Huanmin Lu
The University of Texas at El Paso
Center for Environmental Resource Management
500 West University Avenue
El Paso, Texas, USA 79968
e-mail: Lhuanmin@utep.edu.

Andrew H. P. Swift
Texas Tech University
Lubbock, Texas, USA 79409

Herbert D. Hein, Jr.

John C. Walton

The University of Texas at El Paso
Center for Environmental Resource Management
500 West University Avenue
El Paso, Texas, USA 79968

Advancements in Salinity Gradient Solar Pond Technology Based on Sixteen Years of Operational Experience

The El Paso salinity gradient solar pond, initiated in 1983, has been in operation since 1985. Through 16 years of research and operation, the El Paso Solar Pond has successfully demonstrated applications including desalination, waste brine management, industrial process heat production, and electricity generation; and has developed and implemented key technical advancements to improve the technical viability and economic feasibility of salinity gradient solar ponds, including: 1) an automated instrumentation monitoring system, 2) a stability analysis strategy and high temperature (60–90°C) gradient maintenance methods, 3) a scanning injection technique for improved salinity gradient construction and maintenance, 4) new liner technology, and 5) an improved heat extraction system. [DOI: 10.1115/1.1667977]

1 Introduction and Overview

A salinity-gradient solar pond (SGSP) is a body of water that collects and stores solar energy. A typical salinity-gradient solar pond has three regions: surface zone, main gradient zone, and bottom zone. The surface zone, also called the upper convective zone (UCZ), is a homogeneous layer of low-salinity brine or fresh water. The bottom zone, also called the lower convective zone (LCZ), or storage zone, is a homogeneous layer of concentrated salt solution. Between the surface and bottom zones is the main gradient zone, which contains positive salinity and density gradients with depth and serves as a transparent insulating layer. Since there is no convection in the main gradient zone, the gradient zone is also called the non-convective zone (NCZ). Solar energy is collected and accumulated in the LCZ causing the temperature to increase. A temperature of 109°C has been recorded in an experimental solar pond at the University of New Mexico [1]. The insulating properties of the gradient zone, combined with the high heat capacity and large volume of water make the solar pond both a solar thermal collector and a long-term thermal storage device.

Solar ponds have a low cost per unit area of collector, inherent storage capacity, and are easily constructed over large areas. It has been demonstrated that salinity-gradient solar ponds can be a reliable heat source for a wide range of industrial and agricultural applications, such as desalination, process heating, space heating, and electricity generation. The first paper describing the behavior of constructed solar ponds was published in 1964 [2], and a comprehensive book on salinity gradient solar pond technology was published in 1989 [3].

One of the longest operating solar pond projects in the world, the El Paso Solar Pond Project has provided valuable experiences through 16 years of operation and research. A series of techniques have been developed in order to make salinity gradient solar pond technology more reliable, productive, and economic. This paper describes the technical advancements developed at the El Paso Solar Pond Project. These advancements include: 1) an automated instrumentation system for solar pond monitoring, 2) a stability analysis strategy and gradient maintenance methods, 3) a scanning injection technique for improved salinity gradient construction and maintenance, 4) new liner technology, and 5) an improved heat extraction system.

2 Brief History of the El Paso Solar Pond Project

The El Paso Solar Pond, shown in Fig. 1, is a 3000 m^2 research, development and demonstration project operated by the University of Texas at El Paso. Historically the majority of funding has come from the U.S. Bureau of Reclamation and the State of Texas. The project, located on the property of Bruce Foods, Inc.-a food canning plant-was initiated in 1983. The El Paso Solar Pond has been operated, intermittently, since 1985, when it became the first in the world to deliver industrial process heat to a commercial manufacturer. In 1986 the El Paso Solar Pond became the first solar pond electric power generating facility in the United States; and in 1987 the nation's first experimental solar pond powered water desalting facility [4–6].

Figures 2 and 3 show typical density and temperature distributions in the El Paso Solar Pond. An annual temperature plot for both the LCZ and UCZ and average ambient temperature is shown in Fig. 4, based on the operation from 1991 through 1993. The typical operating temperature of the pond ranges from 70°C in winter to 90°C in early fall. The highest temperature observed was 93°C, and the maximum temperature difference between the LCZ and UCZ was above 70°C. The El Paso Solar Pond Project is currently focused on the research of solar pond coupled desalination and brine management, while continuing to advance and improve the techniques for solar pond operation and maintenance.

3 Scanning Injection Technique for Gradient Establishment

3.1 Traditional, Fixed Level Injection Technique. The salinity gradient zone is the key element of salinity gradient solar ponds. The first major task of applying solar pond technology is determining how to construct a prescribed salinity distribution profile effectively and efficiently. A number of research projects have been conducted describing various techniques for gradient establishment [3,7,8]. One common method of constructing the gradient is water injection, in which the solar pond is partially filled with concentrated brine (usually near saturation), then fresh

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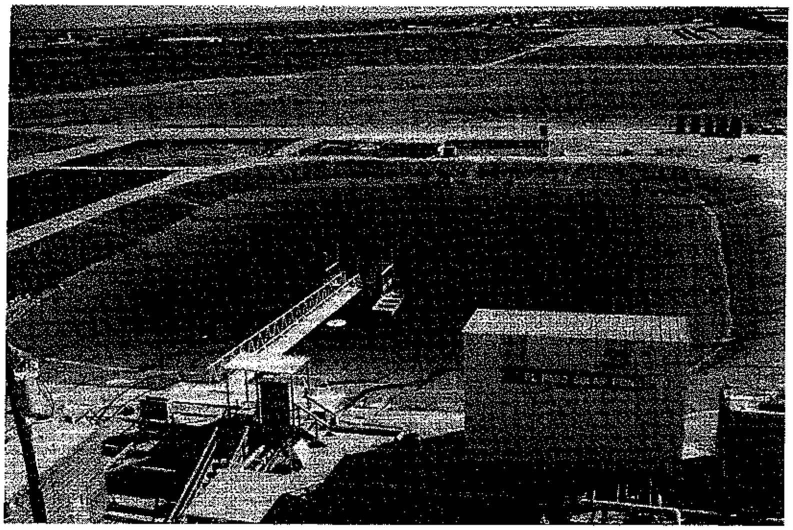

Fig. 1 Picture of the El Paso Solar Pond

or brackish water is injected into the brine at successively higher elevations so as to progressively dilute the concentrated brine, creating the gradient.

The Froude number, Fr, is a critical parameter for the fixed level injection process. Froude number is a dimensionless number representing the ratio of the kinetic energy to the gravitational potential energy of the injected fluid, and is defined as

$$Fr=[\rho v^2/(g\Delta\rho B)]^{1/2} \tag{1}$$

where ρ is the density of the injected fluid, v is the injection velocity at the diffuser outlet, g is the gravitational acceleration, $\Delta\rho$ is the density difference between the injected fluid and the surrounding fluid, and B is the width of the diffuser gap [3]. It has been found that the Froude number needs to be maintained at a constant value of approximately 18 in order to achieve complete mixing at the injection diffuser level [7,8]. For Froude numbers smaller than this value the injected fluid rises, by buoyancy, and mixes above the diffuser level. For Froude numbers larger than this value, the injected fluid entrains significant quantities of fluid from below the diffuser level. Either of these cases leads to an improper gradient profile. To satisfy this Froude number requirement during the entire injection process using the fixed level method, either the flow rate or the diffuser geometry must be adjusted to match the density changes of the ambient fluid at each injection step. Usually, the radius of the diffuser is fixed and the flow rate is kept at or near the maximum possible value in order to minimize construction time. Therefore, the gap of the injection diffuser needs to be adjusted frequently during a fixed level injection process [9,10]. The diffuser gap is generally about 2 to 3 mm [3], and the gap is usually limited at 10 to 20 mm [9,10]. The limitation of maximum diffuser gap and the need for the critical Froude number, limits the maximum flow rate of injection, resulting in an increased time required for gradient establishment. The

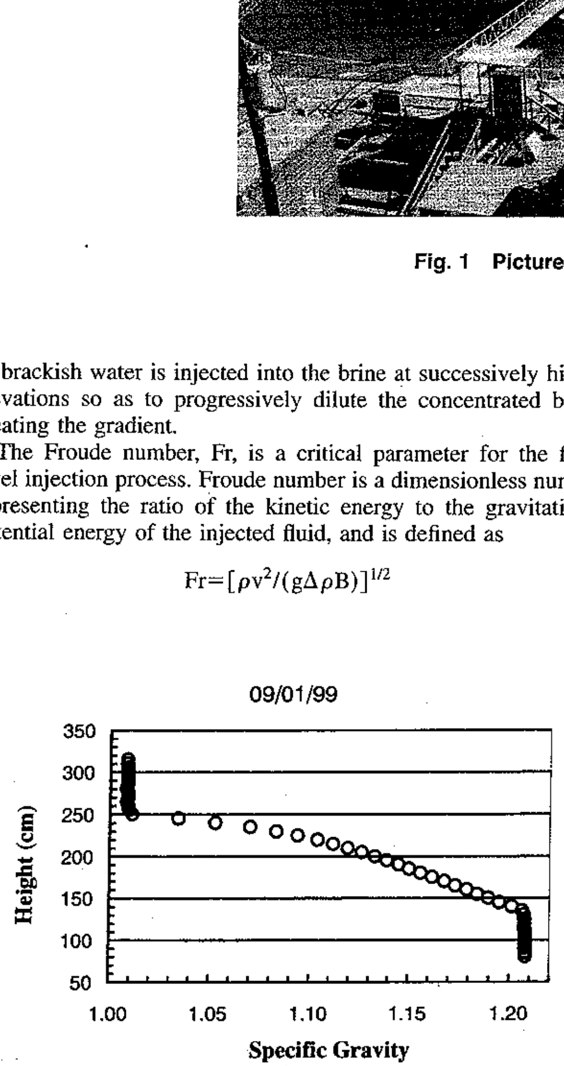

Fig. 2 Density Profile of the El Paso Solar Pond

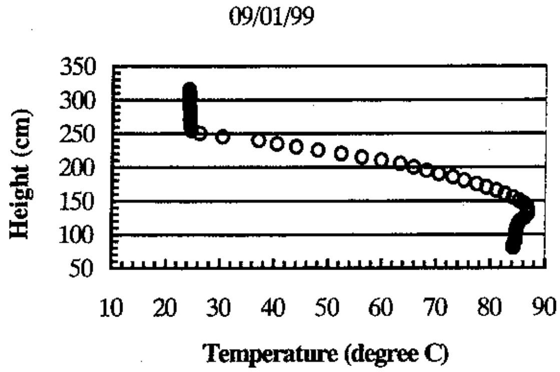

Fig. 3 Temperature Profile of the El Paso Solar Pond

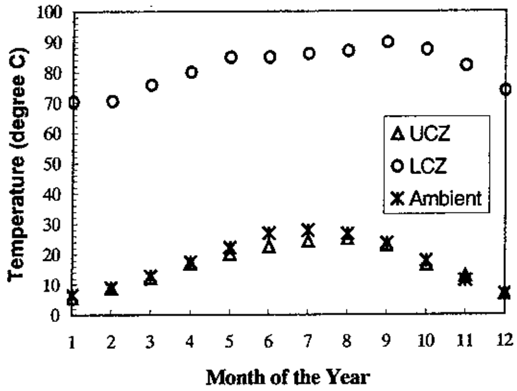

Fig. 4 Temperature History in the El Paso Solar Pond. UCZ-temperature of upper convective zone. LCZ-temperature of lower convective zone. Ambient-temperature of ambient air.

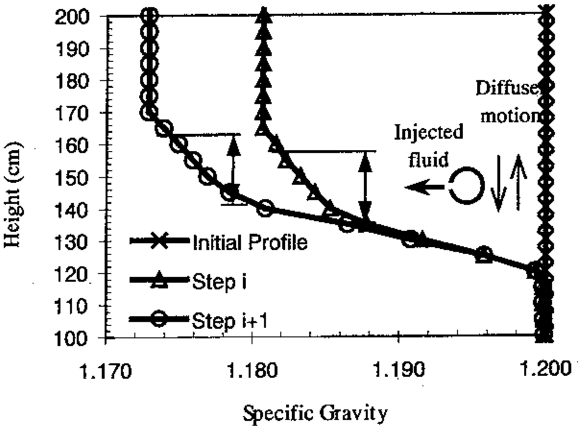

Fig. 5 Schematic of Scanning Injection Method

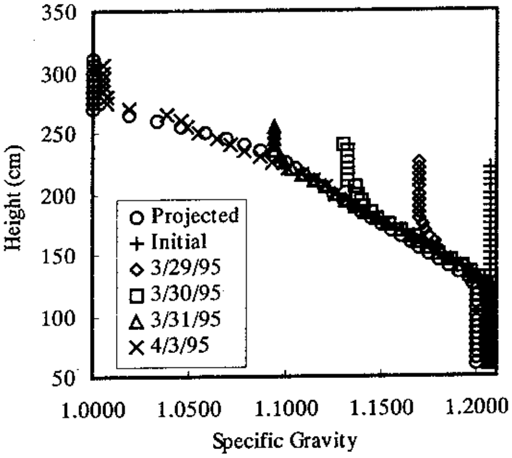

Fig. 6 Salinity Profile Development during Gradient Establishment

fixed level injection method, used at the El Paso Solar Pond prior to 1995, is tedious, labor intensive, and time consuming.

3.2 Scanning Injection Technique. In 1995, a scanning injection technique was developed for salinity gradient establishment. The scanning injection technology was first used for gradient modification [11], and then adapted and successfully implemented in salinity gradient construction [12].

Figure 5 shows a schematic of the scanning injection technique. Instead of remaining at a set level, the diffuser is continuously moved up and down within a preset region during each step of the injection. This procedure can be divided into the following steps:

1. Design the pond configuration, (i.e. the depth of the pond, thickness of each zone, and desired salinity distribution profile). For details about how to determine an optimal pond configuration, see Hull, et al. [3].
2. Estimate the mass of salt required to form the desired salinity profile. The mass of salt is converted to a volume and initial depth of saturated brine needed to be put into the pond.
3. Plan the injection process. The entire injection process consists of a series of steps. During each step, the injection diffuser moves (scans) up and down within a small range that is called the "scan range." The scan range used at the El Paso Solar Pond was 20 cm for all but the last five steps when smaller ranges were used. The major parameters that need to be determined for each injection step are: upper and lower limits (elevations), and the volume of fresh (or brackish) water to be injected. The lower limit of the first injection step will be the elevation of the boundary between the LCZ and NCZ. The lower limit is increased by approximately 5 cm for each consecutive step, as shown in Fig. 5. The volume of water injected at each step is determined based on the desired salinity profile, the salinity distribution result from the previous injection step, and the balances of water and salt. For the nth injection step, the mass balance for the water can be expressed as

$$(V_z)_f=(V_z)_i+V_{inj} \tag{2}$$

The salt balance equation can be written as

$$(V_z\rho_zS_z)_i+(V\rho S)_{inj}=(V_z\rho_zS_z)_f \tag{3}$$

where V_z is the volume of pond water above the lower limit (elevation z) of the n^{th} step, ρ_z and S_z are the average density and salinity (% by weight) of the n^{th} step, respectively. Subscripts i and f indicate the initial and final values of corresponding parameters of the n^{th} step, respectively. V_{inj}, ρ_{inj}, and S_{inj} are the volume, density and salinity of the injected fluid, respectively. The injection volume for the n^{th} step, V_{inj}, can then be expressed as

$$V_{inj}=(V_z)_i[(\rho_zS_z)_i-(\rho_zS_z)_f]/[(\rho_zS_z)_f-(\rho S)_{inj}] \tag{4}$$

If the injected fluid is fresh water, $S_{inj}=0$, then

$$V_{inj}=(V_z)_i[(\rho_zS_z)_i-(\rho_zS_z)_f]/(\rho_zS_z)_f \tag{5}$$

4. Perform injection until the pond water level reaches the upper boundary of the gradient zone specified in the design.
5. Add fresh (or brackish) water onto the pond surface through a floating diffuser to avoid mixing, until the pond level reaches the design value.

As an example of using the scanning injection technique, the process as applied at the El Paso Solar Pond is described below. The desired salinity profile is shown in Fig. 6 as the "Projected" curve. The total depth of the pond was 320 cm (10.5 feet). The UCZ, LCZ and NCZ were to be 50 cm (1.6 feet), 120 cm (3.9 feet) and 150 cm (4.9 feet) thick, respectively. Based on this profile, it was calculated that the total quantity of salt required for building the pond was 990 metric tons, which is equivalent to approximately 3160 m^3 of brine at a specific gravity of 1.200. The initial depth of the saturated brine was 215 cm (7.1 feet).

The entire injection contained 30 steps, as highlighted in Table 1. The injection flow rate ranged from 8.2 to 9.8 liters per second (130 to 155 gallons per minute) for most steps. The exiting flow velocity of injected fluid was 2.5 to 2.9 m/sec (8.3 to 9.5 ft/sec). The variation of the flow rate was mainly due to the fluctuation of water line pressure. The average scanning speed of the injection diffuser was 10 cm/min for downward movement and 7 cm/min for upward movement.

During the injection process the resulting salinity gradient profile was monitored daily, the entire process taking about one week. If there was a significant difference between the resulting salinity profile and the projected one, the day's injection plan would be modified to correct the difference. The day-by-day development of the salinity distribution of the pond during the gradient estab-

Table 1 Example of Injection Steps for Gradient Construction

Step	Scan Range (cm)	Volume Injected (m^3)	Flow Rate (l/s)	Froude Number
1	120–140	36.8	9.5	35
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24	235–255	41.8	9.1	51
25	240–257	45.4	9.1	54
26	245–259	41.6	9.1	58
27	250–261	47.1	8.2	57
28	260	47.7	7.6	59
29	265	49.1	7.6	69
30	270	Adding fresh water onto the pond surface		

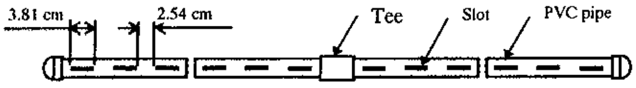

Fig. 7 Schematic of Injection Diffuser

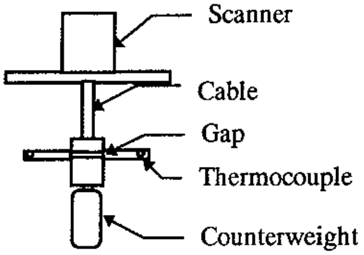

Fig. 8 Scanner and Sensor Head

lishment in 1995 is shown in Fig. 6. It can be seen that the daily injection results fit the projected salinity profile very well.

Compared to fixed level injection, the scanning injection technique offers several advantages. First, the achieved salinity profile was much smoother and resulted in a more accurate match with the desired profile. Second, the scanning injection technique is easier to use, less labor-intensive, and less time-consuming. For the El Paso Pond, the scanning technique reduced the time for gradient establishment by 50% as compared with the fixed level injection method. Third, scanning injection is not as sensitive to the Froude number. The only requirement for the scanning injection process is that the injection flow rate (hence the injection velocity at the outlet of the injection diffuser) be sufficient for achieving a minimum Froude number of 18 to ensure adequate mixing. The minimum Froude number used in the scanning injection at the El Paso Solar Pond was 35. Since the Froude number increases during the injection (as $\Delta\rho$ decreases), no flow adjustments are necessary.

3.3 Injection Diffuser. The injection diffuser design and its driving mechanisms have also been improved. Prior to 1995, circular double plate diffusers were used. In order to avoid interference, the diffusers must be placed away from the banks or instrumentation tower. In 1995, a pipe diffuser, mounted on the instrumentation tower, was designed, constructed and used for gradient construction. The diffuser is constructed of two pieces of 10 cm (4 inch) diameter PVC pipe. The two pieces have equal length and are glued to a tee which connects with the fresh water line through a 7.6 cm (3 inch) rubber hose. On each piece of the PVC pipe there are 14 slots 3.8 cm (1.5 inches) long and 0.32 cm (1/8 inch) wide, spaced 2.5 cm (1 inch) from each other (see Fig. 7). The design flow rate is 0.57 m^3/min (150 gpm), and the exiting velocity of injected fluid is 2.8 m/sec. The movement of the injection diffuser is driven by a DC motor and a drum-cable system mounted under the decking of the instrumentation tower. A precision potentiometer is employed as a position feed-back system. Both upper and lower limits of each injection region can be set and displayed on a computer/data logger. The scanning position, range and direction of the injection diffuser are controlled by the computer and relay circuitry. When the diffuser moves in one direction and reaches the preset limit, the computer will automatically reverse direction of the motor. After one injection step is completed, the upper and lower limits can easily be reset for the next step.

4 Instrumentation and Solar Pond Monitoring

Reliable instrumentation and monitoring procedures are essential for successful solar pond operation [3,13,14]. Critical data, such as temperature and salinity distributions in the pond, stability status, and clarity status, must be measured and analyzed on a regular basis. The selection of appropriate measurement methods and the development of a reliable, "user friendly" and "real-time" monitoring system, are essential for practical solar pond operation and the commercialization of solar pond technology.

Several measurement methods and instrumentation systems have been investigated and tested at the El Paso Solar Pond Project from 1986 to 1992, resulting in an automated, integrated system which uses scanner technology and a computer controlled data logger. In addition, the procedures for adequate data collection and analysis were developed, tested and refined.

4.1 Automated Instrumentation System. The automated instrumentation system consists of a drum-cable scanner, sensor head, sample pump, "U" tube density meter (trade name Dynatrol), pH probe, turbidimeter, cooling heat exchanger, and computer. The sensor head is mounted on the scanner. The scanner and sample pump are mounted on the deck of an instrumentation tower, with its base 61 cm (2 feet) away from the south toe of the pond wall. The density meter, pH probe, turbidimeter and heat exchanger are all mounted in the same enclosure on the pond bank near the instrumentation tower. The computer, which is used for both control and data logging, is housed in an instrumentation room adjacent to the pond. With the integrated instrumentation system, the temperature, salinity, and the brine quality at selected depths of the pond can be measured simultaneously. Measurement for the entire pond can be completed in about three hours using this system. This allows for a near "real time" view of the pond status thereby enabling more precise gradient maintenance required for high thermal performance operation.

The drum-cable scanner utilizes a stepping motor and is controlled by a computer for precise depth control. The position accuracy of this scanner for the required 3 m (10 foot) scan is ±0.1 cm (0.04 inch). This design offers the following advantages: it is easy to use, delivers high spatial resolution and accuracy, is reliable, provides continuity in pond data collection, and is easy to assemble and maintain.

The sensor head, as shown in Fig. 8, is made of a 7.6 cm (3 inch) diameter and 12.5 cm (4.9 inches) long polypropylene rod. A semi-circle, 0.2 cm (0.079 inch) inlet gap was cut on the middle of the sensor head which serves as the extraction diffuser through which the brine samples are withdrawn and flow through the heat exchanger, and the external devices—the Dynatrol density meter, pH probe, and turbidimeter. Two T-type thermocouples, providing redundancy, are mounted on the two opposite sides of the sensor head via two 1 cm (0.4 inch) diameter polypropylene rods, which are attached on the sensor head and extend outward. The two thermocouples are about 20 cm (7.9 inches) apart and have been aligned to the level of the diffuser inlet gap. In order to overcome the buoyancy of the sensor head in heavy brine and let the scanner move downward more smoothly, a counterweight is attached to the bottom of the sensor head. For more detailed information about this instrumentation system, see [12,15].

In addition to the integrated instrument system, a "string scanner" system is used as a temperature measurement back-up system. It consists of a T-type thermocouple scanned vertically through the depth of the pond on a weighted nylon string attached to a drum and DC motor.

4.2 Measurement Procedure. At the El Paso Solar Pond, salinity, pH, and turbidity distributions are measured on a weekly basis, since these changes occur at a very slow rate. However, temperature measurement is taken on a daily basis, or occasionally twice a day, during extreme operating conditions.

The spatial interval of measurement is important. Since the minimum thickness for persistent internal convective zones (gradient breakdown) is of the order of 5 cm [3], temperature and salinity profiles are measured simultaneously at 5 cm intervals. During some critical situations, such as gradient modification, the measurement interval is reduced to 2.5 cm, or even 1 cm. The pH and turbidity profiles are normally measured at 10 cm intervals. In order to minimize the influence of the turbulence on the measurement accuracy, the scanner is moved downward in a step by step fashion from the top to the bottom of the pond.

4.3 Pond Data Analysis. Data analysis is an important aspect of solar pond monitoring, especially for high temperature operation. Without data analysis, it is impossible to understand the pond status clearly and to plan for proper gradient maintenance. Most pond operation problems, such as gradient breakdown, can be avoided through timely data collection and analysis. From the experiences obtained at the El Paso Solar Pond, the major data analysis items which need to be performed routinely are: stability, salt management analysis, clarity and thermal performance.

4.3.1 Pond Stability Analysis. Stability analysis includes both boundary and internal stability analysis, both of which are essential for keeping the pond stable. Determination of boundary locations, monitoring boundary movement, and the temperature and salinity gradients at the boundary region are the most important aspects of the analysis for the boundary stability and equilibrium conditions. At the El Paso Solar Pond, the boundary positions are determined by using the temperature and salinity data collected at 5 cm intervals and by a "four point method" [15]. In this method, a curve is fit with only the four data points which are in the gradient zone and immediately adjacent to the boundary to obtain the equation representing the temperature or salinity distribution in the boundary region of the gradient. The equation is used to locate the boundary positions. By comparison with the 1 cm-interval-data, it has been determined that the uncertainty of the boundary positions determined by using the four point method and 5 cm-interval-data is less than 1 cm [15].

At the El Paso Solar Pond, the internal stability of the gradient is indicated by the stability margin number (SMN), which is defined as the ratio of the measured stability coefficient to the calculated stability coefficient required to satisfy the dynamic stability criterion. This concept was developed for the El Paso Project by Xu [16] and has been applied to the El Paso pond since 1990 [17]. The SMN can be mathematically expressed as

$$\mathrm{SMN} = (dS_a/dz)/(dS_j/dz) \tag{6}$$

where dS_a/dz is the actual salinity gradient (percent salt/m) as computed from measured values and dS_j/dz is the indicated theoretical salinity gradient value, in percent salt/m, required to satisfy the dynamic stability criterion for the given (measured) temperature profile at height z within the gradient zone. For details about how to evaluate dS_j/dz, see [3].

In principle, the SMN must be greater than 1 in order to sustain local stability in the gradient zone. In operating the El Paso Solar Pond, however, it has been found that when the calculated SMN goes below approximately 1.6 at a given depth, gradient breakdown usually occurs [17]. The possible explanation for this phenomenon is that some external turbulence triggers the gradient to become unstable and break down. At the El Paso Solar Pond, a value of 2.5 has been selected as an operational safety limit. If the SMN approaches this limit, corrective measures are used to maintain the internal stability within the gradient zone.

For computing the SMN, the temperature and salinity gradients must be determined using the measured pond data. Two methods have been used at the El Paso Solar Pond to estimate the actual temperature and salinity gradients: the "straight line method" and the "curve fit method" [15]. When using the straight line method, it is assumed that the gradient between two consecutive points is linear, and the temperature or salinity of the point centered between two consecutive points is the arithmetic average of the two measured points. With this method, the temperature and salinity gradients at the centered point are computed by the following equations.

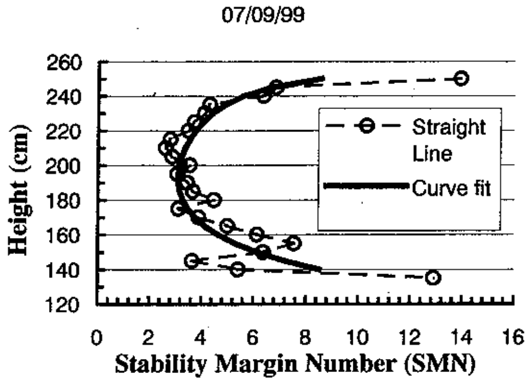

Fig. 9 Plot of Stability Margin Number of the El Paso Solar Pond

$$dT/dz = (T_2 - T_1)/(z_1 - z_2) \tag{7}$$

$$dS/dz = (S_2 - S_1)/(z_1 - z_2) \tag{8}$$

where T_1 and T_2 are the measured temperature at height z_1 and z_2, respectively, S_1 and S_2 are the measured salinity at z_1 and z_2, respectively.

When using the curve fit method, the temperature and salinity gradients in the gradient zone are expressed as continuous, smooth functions of height by fitting third order polynomials to the measured data. Third order polynomials are chosen because they best represent the functions, as determined by trial and error and operating experience at the El Paso Solar Pond. With the curve fit method, the SMN at any point in the gradient zone can be easily determined, and is not limited to the points centered between two consecutive measured points as in the straight line method. As an example, Fig. 9 shows typical SMN plots of the El Paso Solar Pond.

The straight line method produces scattered SMN profiles. The scatter of SMN data is caused by the uncertainties in the determination of actual temperature and salinity gradients. On the other hand, the curve fit method produces smooth SMN profiles and are easier to interpret. Although errors resulting in scatter of the SMN are reduced by the curve fit method, care must be exercised when recent changes to the salinity profile, or temperature profile, result in large changes in the derivatives at a local area. These "kinks" in the profiles may be smoothed over erroneously by the curve fit algorithm, thereby giving inaccurate stability margin number data. It is highly recommended that both the straight line and curve fit methods be used to analyze stability in critical situations. If there have been no recent gradient modifications or local heating, diffusion usually removes any local "kinks" and both temperature and salinity profiles in the gradient zone are smooth, and the curve fit method works well. However, during or just after gradient modification, or when there is local heating, the straight line method is required to analyze the local stability of some specific regions.

4.3.2 Salt Inventory Analysis. Salt inventory analysis is also important, especially for ponds in locations where salt is expensive and/or must be transported a substantial distance. A carefully planned salt recycling program can make solar pond operation more economical. The salt inventory analysis at the El Paso Solar Pond includes computing the quantities of salt in different zones of the solar pond, the total amount of salt in the solar pond, and the total amount of salt in the evaporation ponds. The salt inventory analysis helps not only in planning and budgeting salinity gradient modification and salt recycling, but also in leak detection, as experienced in the El Paso Solar Pond in 1992 [15,18].

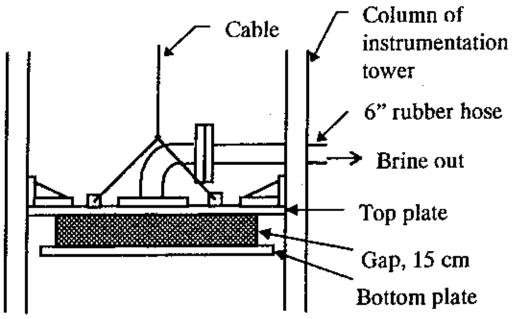

Fig. 10 Schematic of Suction Diffuser

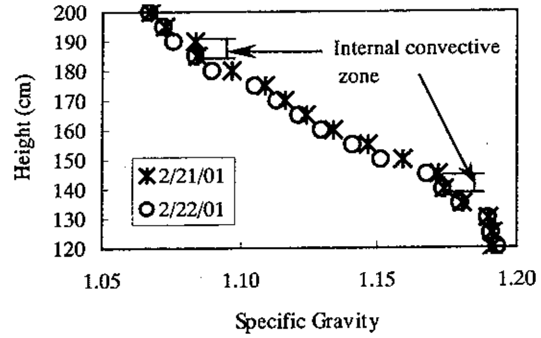

Fig. 11 Gradient Modification by Brine Extraction

5 Heat Extraction System

Heat in the solar pond can be extracted with either a submerged heat exchanger or by brine-withdrawal and return. In the submerged heat exchanger method, a heat exchanger is submerged in the lower zone of the solar pond and heat-exchange fluid (usually fresh water) is pumped through it to extract heat. In the brine-withdrawal method, the hot brine is pumped from the storage zone by means of a diffuser (extraction diffuser) mounted in the storage zone, passed through an external heat exchanger, then returned to the bottom of the pond through another diffuser (return diffuser). The brine-withdrawal method had been used exclusively at the El Paso pond and experience indicates that this method is effective and preferable. The extraction diffuser can be moved to the height of maximum temperature in the storage zone and the return diffuser is placed below it. This method allows placement for both diffusers near the point of use. Also, this method insures that the cooler brine is returned to the bottom, reducing ground losses.

Before refurbishing in 1994, the diffusers and pipes used in the heat extraction system were all made of steel. After several years of operation, they all indicated selective rusting. Besides the corrosion problem, the free ions of iron were suspected to contribute to clarity problems. In 1991 a black layer appeared in the pond and the brine became very turbid [19], interfering with normal pond operations. Iron reduction bacteria were a possible cause. Based on this experience, the heat extraction system was redesigned and reconstructed in 1994, when steel diffusers were replaced with new ones made of 1.9 cm (3/4 inch) polypropylene plate, and connected by 15 cm (6-inch) rubber hose to the external piping system.

Both suction and return diffusers are of a double-plate design. The suction diffuser, Fig. 10, is mounted under the deck of the instrumentation tower 20 cm below the lower boundary. The larger top plate helps to protect the lower gradient interface from being eroded by suction entrainment at the diffuser. The vertical position of the diffuser can be adjusted by a winch and cable attached to the diffuser. The return diffuser is placed on the pond bottom, about 15 m (50 feet) away from the instrumentation tower.

6 Solar Pond Maintenance

6.1 Gradient Maintenance.

Maintaining a stable gradient zone with a sufficient thickness and good clarity is the key to operating a salinity gradient solar pond successfully. If the salinity gradient is not strong enough to balance the effect of the destabilizing temperature gradient, both statically and dynamically, instability will occur, internal convective layers will form and can lead to destruction of the entire gradient.

It has been found that salinity gradient modification by scanning injection is the most effective method to control local stability, and prevent gradient failure; for details, see [20]. Gradient modification can also be accomplished using brine extraction from the gradient zone. Brine extraction has been successfully used at the El Paso Solar Pond to eliminate thin (less than 10 cm) internal convective zone(s). As an example, Fig. 11 shows the result of the brine extraction method at 185 and 145 cm depths which eliminated two internal convective zones.

In addition to controlling internal stability of the gradient zone, it is important to control the movement of the boundaries between the gradient zone and the upper or lower convective zone. Erosion caused by convection, and upward salt transport in the gradient by diffusion causes the upper boundary to move downward and the lower boundary to move upward, naturally. These boundary movements will reduce the thickness of the gradient zone. The best technique to control the boundaries are diluting the UCZ and salt addition to the LCZ. Figure 12 shows typical changes of both upper and lower boundary positions, as well as of pond level, for the period of July 1997 through January 1998. As expected, the upper boundary moved downward, dropping from 265 cm on July 24, 1997 to 222 cm on January 14, 1998. The lower boundary was quite stable, except for the first month after gradient establishment, and for January 1998. The lower boundary dropped from 110 cm to 100 cm in the first month after the gradient had been built, and stayed at 100 cm for more than four months. Then, in mid January 1998, it moved upward about 15 centimeters (6 inches), from 100 cm on December 15, 1997 to 115 cm on January 14, 1998. It has been observed that the lower boundary is more likely to rise during winter months (December to January). Additional investigations are needed to determine the causes for this boundary movement. However, based on these observations, action should be taken during winter and early spring months to control lower boundary movement. At the El Paso Solar Pond, saturated brine and some solid salt have been added to the pond bottom during the winter months. For maintaining the upper boundary position, concentrated surface brine removal and fresh water addition are necessary.

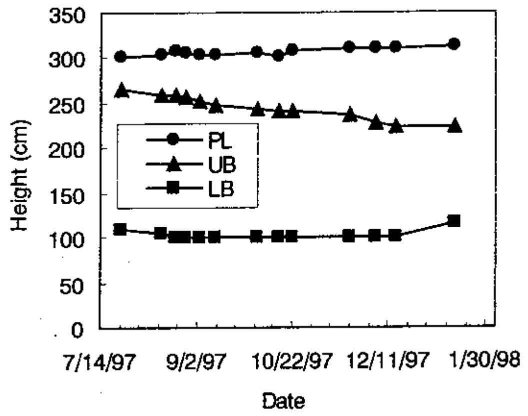

Fig. 12 Changes of Pond Level (PL), Upper Boundary (UB), and Lower Boundary (LB) of El Paso Solar Pond

6.2 Clarity Maintenance. Clarity is one of the most important factors in achieving good thermal performance. Salt concentration has no significant effect on the solar transmittance of brine [21,22], but suspended particles in a solar pond can seriously diminish solar energy input to the storage zone. Suspended particles can include both organic and inorganic matter. Clarity of the El Paso Solar Pond has been controlled successfully by lowering the pH level of the pond brine. The pH level in both the surface and gradient zones is maintained between 3 to 4 by addition of hydrochloric acid (HCl).

7 Pond Construction and Liners

The pond lining system is important for brine containment and is one of the major cost elements. Liners must be robust, able to withstand the harsh salinity gradient solar pond environment, have long lifetime of use, and be cost effective. Pond leakage must be prevented to avoid the loss of salt, where salt costs are appreciable, and to avoid environmental contamination where salt would be a problem. Several different lining systems have been used in solar ponds, including flexible membrane liners and compacted clay/plastic buried liners. During the past 16 years, the El Paso Solar Pond has experienced liner failures [10,23], and used three different liners: an XR-5 8130 liner, a geosynthetic clay liner (GCL), and a polypropylene liner.

7.1 XR-5 Liner. The XR-5 liner, a PVC coated polyester fabric, had been used since the 1970s in several solar ponds [3]. This liner, having a 1.0 kg/m^2 finished weight, was installed at the El Paso Solar Pond in 1984 as part of a double lining system with an existing hypalon liner beneath forming a secondary containment [24]. The projected lifetime of the XR-5 liner was 20 years. However, it failed in 1992 after seven years of pond operation. Over 100 holes were identified on the XR-5 liner on the lower side walls. A failure analysis indicated that the XR-5 liner, near the storage zone in the pond, where the liner was exposed to high temperature, had become very brittle and the strength of the material deteriorated to as low as 10% of its original strength [25].

7.2 Geosynthetic Clay Liner (GCL). An alternative to a geomembrane liner is a compacted clay/plastic lining (CCL) system, which was used for the solar ponds in Israel and Mexico. A CCL offers many advantages, such as low cost and puncture resistance. However, the characteristics and cost of CCL are very site specific, and can vary depending upon the experience of the installers [26]. It can also be difficult to find a suitable local clay for the CCL. In El Paso, five local clays were tested to determine optimum compaction, hydraulic conductivity, and mineralogical composition. None of the five clays proved acceptable for use in a solar pond environment.

After an investigation of various types of lining systems, two separate lining systems—a flexible polypropylene geomembrane and a geosynthetic clay liner (GCL) for the pond bottom were selected and designed specifically for the El Paso Solar Pond. The GCL used at the El Paso pond consists of a 0.2 inch layer of sodium bentonite clay glued to 30-mil polypropylene. It is manufactured by Gundle Lining Systems, Inc. The GCL is overlapped and thus requires no seaming, making installation much easier and less expensive. The bentonite has a 92% montmorillonite content and is formulated to resist the effects of contamination from salt water. It has a free swell of 31 ml per 2 grams of dry material. The two liner systems were installed in May 1994. The sidewall liner was a 40-mil polypropylene seamed liner installed over a 30-mil polypropylene secondary containment liner. The GCL was installed on the bottom of the pond with the clay side down to minimize contact between the bentonite and the sodium chloride brine. The seams of the GCL were overlapped 30~50 cm (12~20 inches) and a 146 kg/m^2 (30 lb/ft^2) overburden of sand was installed as recommended by the manufacturer. A drainage system installed underneath the GCL was designed to allow monitoring of the leakage rate. After hydration with fresh water, which is required for application in solar ponds, heavy brine with some dry salt was pumped into the pond from the evaporation ponds, and a salinity gradient was constructed in March 1995. Based on measured leak rates, the hydraulic conductivity of the GCL was found to be on the order of 2×10^{-6} cm/sec [27].

7.3 Polypropylene Liner. In summer 1996, about two years after the installation of the geosynthetic liner system, the 40-mil polypropylene liner on the pond sides failed. Because an improper UV stabilizer was added into the resin material during liner manufacturing, the liner degraded under UV exposure. Cracks and splits occurred above the pond water line, especially on the west, north, and east sides of the pond. The pond was drained in February 1997, and the entire pond was covered with an improved 60-mil polypropylene liner. It has worked satisfactorily since this time.

8 Applications of Solar Ponds

During the past two decades, a number of solar pond applications, including electricity generation, industrial process heat, chemical production, space and green house heating, crop drying, aquaculture applications, and desalination, have been demonstrated at sites around the world. Currently, the application of most interest in El Paso (and other arid areas of the world) is in solar pond coupled desalination and brine management.

Desalination with solar energy is an environmentally-friendly concept. Desalination by salinity-gradient solar ponds is one of the most promising solar desalination technologies, and studies have shown that for sites where conditions are favorable, salinity-gradient solar ponds are less costly than the other solar options [5,6,28–30]. Moreover, solar ponds provide the most convenient and least expensive option for heat storage. This is very important, both for operational and economic aspects, if steady and constant water production is required. Another advantage of using solar ponds for desalination is that reject brine, often considered a waste product, can be utilized as a basis to build the solar pond. This is an important advantage when considering solar ponds for inland desalting for fresh water production, or brine concentration for use in salinity control and environmental cleanup applications.

Research on desalination has been conducted at the El Paso Solar Pond Project since 1987, when it became the nation's first experimental solar pond powered desalting facility [31]. The desalination research can be divided into two phases. The research of Phase I (1987 to 1994) focused on the technical feasibility of solar pond coupled desalination technology. During this phase, two single-effect, 24-stage falling-film desalination units, (Spin-flash Mark I and Mark II), and a multi-effect, multi-stage (MEMS) flash evaporator were tested [32–34]. The research of Phase II (starting in 1997) focused on improving the efficiency and economics of solar pond coupled desalination, and has three major tasks: 1) to improve the thermodynamic efficiency of multi-stage flash evaporation powered by a solar pond; 2) to search and test other low temperature thermal desalination technologies; and 3) to develop a systems approach which integrates salinity gradient solar ponds with multi-process desalination systems and brine concentration technologies.

A used MEMS unit was refurbished and installed at the El Paso Solar Pond site in September 1997. This unit was tested under different operational conditions including variable heat input, temperature level, and brackish water sources. Major factors affecting distillate production and energy consumption rate were identified. It was also found that solar pond surface water can be an effective cooling source for thermal desalination, and electricity consumption can be reduced, thereby eliminating the cooling tower [35].

Besides the MEMS flash evaporation technology, membrane distillation (MD) has also been studied. MD differs from other membrane filtration methods in that the driving force for desalination is a differential in vapor pressure rather than total pressure. Water vapor, but not liquid water, will migrate through the hydro-

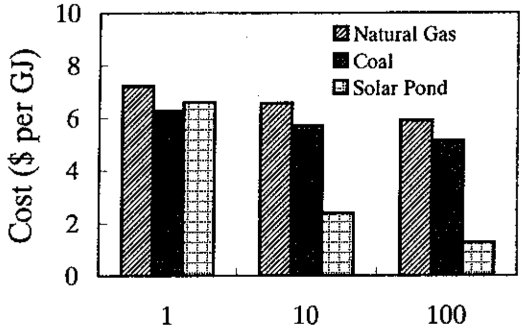

Fig. 13 Cost of Industrial Heat

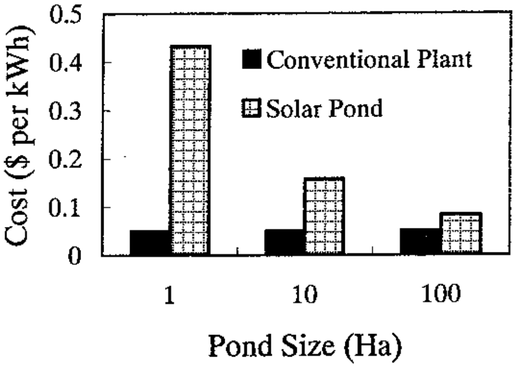

Fig. 14 Cost of Base Load Electricity

phobic membrane pores from the high vapor pressure (warm) side to the low vapor pressure (cold) side [36]. Since it requires low operating temperatures (30 to 90°C), membrane distillation can use low grade heat. In order to determine the technical viability and operational effectiveness of membrane distillation coupled with a salinity gradient solar pond, a small MD unit (about 350 liters/day) was tested at the El Paso Solar Pond in 1999. The experimental results demonstrate that salinity gradient solar ponds represent a feasible source of thermal energy to drive membrane distillation desalination [37].

Brine concentrate management or disposal is one of the major issues for application of desalination at inland sites. Inland desalination of brackish water must consider not only the equipment and energy required to drive the process, but also environmentally appropriate and cost effective brine concentrate management and/or disposal. Combining solar pond technology with desalination can lead to a "zero discharge" system, in which the reject concentrate from the desalination processes is reused by the solar pond thereby negating the need for disposal (zero discharge), and then converted to pollution-free energy for the desalting processes [38]. In order to study the technical and economical feasibility of this systems approach and to gather data and information for developing a "zero discharge desalination plant," a Brine Concentrator and Recovery System (BCRS) was constructed in 1999 and tested in 2000 at the El Paso Solar Pond [39]. Details of the "zero discharge" concept are discussed in [38].

9 Economics of Salinity Gradient Solar Pond Technology

A comprehensive study on the economics of salinity gradient solar pond technology was conducted by Esquivel [40] based, in part, upon the operation and performance of the El Paso Solar Pond. Economic data are presented here for utilizing salinity gradient solar ponds for producing industrial process heat and generating base load electricity. The study examined the economic feasibility as a function of salt costs, liner costs, and pond size, and determined that solar ponds can be economically feasible for those sites where land, brackish salt water, and solar insolation are favorable. Economic parameters for these results are based on 1991 dollars and 1992 interest rates. It is also assumed that liner costs are $4 per square meter and salt costs are $2 per ton.

9.1 Industrial Process Heat. As shown in Fig. 13, for industrial process heat at medium temperatures of 50–90°C (120–190°F), the levelized energy cost (LEC) ranges from $6.60 per giga-joule (GJ) for a 1-hectare (Ha) pond to $1.30/GJ for a 100 Ha pond at sites having similar climate conditions to El Paso, Texas. The delivered thermal LEC for solar ponds is compared with the delivered costs of heat from both natural gas and coal, also shown in Fig. 13. It can be seen that the unit cost of supplying industrial process heat from a salinity gradient solar pond is less expensive than either natural gas or coal for even modest pond sizes.

9.2 Electricity Generation. For generating electricity, maximum revenue is obtained by maximizing operating hours of the engine or in a base load mode of operation. This is due to the relative high cost of the organic Rankine cycle (ORC) generation equipment. Figure 14 shows that the production of base load electricity using solar ponds is more expensive than current electrical base load generation technologies. However, it can become more cost competitive when the pond size is larger, say greater than 100 Ha, and if the impact of environmental costs associated with burning fossil fuels are considered.

9.3 Desalination. Desalination of brackish water appears to be an extremely useful application of solar pond technology, as discussed above. In addition to providing clean renewable energy to power the desalination processes, salinity gradient solar ponds can utilize the waste brine. Table 2, based on a recent study at the El Paso Solar Pond Project, shows the cost of water produced by a zero discharge desalination system - which combines a solar pond with membrane filtration, thermal desalination and brine concentrator [41]. As shown in Table 2, the overall cost of product water ranges from $1.06/m^3 ($4.0/1000 gallons) for a 3,800 m^3 per day (1.0 million gallons/day, MGD) plant to $0.92/m^3 ($3.5/1000 gallons) for a 75,700 m^3/day (20 MGD) plant.

Table 2 Costs of Produced Water with Zero Discharge System

Plant Capacity (MGD)	1	5	10	20
Cost ($/kgal)	$4.00	$3.70	$3.60	$3.50

10 Conclusions

Salinity gradient solar pond technology has been significantly advanced during the past two decades. This paper has outlined operational experiences gained and key technical advancements developed at the El Paso Solar Pond Project.

The five key advancements are:

- An automated, integrated instrumentation system for solar pond monitoring, which allows for a near "real time" view of the pond status.
- Stability analysis strategy and gradient maintenance methods, that are critical for ensuring long term operation of the solar pond.
- A scanning injection technique for improved salinity gradient construction and maintenance.
- Improved heat extraction system with brine withdrawal method.
- New liner technology.

In addition, economic analysis indicates that SGSP technology is highly dependent on local conditions, application and size (i.e. larger ponds are more economically feasible). Also, the most economically attractive applications appear to be for medium temperature process heat and desalination.

Salinity gradient solar ponds have been demonstrated for a variety of applications, especially for low or medium temperature thermal applications. One of the most promising applications is desalination with associated waste brine management.

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Nomenclature

B = gap of diffuser (cm)
Fr = Froude number
S = salinity (% by weight)
T = temperature (°C)
V = volume (m^3)
v = velocity (m/s)
z = height (m)

Greek Letters

ρ = density (kg/m^3)

Subscripts

a = actual values
i = the initial values of corresponding parameters of the n^{th} injection step
f = the final values of corresponding parameters of the n^{th} injection step
inj = the values of injected fluid
z = height, elevation

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