MAINTENANCE STRATEGY FOR A SALT GRADIENT SOLAR POND COUPLED WITH AN EVAPORATION POND

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ABSTRACT - In this paper, all the results presented were predicted for the first three years of operation. The daily variations of brine concentration in the Evaporation Pond (EP) of Tajoura's Experimental Solar Pond (TESP) and those based on different designs were predicted and discussed under different scenarios. The quantities of brine provided by the evaporation pond and that required by SGSP were predicted for both cases of surface water flushing (fresh water and seawater) under the different design conditions. The quantities of salt that can be contributed by (EP) were predicted to be in the range of 20% to 40% during the first year and 45% to 95% during the third year depending on the design selected. Comparing the percentage of salt provided for different designs, it can be clearly seen that the Autumn design presents a favorable condition. It provides a reasonable percentage reaching 79% in the case of fresh water surface flushing and 93% in the case of seawater surface flushing. Under the prevailing weather conditions of Tripoli, the results have shown that in addition to the higher flushing quantity required during the Summer, flushing is needed more frequent. It was predicted that the number of flushing varies between five times per month during the summer to two or three times per month during winter. Also, the study predicted that the quantity of seawater surface flushing is bigger than that of fresh water.

1. INTRODUCTION

Salt gradient solar ponds (SGSP) present an attractive method of collecting and storing solar energy on a large scale. A SGSP consists of three distinct zones, the Upper Convective Zone (UCZ) of thickness varying between 0.15 and 0.30 meter, which has a low and nearly uniform salt concentration. Beneath the (UCZ) is the Non-Convective Zone (NCZ) of thickness, which varies between 1.0 and 1.5 meter and has a salt concentration increasing with depth, and it is therefore a zone of variable properties. The bottom layer is the Lower Convective Zone (LCZ), also called the storage zone, which has a thickness varying between 1.0 and 2.0 meter and has a nearly uniform high salt concentration. The salt gradient zone (NCZ) is the key to the working of a SGSP. It allows solar radiation to penetrate into the storage zone while prohibiting the propagation of long wave radiation because water is opaque to infrared radiation. The zone suppresses global convection due to the imposed density stratification. It offers an effective conduction barrier because of the low thermal conductivity and the zone thickness, which averages over 1.0 meter.

A (SGSP) located in Tajoura to the east of Tripoli has been designed and constructed by (CSES) in joint cooperation with a Swiss company as an experimental facility. Tajoura's Experimental Solar Pond (TESP) consists of a main SGSP with a surface area of 830 m^2 and a total depth of 2.5 m and an evaporation pond (EP) with a surface area of 105 m^2 and 1.5 m depth. The salt concentration profile is constructed with three zones, the (UCZ) of 0.30 m thickness and a salt concentration of about 41 Kg/m^3, the (LCZ) of 1 m thickness and salt concentration of 256.94 Kg/m^3. Separating these two zones is the (NCZ) of 1.2 m thickness and variable salt concentration. The pond, fully equipped with systems to monitor all relevant parameters, is designed as an experimental facility enabling the investigation of various aspects of pond performance.

There are a number of difficulties and limitations that affect the performance of solar ponds, and in some locations limit their use, were recognized and several schemes for solution have been proposed to eliminate or minimize their effect. These problems include, among others, salt diffusion from LCZ to UCZ, wind mixing, evaporation, dust and dirt falling on pond surface. Some of these problems were first investigated by (Tabor, 1963). Tabor, 1981 and Weinberger, 1965 addressed the physics of pond's stability. More recently, Hassab et al, 1989 presented a field report on a solar pond constructed in the State of Qatar. They reported the problems encountered in operating SGSPs in the Arabian Gulf region, characterized as a windy and dusty environment. These problems are excessive erosion of the gradient zone, the formation of sizable localized convective zones, the deterioration of pond water clarity and high rates of surface evaporation. These weather related problems severely impair the pond operation and performance.

The salinity in the UCZ increases due to convective mixing (wind, evaporation. .) with NCZ and salt diffusion from the bottom. In a typical case this diffusion amounts to about 60 ($tons/km^2$ Day). Weinberger, 1965, estimated the annual rate of this natural diffusion of salts, to be in the range of 20 - 30 Kg/m^2, depending on the thickness of NCZ, the temperature profile and the concentration difference between the UCZ and the LCZ. Newell et al, 1994, estimated the salt transported per year from the LCZ to the UCZ for 2000 m^2 solar pond at the University of Illinois, in the range of 25 to 50 tons.

In addition to wind mixing, evaporation can cause a local concentration of salt and possibly local reversal of the density gradient. Surface washing can eliminate the effect of evaporation. Schladow, 1984, showed that evaporation can be the dominating mechanism in surface layer mixing under light winds. Whereas in the case of strong wind, the evaporation is of secondary importance compared to direct wind stirring.

The common method of maintaining the salt gradient is to flush fresh water to the pond surface and inject saturated brine, or salt, at the bottom to offset the salt that diffused to the surface. In locations like North Africa, where fresh water is very short, the surface can be washed by seawater. Also, North Africa has very high rates of evaporation and very low rates of rain, and therefore recycling of salt by evaporation is practical and economical.

To over come the salt supplies problem and to ensure the continuous high performance operation of solar ponds with a minimum environmental damage caused by the salt disposal, a salt recycling system is a necessity. Based on the a above considerations, it is felt essential to demonstrate the capability of a long term, closed cycle salt management facility by evaporative brine concentration, which is the topic addressed in this paper.

Several schemes have been proposed for preserving a salinity gradient against diffusion. Tabor, 1963, suggested the falling pond i.e. a three- terminal flow system in which density profile is nearly exponential. More recently Rabl and Nielsen, 1975, suggested the use of a linear gradient which results from a four terminal flow system. The common method of maintaining the salt gradient suggested by Tabor, 1963, is to flush fresh water to the pond surface and inject saturated brine, or salt, at the bottom to offset the salt which diffused to the surface.

A mathematical model has been developed by Batty, Riley and Panahi, 1987, to estimate the area of salt gradient solar ponds, associated evaporation ponds, and storage reservoirs that could be maintained with a given water source. They concluded that salt and water requirements might be the physical factor that limits solar pond applications in many locations. Alagao et al, 1994, presented the theoretical basis and its validation of a Closed Cycle Salt Gradient Solar Pond (CCSGSP). Results from the initial operation of the solar pond show that wind action and convective mixing caused some erosion of the gradient layer thereby increasing the surface layer thickness.

In locations like North Africa, where fresh water is very short, the surface can be washed by sea-water. Also, North Africa has very high rates of evaporation and very low rates of rain, and therefore recycling of salt by evaporation is practical and economical. In order to generate the initial salt concentration gradient required to prevent convection, a usual practice is to fill the pond with several layers of salt solution. This is normally start with near saturation layer at the bottom followed by layers lower in concentration up to the top layer, which nearly reaches fresh water conditions. The initial quantity of salt required is estimated to be about 500 kgs of salt per square meter in a pond 3 m deep, and 800 Kgs of salt per square meter in a pond 4m deep Newell et al, 1994. This huge amount of salt can be a problem for a large scale solar ponds in areas short of natural resources of salt. Solar ponds also require large quantities of water to replace evaporation loss and flush away salt diffusing to the surface from the concentrated brines below.

In a previous study, the authors have shown that the (EP) of (TESP) is under sized and can provide only a bout 30% of the salt required by the SGSP. The anticipated size of EP were estimated and presented in that study under different design conditions. The design conditions considered in that study include Summer, Autumn and Spring designs, while the winter design was excluded due to the low rates of net evaporation during the winter season. The objective of this paper is to establish a physical understanding of the problems associated with the operation and maintenance of solar ponds. And then develop a guide for a systematic operation and maintenance of such systems.

The results of this paper will help the designers of solar pond systems and the operation engineers of such systems by giving the following parameters:

- The effects of the local weather conditions on the thermal stability of the SGSP, and those recommendations on how to minimize their effects on future designs.
- The best method for salt gradient maintenance.
- A day to day operation for solar ponds.
- A guide for a systematic operation and maintenance of solar ponds.

2. MATHEMATICAL MODELING:

A major concern related to the use of solar ponds is salt gradient maintenance. Over time, salt diffuses from the LCZ to the UCZ. To maintain the salinity gradient surface brine has to be removed and replaced with fresh water (or sea water) consequently, more salt has to be added to the LCZ . One way of recycling the salt is to re-concentrate the removed surface brine in an evaporation pond.

Operating SGSP starts with building the required salt gradient profile and filling the EP with seawater. During the heating up period, the storage zone temperature increases gradually which increases the salt diffusion rate and thus leading to the problem of thermal stability and keeping the salt gradient profile within a certain margin.

For the purpose of analysis, an energy balance model was used based on the one-dimensional transient model formulated by Pancharatnam (1972) and mentioned by Newell, T.A. et al, (1994). In this study, the model was modified to accommodate the measured evaporation rates. The model used in this paper can be written as;

$$mc\frac{dT}{dt} = a * A_{ep} * Q_s - h_r * A_{ep}\left(T - T_{sky}\right) - h * A_{ep}\left(T - T_a\right) - E_{fw} * a_{ep} * L * r_w$$

the coefficient of convective heat transfer (h) in (w / m^2. ^{o}k) is based on the following correlation;

$$h = 5.6779\ \left(1 + 0.671 * V\right)$$

the radiation heat transfer coefficient (hr) is taken to be equal to 5.7 (w/m^2.^{o}k) for shallow solar ponds .

The model is applied to the evaporation pond of TESP, with surface area of 105 (m^2), the block diagram below (Figure(1)) illustrates the method of programming and solution procedure.

3. RESULTS AND DISCUSSION:

3.1. The Growth of Upper Convective Zone and its Control:

The UCZ thickness and its concentration are known to affect the overall performance of SGSP, and it must be closely monitored and controlled to minimize its effect. As mentioned above, the growth of the UCZ depends on many parameters including, among others, the net evaporation rate, wind speed, and salt diffusion rate.

This section presents the results regarding the quantities of surface water flushing, overflow water, for both cases (fresh water or seawater) and their timing with the assumption that 4% and 5% constitute the lower and upper limits of salt concentration in the UCZ respectively. It should be noted that these limits might not be representing the actual happenings in practical applications. Figure (2) shows the

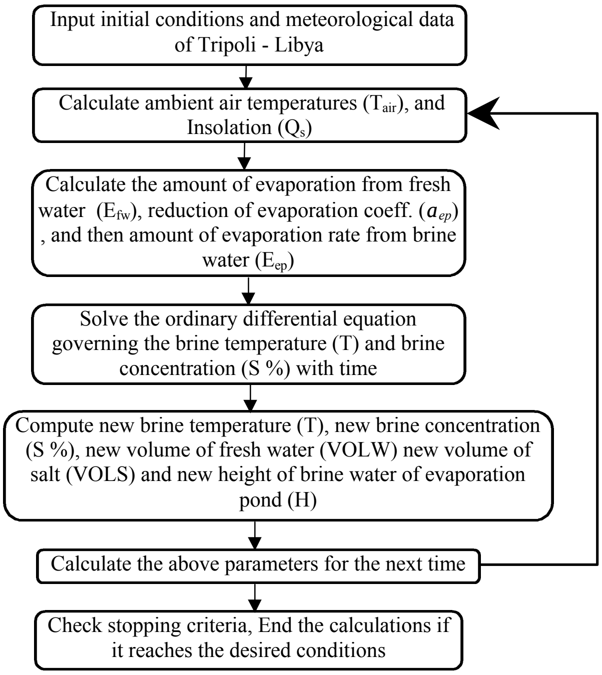

Figure (1) Flow chart of the mass and energy balance model

estimated daily variations in the UCZ concentration during the first year of operation under the meteorological conditions of Tripoli- Libya for a SGSP of 830 m^2 surface area, 0.30 m UCZ initial thickness, and 3.5% initial concentration (concurrent with TESP). The figure also shows the quantities of surface water flushing and overflow water and their timing for both cases (fresh water and seawater).

Figures (3a, b & c) show the same results for the months of January, May and September respectively. These results clearly show that comparing Winter and Summer seasons, flushing is required more frequent during the Summer season resulting in higher flushing quantities, which is attributed to the high rates of net evaporation in the Summer season. It was predicted that the number of flushing varies between five times per month during the Summer to two or three times per month during the Winter. It also shows the huge differences between the quantities required for fresh water flushing and those of seawater flushing. This is due, as mentioned earlier, to fact that in addition to replacing the evaporation losses, washing the surface is expected to flush away salt diffusing to the surface from the concentrated brines below.

As explained above, the higher the flushing water concentration (C1), the higher quantities of flushing water and overflow. The effect of C1 on the quantities of flushing water and overflow can be further investigated by estimating the ratio of the quantity at the desired concentration to that of fresh water $\left(\frac{\mathbf{Q1,C1}}{\mathbf{Q1,F}}\right.$ **and** $\left.\frac{\mathbf{Q4,C1}}{\mathbf{Q4,F}}\right)$. The results of such an estimation is presented in Figures (4a, b, c) for the TESP (Asp=830 m^2).

Figure (4a) shows the effect of increasing C1 on $\left(\frac{\mathbf{Q1,C1}}{\mathbf{Q1,F}}\right)$ and $\left(\frac{\mathbf{Q4,C1}}{\mathbf{Q4,F}}\right)$. It can be clearly seen that both ratios increase exponentially with increasing C1. The figure also shows that the quantity of seawater (C1=3.5%) required for surface flushing is about 8 times that of fresh water, while, the over flow increases rapidly to about 55 times. The large over flow quantity for the case of seawater has resulted due to the fact that flushing is expected to replace the evaporation and wash the top surface of the pond. The quantity of evaporation to be replaced is the same regardless of flushing water concentration.

Figure (4b) shows that the ratio $\left(\frac{\mathbf{Q1,C1}}{\mathbf{Q1,F}}\right)$ is constant for all year round for the same concentration and it increases as the flushing water concentration increases. Therefore, this ratio depends only on the value of surface flushing water concentration C1, and the overflow water concentration C4. It is independent of prevailing conditions. For example, for seawater surface flushing (C1=3.5%), the ratio $\left(\frac{\mathbf{Q1,C1}}{\mathbf{Q1,F}}\right)$ as stated above is about 8 and remains constant throughout the year. The quantity of water used for flushing away the salt changes according to the variations occurring in the evaporation rate of the solar pond. These changes do not affect the overall value of the above ratio as clarified by the following example:

<u>For the month of March</u>

Net Evaporation from Solar Pond (Esp-R) = 130.8 m^3
Quantity of Fresh water used for flushing away the salt (Q4,F) = 33.4 m^3
Quantity of sea water used for flushing away the salt (Q4,S) = 1154 m^3

<u>For the month of June</u>

Net Evaporation from Solar Pond (Esp-R) = 260.6 m^3
Quantity of Fresh water used for flushing away the salt (Q4,F) = 27.65 m^3
Quantity of sea water used for flushing away the salt (Q4,S) = 1995 m^3

And Therefore;

$$\left(\frac{Q1,C1}{Q1,F}\right)_{\text{March}} = \frac{130.8+1154}{130.8+33.4} = 7.82$$

$$\left(\frac{Q1,C1}{Q1,F}\right)_{\text{June}} = \frac{260.65+1995}{260.65+27.65} = 7.82$$

And remains constant throughout the year as depicted in Figure (4b).

Figure (4c) shows that the ratio $\left(\frac{\mathbf{Q4,C1}}{\mathbf{Q4,F}}\right)$ increases during Summer months for the same flushing water concentration and increases with the flushing water concentration. This is due to the fact that it depends on the prevailing conditions and on other parameters known to affect the growth of the UCZ (C1, C4, C7, …etc).

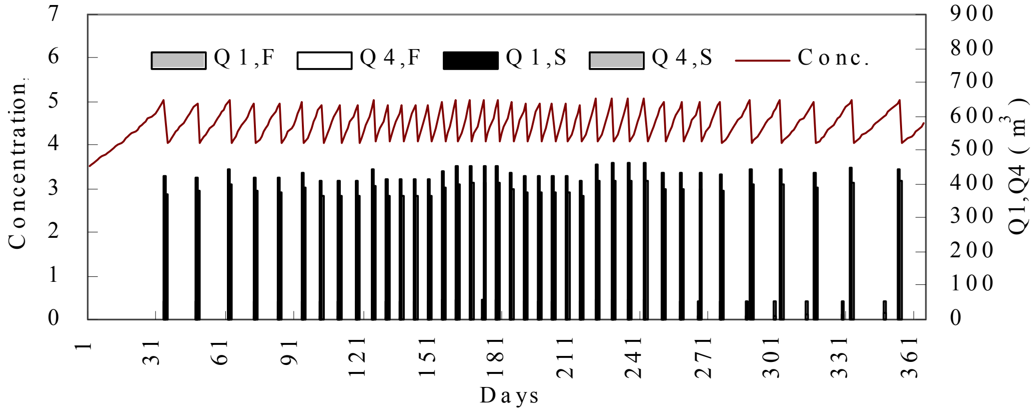

Fig. 2: Daily variations of UCZ concentration, quantities of flushing water, Q1 for SP and overflow water, Q4 to EP for first year of operation.

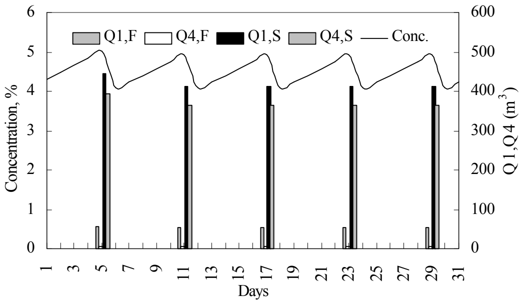

Fig.3b: Daily variations of UCZ concentration, quantities of flushing water, Q1 for SP and overflow water, Q4 to EP in MAY for first year of operation.

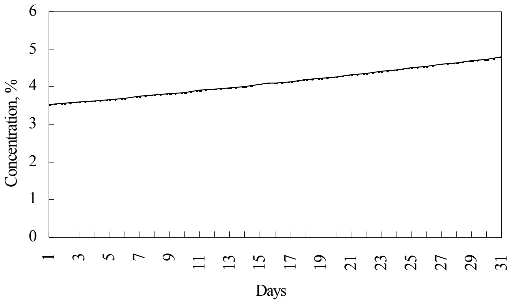

Fig.3a: Daily variations of UCZ concentration, quantities of flushing water, Q1 for SP and overflow water, Q4 to EP in JAN (under the assumption of first of January as the starting day).

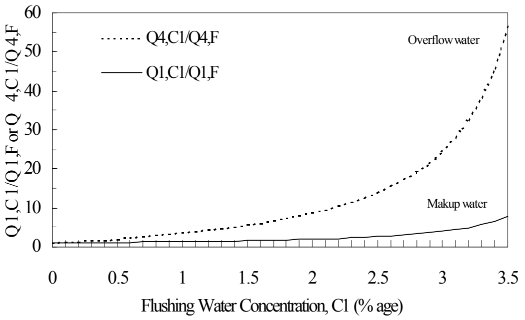

Fig. 4a: The effect of Flushing Water Concentration on the make up water and over-flow quantities.

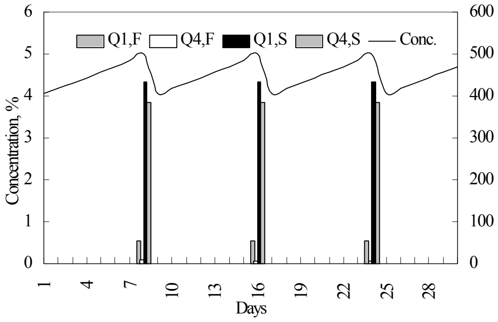

Fig. 3c: Daily variations of UCZ concentration, quantities of flushing water, Q1 for SP and overflow water, Q4 to EP in SEP for first year of operation.

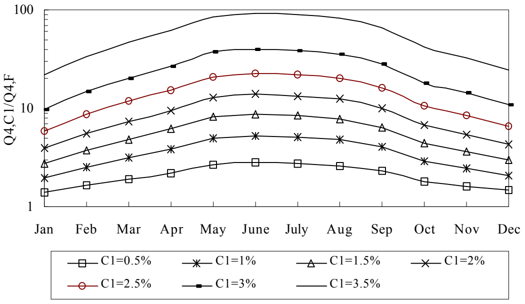

Fig. 4c: The effect of Flushing Water Concentration on the overflow water quantities for different months under the prevailing conditions of Tripoli – Libya.

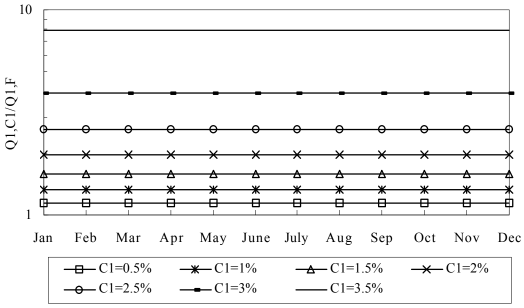

Fig. 4b: The effect of Flushing Water Concentration on the make up water quantities for different months under the prevailing conditions of Tripoli – Libya.

3.2. *The Evaporation Pond Potential:*

In this section, the daily variations of brine concentration in the EP of TESP and those based on the design conditions defined in reference (Agha et al, 2000) are presented and discussed for the first three years of operation under different scenarios.

Figures (5a, b, c and d) show the variation of salt concentration in the EP, with the 1st of January as the starting day, for both types of surface water flushing, fresh water and sea water, starting from primary salt concentration of seawater (C1=3.5%) and RO-Plant brine reject concentration (C1=7%), under different design conditions. As stated above, it should be noted that these results are based on the assumption of Closed Cycle Salt Gradient Solar Pond (CCSGSP), i.e. the evaporation pond is coupled with the solar pond. This case was carried out to simulate the real case scenario.

These figures clearly show that the maximum concentration levels occur at the months of August and September, while, the minimum concentration levels occur at the months of December and January.

It seems that the difference in the initial concentration (3.5% to 7%) vanishes by the end of the first year, and no difference exists during the second and third years of operation. All the figures show maximum concentration levels for the Spring design and minimum concentration levels for TESP design. This is, of course, due to the high area ratio for Spring design and low area ratio for TESP as given in Table (1).

A Comparison between the results for the uncoupled (separate) evaporation pond (Figure (6)) with those for the coupled evaporation pond (Figures (5a, b, c and d) clearly shows the effect of coupling on the concentration level of the evaporation pond. For the case of uncoupled evaporation pond, a concentration level of about 35% were achieved by the end of June, while the end of June concentration level in the coupled evaporation pond was only 6%.

For the Spring design, the maximum concentration levels for fresh water surface flushing were 27%, 43% and 43% for the 1st, 2nd and 3rd years of operation, respectively. For flushing by seawater, these concentration levels were 22%, 40% and 40% during the same years of operation. For the particular case of Summer design, the big difference in area ratio shown in Table (1) seems to affect the rate of change of concentration level in the EP. This effect is not so clear in the other designs despite the difference in area ratio.

As mentioned in the previous sections, the EP of TESP is under-sized, this is very clear from the results given in Figures (5a, b, c and d) regardless of the type of surface water flushing.

3.3. *The Salt Concentration Profile Maintenance:*

The quantities of brine required by the SGSP of TESP (830 m^2) and that provided by the EP based on different design conditions were predicted for both cases of surface water flushing (fresh water and seawater) for three years of operation. It should be noted that these predictions simulate the real case scenario by assuming the following conditions;

- The EP and the SGSP are completely coupled together through Q4 (over-flow from SGSP) and Q7 (high concentrated brine injection).
- The 1st of January was assumed as the starting operating day.

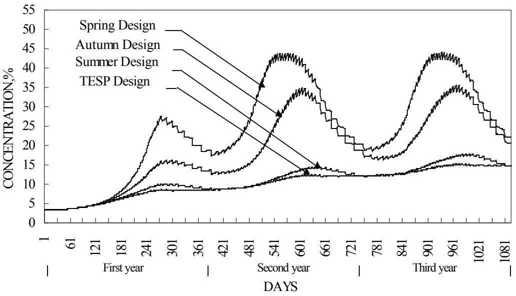

Figure (5a): Variation of salt concentrations in EP started at JAN with primary salt concentration (3.5%), seawater under three years of operation for Fresh water surface flushing.

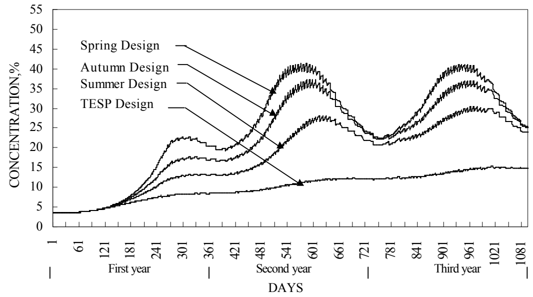

Figure (5b): Variation of salt concentrations in EP started at JAN with primary salt concentration (3.5%), seawater under three years of operation for Seawater surface flushing.

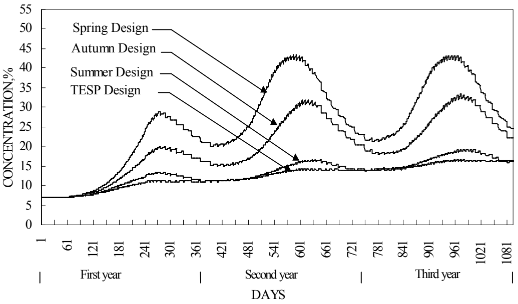

Figure (5c): Variation of salt concentrations in EP started at JAN with primary salt concentration (7%), brine reject from RO-Plant under three years of operation for Fresh water surface flushing.

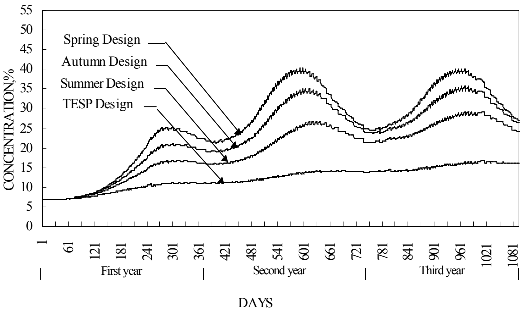

Figure (5d): Variation of salt concentrations in EP started at JAN with primary salt concentration (7%), brine reject from RO-Plant under three years of operation for Sea-water surface flushing.

- The natural rate of salt diffusion was assumed as 16.6 kg/m^2-year (as assumed by TESP team).
- The LCZ concentration is allowed to decrease from 26% to 22%. These were taken as the upper and lower limits of marginal stability.

Figures (7a, b, c and d) show the results of the fresh water surface flushing for the Spring, Autumn, Summer and TESP design conditions respectively. These figures clearly demonstrate the ability of salt recycling scheme by re-evaporation in the EP. It can be seen that during the first year of operation non-of the design conditions considered is able to provide a complete quantity of the salt required by the SGSP.

For the first five months of operation, all the design conditions seem to provide the same quantity of salt ranging from 10% to 17% of that required. At the start of the summer season of the 1st year, a difference in the amount of salt provided by the design conditions start to appear. The highest quantities of salt are for the Spring design and the lowest quantities are for TESP. This is of-course due to the high area ratio (Ar) for the Spring design (refer to Table (1).

By the end of the 1st year the quantity of salt contributed by the Spring and Autumn design conditions are 75% and 50 %respectively, while, for summer and TESP design conditions, it is only about 30%.

The Spring design can provide a complete quantity of salt required by the beginning of the summer season of 2nd year, whereas, the Autumn design can provide the complete quantity by the end of this summer season. At the same time, the other two design conditions (Summer and TESP) can provide a maximum of about 60% at the end of summer season of the 3rd year. This re-emphasizes the results presented by the authors in a previous study concerning the size of EP of TESP [ ].

Figure (7) also show the quantity of brine to be injected into the SGSP (Q7). An amount of about 3.4 m^3 with a brine concentration of 26% is being drawn from the EP and injected into the LGZ of SGSP every 49 days (corresponding to the marginal stability conditions of the pond, stated above). In cases of high concentration in the EP (higher than 26%, refer to Figure (5), the required quantity of salt can be obtained by withdrawing lower amount of brine from the EP. On the other hand, in times of low concentration in the EP, a fresh salt must be added to the brine drawn from the EP to make-up the required quantity of salt.

Figures (8a, b, c d) shows the predicted salt quantities for the case of seawater surface flushing for Spring, Autumn, Summer and TESP design conditions, respectively. As in the case of fresh water surface flushing, the quantity of salt provided by the EP during the first five months of operation appear to be the same for all the design conditions and ranging from 10% to 17% of that required. Although, the difference in the amount of salt provided by the different design conditions appears at the start of the summer season for the case of fresh water surface flushing, this difference is delayed to the end of the summer season if seawater is used for surface flushing. This is attributed to the high overflow quantities for the case of seawater surface flushing.

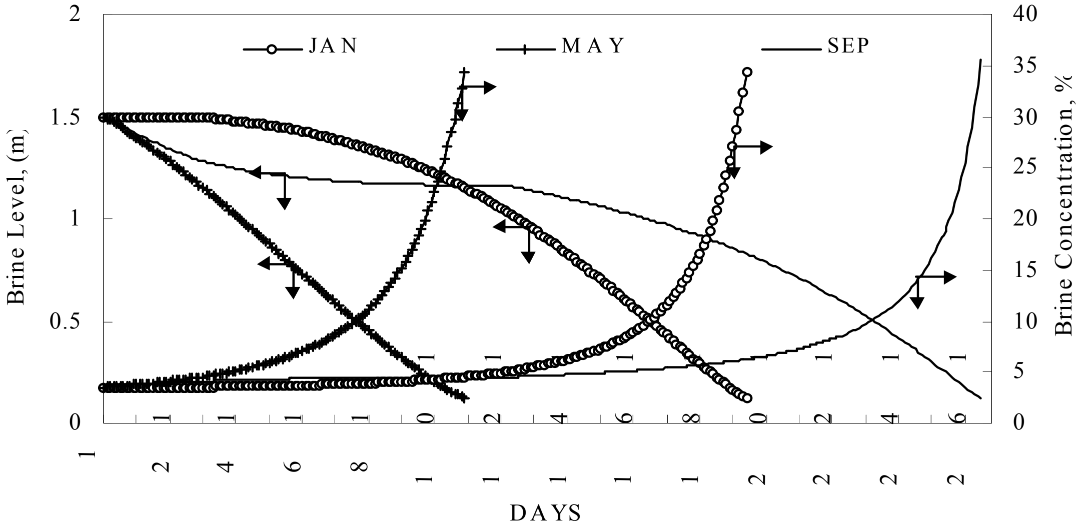

Figure (6): Daily variations in brine concentration and depth for actual EP (Aep=105 m^2, Depth=1.5 m) for concentration to reach (35%) starting from seawater concentration (3.5%) for different starting months.

Table (4.2): Comparison between the quantities of salt that can be provided by the Evaporation Pond for the first three years of operation under different design conditions.

Design	Area Ratio (Ar=Aep/Asp)		%age of salt provided by EP						Overall (%age)	
			fresh water flushing			sea water flushing				
	Fresh water	Sea water	1st yr	2nd yr	3rd yr	1st yr	2nd yr	3rd yr	Fresh water	Sea water
Spring	0.65	28.40	44	89	87	39	92	95	74	76
Autumn	0.32	20.20	30	73	79	32	85	93	61	71
Summer	0.17	14.40	21	36	48	26	69	88	36	62
TESP	0.13 (constructed)		20	33	44	19	33	44	33	32

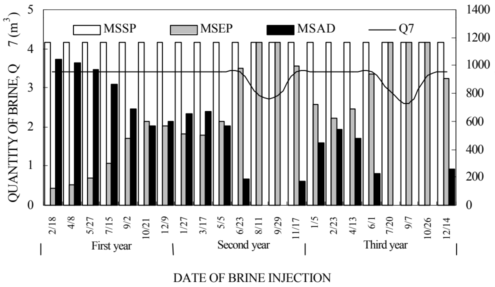

Figure (7b): Quantity of salt and brine required to SP and that provided by EP for Autumn Design (Fresh water surface flushing).

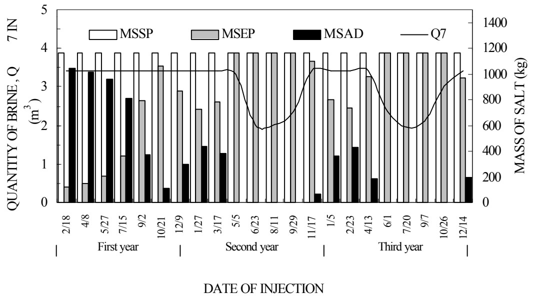

Figure (7a): Quantity of salt and brine required to SP and that provided by EP for Spring Design (Fresh water surface flushing).

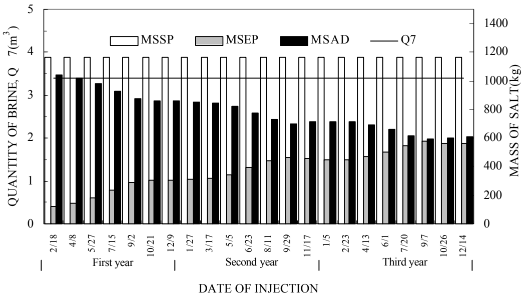

Figure (7d): Quantity of salt and brine required to SP and that provided by EP for TESP Design (Fresh water surface flushing).

Figure (7c): Quantity of salt and brine required to SP and that provided by EP for Summer Design (Fresh water surface flushing).

Figure (10) presents an overall comparison between all the cases considered. The least contribution comes from the TESP, which is, as stated above, due to the low EP area.

Table (1) summarizes the predicted quantities of salt that can be contributed by (EP) (as, a percentage). It can be seen that (EP) provide 20% to 40% during the first year and 45% to 95% during the third year depending on the design selected. Comparing the percentage of salt provided for different designs, it can be clearly seen that the Autumn design presents a favorable condition. It provides a reasonable percentage reaching 79% in the case of fresh water surface flushing and 93% in the case of seawater surface flushing with a relatively low area ratio.

3.4. *Comparison between Evaporation Ponds and Evaporation Surfaces:*

This section investigates the effect of EP depth on the area ratio and the related performance of EP. In order for the EP to provide the required amount of salt, decreasing the EP depth leads to increasing the EP area. The idea of using large surface areas is very attractive, especially in areas of low to moderate net evaporation rates.

Figures (11a and b) show the effect of decreasing the EP depth on the area ratio for both cases of surface water flushing and under different design conditions. Noting that a depth of 0.2 m was treated in this study as an evaporation surface (ES) condition.

Figures (12a and b) show the daily variations in salt concentration for various EP depths under the Autumn design condition. It can be seen that the improvement in salt concentration increases for the ES, especially during the first year where the concentration has reached 35% at the start of the summer months.

It seems that the type of water used for surface flushing does not have a noticeable effect on the quantity of salt provided by the EP for all the design conditions (except Summer design condition). Comparing Figure (7c) (Summer design condition and fresh water surface flushing) with Figure (8c) (Summer design condition and seawater surface flushing) show that the quantity of salt provided in the case of seawater surface flushing is almost double that provided by the case of fresh water surface flushing. This is believed to be due to the high area ratio for the case of seawater surface flushing under the condition of Summer design as compared with that of fresh water surface flushing. Changing the type of flushing water from fresh water to seawater is expected to increase the overflow quantity by about 55 times (as shown in Figure (4a)). While, the area ratios are expected to increase by about 44, 63 and 85 times for the design conditions of Spring, Autumn and Summer respectively.

The overall year contribution of EP under different design conditions in providing the required salt quantities for both types of surface water flushing is shown in figures (9a, b, c and d). These figures clearly show the differences existing between the design conditions considered for the first three years of operation. The highest contribution comes from the Spring design for both types of surface water flushing. Also, for each design condition, the contribution increases by the year.

None of the design conditions can provide a complete quantity of the salt required for the three years. This is, of-course, due to the reduction in the concentration levels resulting from the precipitation rate during the winter season, and can be overcame by storing salt from the Summer season for use during the winter season.

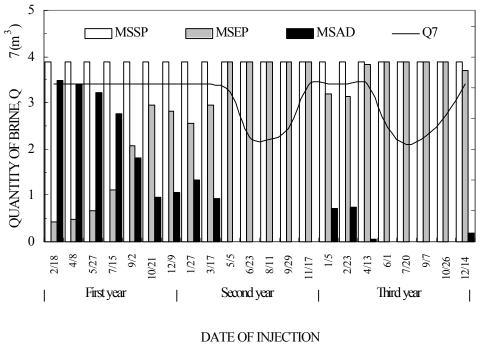

Figure (8b): Quantity of salt and brine required to SP and that provided by EP for Autumn Design (Seawater surface flushing).

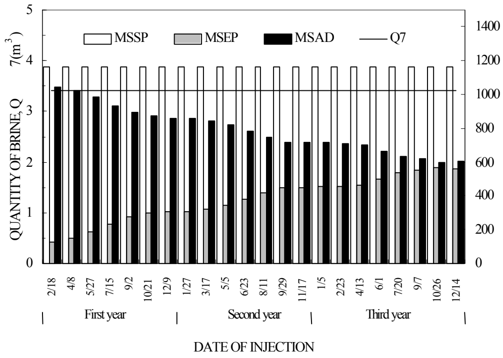

Figure (8d): Quantity of salt and brine required to SP and that provided by EP for TESP Design (Seawater surface flushing).

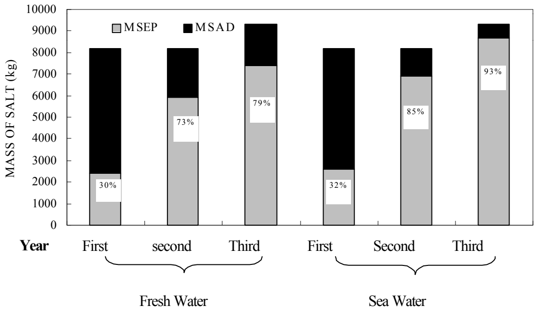

Figure (9b): Quantity of salt provided by EP and that added to SP for both types of surface water flushing under three years of operation for Autumn Design.

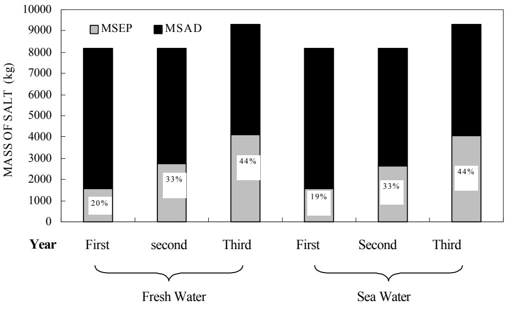

Figure (9d): Quantity of salt provided by EP and that added to SP for both types of surface water flushing under three years of operation for TESP Design.

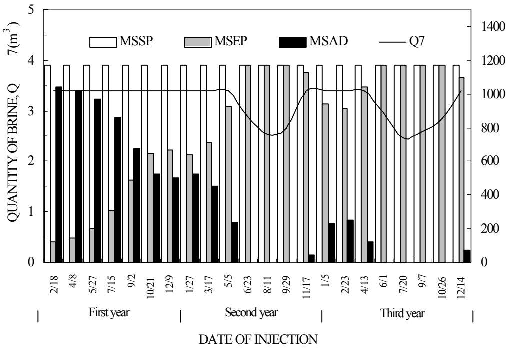

Figure (8a): Quantity of salt and brine required to SP and that provided by EP for Spring Design (Seawater surface flushing).

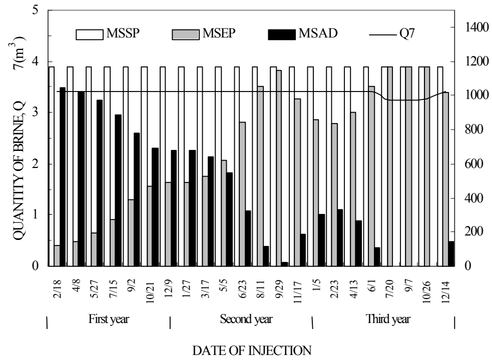

Figure (8c): Quantity of salt and brine required to SP and that provided by EP for Summer Design (Seawater surface flushing).

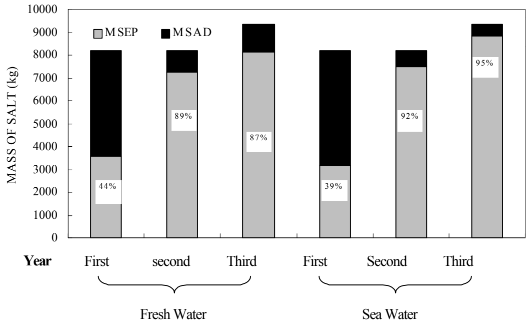

Figure (9a): Quantity of salt provided by EP and that added to SP for both types of surface water flushing under three years of operation for Spring Design.

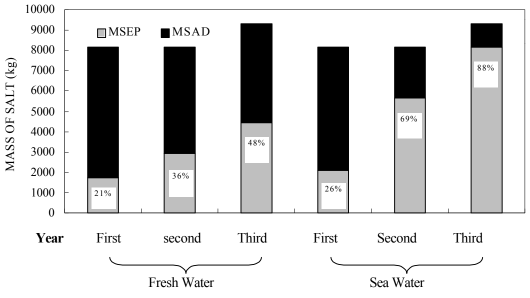

Figure (9c): Quantity of salt provided by EP and that added to SP for both types of surface water flushing under three years of operation for Summer Design.

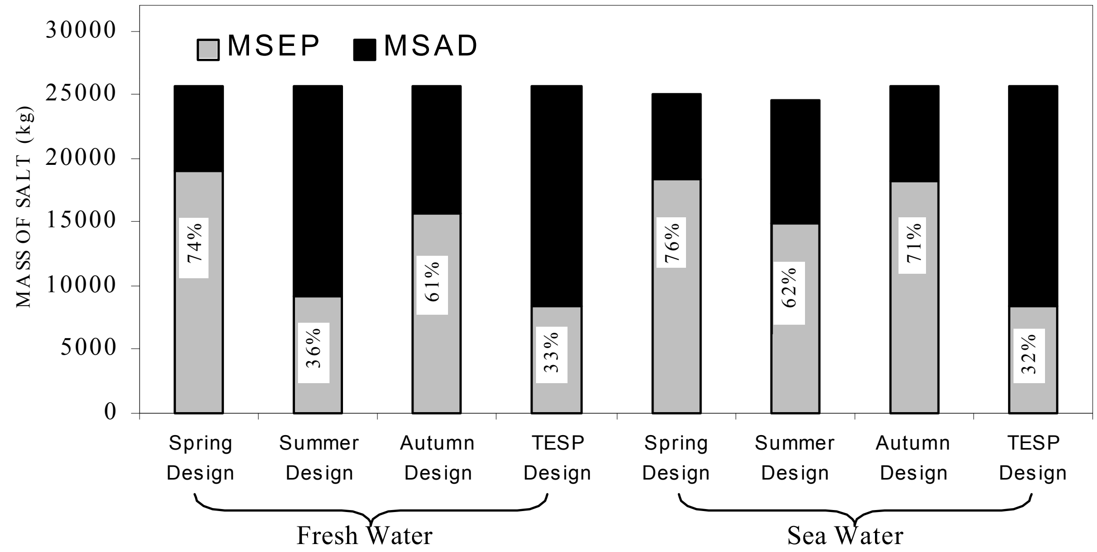

Figure (10): Quantity of salt provided by EP and that added to SP for both types of surface water flushing under different design conditions.

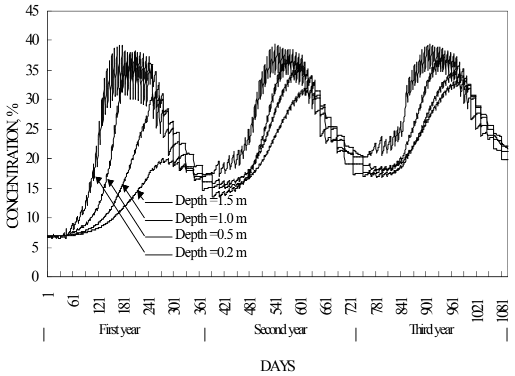

Figure (11b): Variation of Area Ratio with Depth for Different Design conditions for Seawater surface Flushing.

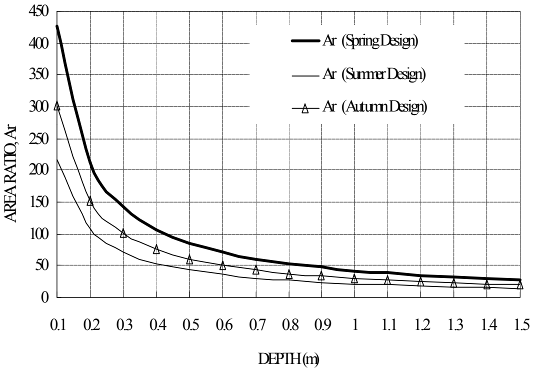

Figure (11a): Variation of Area Ratio with Depth for Different Design conditions for Fresh water surface Flushing.

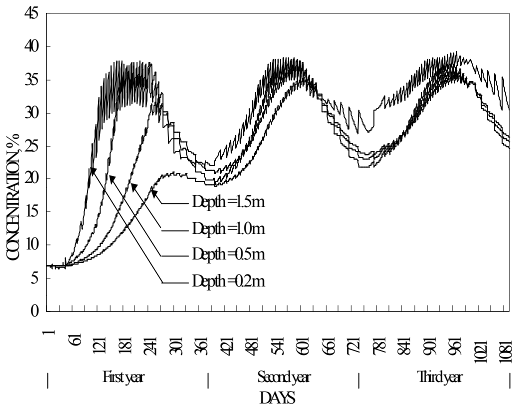

Figure (12b): Daily variation of salt concentrations with depth in EP started at JAN with primary salt concentration (7%), brine reject from RO-Plant for seawater surface flushing under Autumn design for three years of operation.

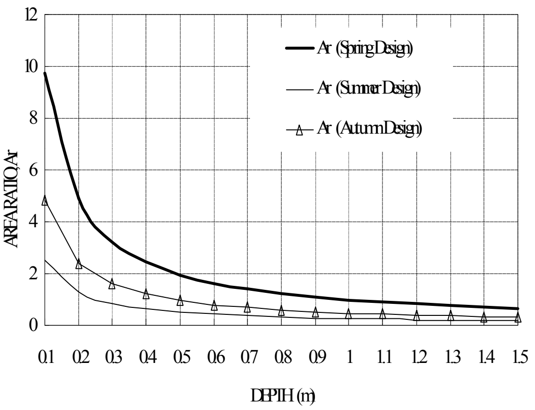

Figure (12a): Daily variation of salt concentrations with depth in EP started at JAN with primary salt concentration (7%), brine reject from RO-Plant for fresh water surface flushing under Autumn design for three years of operation.

4. CONCLUSIONS:

Considering the results presented for each set of circumstances, the following conclusions were drawn:

1. The net evaporation rate is the dominant factor during summer months while salt diffusion rate is the dominant factor during winter season.
2. In all cases, the required salt can not be met during winter months.
3. In all cases, the EP can not be used for the first six months of operation due to very low concentration levels.
4. Although the model used was developed to be used under the closed loop condition, but due to the high quantities of flushing by sea-water part of the overflow was rejected.
5. Very large EP areas are required for seawater surface flushing.
6. Due to high net evaporation rates in summer months, the required number of surface flushing the SP is five times in summer, while it is estimated to be from two to three times in winter months.
7. EP can provide 20% to 40% of the salt required by SGSP during the first year of operation and 45% to 95% during the third year of operation depending on the design selected.
8. Under the assumption of 16.6 (kg/m^2-year) for the natural rate of up ward salt diffusion (assumed by TESP team), the brine must be injected from EP to the LCZ every 49 days or earlier to keep the pond stable.
9. For EP saturated brine of (26%) salt concentration, the quantity of the brine to be injected to LCZ is about 3.4 (m^3).
10. Reducing the depth of EP improves the capability of EP for brine re-concentration.

REFERENCES:

Alagao, F. B., Akbarzadeh, A. and Johnston, P. W. (1994),“ The design, construction, and initial operation of a closed cycle, Salt Gradient Solar Pond “, Solar Energy, vol 53, PP. 343 –351.

Claire Batty, J., Paul Riley, J., and Panahi, Z., (1987), “A Water Requirement Model for salt gradient solar ponds”, Solar Energy 39, PP. 483-489.

Hassab et al, (1989), “Problems encountered in operating Salt Gradient Solar Ponds in The Arabian Gulf Region”, Solar Energy, Vol. 43, No. 3, pp. 169-181.

Newell, T.A. et al, (1994), “ Characteristics of a Solar Pond Brine Re-concentration System”, ASME, J. of Solar Energy, Vol. 116, pp. 69-73.

Rable A. and Neilsen C., (1975), “Solar Ponds for Space Heating”, Solar Energy 17, PP. 1-12.

Schladow S. G., (1984), “The Upper Mixed Zone of a Salt Gradient Solar Pond: its Dynamics, Prediction and Control”, Solar Energy, Vol.33, No.5, pp.417-426.

Tabor H., (1981), “ Solar Ponds”, Solar Energy, Vol. 27, No. 3, pp. 181-194.

Tabor, H., (1963), “ Large Area Solar Collectors for Power Production”, Solar Energy, Vol. 7, No.4, pp. 189-194.

Weinberger H., (1965), “ The physics of solar ponds”, Solar Energy 8, PP. 45-56.