperature fairly constant by suitable control of heat extraction level, so as to supply heat to temperature sensitive loads. Tsilingiris found that it is very crucial to maintain as thin a UCZ as possible. It is found that the LCZ thickness does not directly influence heat collection efficiency.
Nielsen 1987 (60) have reported the construction of two solar ponds in the U.S.A. by the California Department of water resources at LosBanos, California. These ponds of 2000 m$^2$ area with 3.8 m depth have used mixed brains as pond solution. These ponds were designed to demonstrate solar pond use as a part of a desalination system and was demonstrated successfully.

Almanza el al. (67) have conducted experiments in order to obtain the same order of permeabilities of membrane liners, in large scale ponds with the use of Kaolinite clays. It was found that the mechanical properties of clays change under the influence of NaCl brine solution due to ion exchange. It was suggested that to obtain lowest permeabilities, a combination of low-cost thin plastic materials can be used between clay liners. However they opined that the behaviour of clay liners exposed to hot brines have to be studied in detail.

Tag and Hassab(68) have investigated the effect of wind suppresses on the performance of a small solar pond, operating in a windy, hot and humid conditions of the Arabian Gulf area. The results have shown that wind suppressers of the floating pipe type have slowed down the movement of UCZ-NCZ interface and prohibited any formation of localized convective zones. Even in hot climates thermal insulation has to be provided to operate a small scale solar ponds.

Srinivasan (69) has constructed a 240 m$^2$ bottom, area solar pond. The problems of erosion of gradient zone and formation of internal convective zones have been highlighted. Different heat extraction techniques have been studied and immersed copper heat exchanger has been found to be most convenient. He has proposed a two zone model for predicting the performance of this solar pond. He has developed a passive method of salt replenishment. The pond temperature had a variation between 50$^\circ$ C to 70$^\circ$C during its operation period from 1984 to 1989.
Newell et al. (70) have reported the construction and operational activities of the University of Illinois salt gradient solar pond. It has been demonstrated that solar ponds for low grade heating applications such as space heating and grain drying can be designed in a simple manner that required minimal maintenance. This pond is of 2000 m$^2$ area and lined with a HDPE liner material which is of 80 mil thickness and Low Reynold number diffuser was used to establish the gradient zone with the injection of fresh water. This pond has reached a maximum temperature of 70° C. Studies on pond clarity, salt recycling, piping system and instrumentation have been made.

Hassab and El-Masry (71) have made studies on the effect of edges on solar energy collection in small solar ponds. In small size ponds, the shading by the side walls adversely affects the collection and storage of energy. They have examined analytically, the influence of aspect ratio, pond size, convective zone thickness and the bottom surface reflectivity on the collection and storage of solar energy. They found that if the bottom reflectivity of a pond is zero, the LCZ thickness does not have any effect on solar energy absorption. If the bottom surface has reflectivity, the solar energy absorption increase with increase of LCZ thickness, due to increase in percentage of reflected energy being trapped in the LCZ. The monthly average daily solar energy stored in the LCZ was found to be maximum in June and minimum in December irrespective of the aspect ratio due to decrease of solar zenith angle as the time passes from December to June and vice versa.

Zhang and Wang (72) have developed a simple computer simulation method to study the ground heat loss and the heat recovery rate under varied combinations of the depth of the underground water table, the thickness of the lower convective zone, the heat withdrawal rate, and the thermal properties of the soil. The
effect of an insulation layer between the pond and the ground has also been examined, which is found to have a negligible effect on the mean storage zone temperature but the deviation in storage zone temperature has been considerably increased which could be used for higher amount of heat extraction during the summer.

Almanza and Lozano (73) have made mechanical and thermal studies on Bentonite clay in order to find its suitability as liner for saltgradient solar ponds. It has been found that the thermal conductivity and the permeability of this clay are better than Kaolinite clay and the absolute value of these properties have been found to be reduced by the influence of hot brine due to ion exchange, which make it a potential clay liner.

Jamal and Muaddi (74) have calculated the total solar energy at various depths in water by adopting two sets of data, namely the extinction coefficient of water in the spectral range of 300-2500 nm, and the solar spectrum at sea level in the same spectral range. A mathematical expression for the integrated solar energy as a function of depth in water has been derived.

Atkinson (75) has developed a solar pond simulation model which includes the capability for predicting surface ice growth. The model has incorporated the effect of salinity on freezing temperature and on the temperatures of maximum density. The calculations have been checked with data from a laboratory experiment. He observed that the maximum depth of surface layer is lower when ice calculations are included than without ice, the surface layer salinity is lower, with ice than without ice, the ice cover shields the pond surface from wind mixing.
Kleis and Sanchez (76) have developed an ultrasonic velocimeter for salinity measurements in a solar pond. Speed of sound in NaCl solutions with salinities from 0% to 21% by weight has been measured over a temperature range of 7-88°C. An equation has been developed to compute salinity from the measured speed of sound and the temperature for NaCl solution.

Raman and Kishore (77) have tested solar pond lining schemes consisting of combinations of clays and Low density polyethylene films (LDPE) in a solar pond liner test rig. The results indicate that LDPE film sandwiched between two layers of clay can be effectively used for lining solar ponds.

Lesino and Saravia (78) have explored the possibilities of using solar ponds in the mining industry. A short account has been given on the hydrometallurgical and salt production processes of interest from the point of view of solar ponds.

Tabor and Doron (79) have designed and constructed the largest solar pond in Israel at Beith Ha'Arava on the shores of the Dead Sea, with the aim of installing large scale solar pond power plant of 5 MW(e) capacity. This 2,50,000 M² pond was constructed in two phases. The first phase was a 40,000 m² solar pond and the second one a 2,10,000 m² solar pond filled with end brine to a depth 4.3 m and a free board of 0.7 m and with wall slopes of 1:3. HSZ thickness was maintained between 2.5 to 2.8 m and UCZ was found to have a variation between 0.3 m to 0.6 m and the NCZ was kept as 1.2 m. Initially with 40,000 m² pond the electric power was generated and later using both 2,10,000 m² ponds and 40,000 m² ponds 5 MW (e) electric power was generated and was coupled to the National electricity grid of Israel. Novel features included extraction of pond surface water to an auxiliary pond for condenser cooling, a low cost liner consisting of polyethylene and clay and a series of high velocity, low-fluid volume jets for gradient formation and repair. The efficiencies and total cost have been presented. An annual pond efficiency of 16% and pond cost of $7.1/m² have been reported.
Al-Marafie et al. 1991 (80) have constructed a 1700 m$^2$ area solar pond of 3.5 m depth, with 1:1 slope, at Kuwait Institute of Scientific Research, Kuwait, where severe weather conditions exist, with the aim of producing 25 m$^3$ of fresh water using Multistage flash Desalination unit. A net rise of temperature of 0.38°C/day has been noticed and a maximum storage zone temperature of 58°C could be achieved. The pond lining was achieved with PVC sheets of 500 micron thickness placed under XR-5 liner. The design of a novel diffuser for gradient establishment and correction has been developed. Severe mixing between UCZ and NCZ was noticed even for a wind velocity of 5 m/sec and no mixing was observed between NCZ-LCZ interface.

Mac Donald et al. (81) have presented a brief report about their 5 years operational experience of a bittern based solar pond in Laverton, Victoria, Australia with special attention to the design of an automatic instrument controller which forms an interface between an instrument and a data acquisition unit. Ring wave suppressers have been used to reduce surface wave mixing and they have developed a suitable and economic filtration system for cleaning Laverton bitterns. An average ground heat loss of 6w/m$^2$ through the bottom and a value 3 times this value was reported at the half the depth of the pond side walls (1).

Sherman and Imberger (82) have reported control strategies, to provide successful high temperature operation of Alice Springs solar pond year-round, which exhibited an average 15% solar to thermal conversion efficiency. The strategies, which consisted mainly of manipulating upper surfaced layer salinity and extracting heat from the storage zone were found to be well suited for automation. These strategies have been tested at the Alice Springs solar pond during the summer of 1989 and maintained temperatures in excess of 85°C for several months without any gradient stability problems. The thermal to electric efficiency of a heat engine with %%% gave an expected peak solar to electric efficiency of just over 1.5%.
Zangrando (83) has discussed the hydrodynamical issues such as mass and energy balance, formation, stability, and maintenance of the gradient layer; energy extraction from the bottom mixed layer, stability of stratified fluids to shearing flows; interface dynamics and wall effects that affect the performance of the solar pond as an energy collector and storage system.

Kanayama et al. (84) have constructed an experimental, 6082 m² area solar pond and its performance has been analysed. It is of circular shape with 44 m diameter, and 3.0 m depth. 8 cm thick Ureihane foam was used as insulation on side walls and bottom of the pond. Storage zone has reached a maximum temperature of 70°C in the first year and in subsequent years, it did not even reach this temperature due to contamination of the pond water. The collector efficiency reached a maximum of 30% in summer and negative values in winter. The calculated values have been found to compare well with the experimental values.

Collado and Lovvrey (85) have reported about their 10 months experience with two sea water storage zone small (16.6 m², 1.2 m deep) solar ponds operated as a source of warm sea water for mariculture facility. This study has confirmed that sea water - SZ solar ponds can consistently give useful temperature elevations. Storage zone temperature was found to be varying between 25 to 35°C, when the UCZ temperature varied between 10 to 20°C.

Akbarzadeh and Golding (86) have obtained of minimum stability criteria due to the presence of wall effects in salt gradient solar ponds. They have discussed the effects of sun-facing wall angle on incident solar radiation and the onset of instabilities in the form of local convective layers. When a sun-facing wall deviates from vertical, then the possibility of setting of the wall induced instabilities is found to be high and there is a
wall angle of maximum instability which is a function of local latitude and is called the worst wall angle and the instability decreases again when the wall angle increases beyond the worst wall angle. When the wall angle is less than the worst wall angle, the stability is rather high.

Messih and Newell (87) have reported about a device made for the measurement of density. Magnetic levitation of a weight is the basis for the density sensor and it has been successfully used in the University of Illinois solar pond, for brine density determination.

Motiani et al. (88,89) have reported about the one year performance of the 6000 m² solar pond at Bhuj, India. A maximum storage zone temperature of 99.8°C has been achieved and after arresting the leakage the pond was relined in June 1993. This pond has been delivering hot water at a temperature of 75°C, to a milk dairy unit at Bhuj. LCZ temperature has been maintained at 80°C. The designed flow rates are 70 m³/Hr for brine and 8 m³/Hr for hot water and on an average the pond heats about 60,000 liters of water every day.

Subhakar and Srinivasamurthy (90,91) have developed a simulation procedure in which a set of non linear partial differential equations of mass and energy balances of UCZ, NCZ and LCZ have been solved numerically, by the weighted average finite difference technique to predict the transient thermal performance of a saturated solar pond with facility that could be used for unsaturated solar ponds also. All thermophysical properties have been considered to be dependent on both the temperature and concentration. Hourly values of solar insolation, relative humidity, Air velocity, Ambient temperature have been considered as external parameters of the pond. Energy balance of the saturated MgCl₂ pond revealed a heat loss of 21% by convection, 22% by
evaporation of water and 31% by long wave radiation. Energy balance of the pond has shown that the top losses contribute to the maximum to the total heat losses. Influence of ground heat loss seems to be negligible of the order of 3.7%. A very low heat removal efficiency of 3% has been reported by this model. It has been concluded that saturated solar pond does not show any significant improvement in thermal performance over a similar unsaturated solar pond, apart from its stability.

Estevadeordal and Kleis (92) have numerically investigated the erosion of the dynamically stable gradient zone of a salinity gradient solar pond due to the extraction of fluid from the storage zone. The effects of fluid withdrawal rate, density stratification level, pond and diffuser geometries and diffuser placement have been considered. Under steady state condition a finite density difference has to be maintained across the lower interface in order to reduce the fluid entrainment from the NCZ layers. The extractor performance depends on its configuration. The double plate extractor diffuser with upper plate larger than the lower plate was found to have highest critical withdrawal rate with least erosion of NCZ layers.

Eghneim and Kleis (93) have proposed a two region model, verified by laboratory experiments, to include both accurate predictions of near-field turbulent jet behaviour and far-field redistribution and diffusion effects. They have concluded that the implementations of the two-region model would be an effective tool for standardizing gradient maintenance of salt gradient solar ponds.

The review of literature reveals that, though there has been quite a lot of technological development in the construction and maintenance of solar ponds since the construction of the first solar pond, there are many problems yet to be tackled. These problems can be broadly related to
1. the containment of the pond brine, as almost all ponds had leakage at sometimes or the other during their construction and operation.

2. the poor clarity of the pond water, due to biological growth leading to reduction in solar intensity inside the pond depths which in turn affecting the performance of the solar pond.

3. the gradient/one erosion, which affects the stability of the solar pond and reduces its solar thermal conversion efficiency which in turn requires periodic surface flushing and salt replenishment operations without disturbing the middle NCZ layers.

4. the extraction of heat from the storage zone of the solar pond without disturbing the bottom layers of the gradient zone.

In the present work an attempt has been made to address to these problems by developing techniques to overcome them in the 500m² solar pond designed, constructed and operated at Pondicherry. The results of the theoretical and experimental studies on the performance of this solar pond are also presented.