SOLAR PONDS

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Contents

1. What is a Solar Pond?
2. The Design and Performance of Solar Ponds
2.1 Design Principles
2.1.1 Designing for an Application
2.1.2 Making Use of Local Resources
2.1.3 Matching Thermal Output to End-Use Requirements
2.2 Site Characteristics
2.3 Thermal Output and Sizing
2.4 Site Preparation, Excavation and Lining
2.5 Sources of Salt
2.6 Source of Water
2.7 Setting-Up and Maintaining the Salinity Profile
2.8 Pond Clarity
2.9 Heat Extraction
2.10 Monitoring Key Parameters
2.11 Calculating and Measuring Pond Performance
2.12 Costs and Economic Evaluation
2.13 Environmental Benefits and Sustainability
3. Experimental and Demonstration Solar Ponds
3.1 Introduction
3.2 Israeli Solar Ponds
3.3 RMIT University Solar Ponds
3.4 UTEP High-Performance Solar Pond
4. Applications of Solar Ponds
4.1 Heating
4.2 Aquaculture and Biotechnology
4.3 Desalination
4.4 Electrical Power Production
4.5 Salinity Mitigation
4.6 Production of Chemicals
5. State of the Art and Future Directions
Acknowledgements
Glossary

Bibliography
Biographical Sketches

Summary

The collection and storage of solar energy in the form of heat is feasible in a purpose-built and carefully-established open water reservoir commonly called a “solar pond.” Solar ponds have several important advantages: ease of construction; use of commonly available salts and waters to form the salinity gradient; combined collection and storage of solar energy; and on-demand extraction of heat for nearby practical applications. The design of a solar pond focuses on the purpose for which it will be used and the local site characteristics. Construction plans, for example, must take account of soil characteristics, to determine if lining is needed. Wherever possible it is beneficial to make use of local materials. Thoughtful attention to environmental sustainability, establishment and operation schedules and pond profile maintenance procedures is also required. Experimental, development and demonstration solar ponds have been built and operated throughout the world. Results from these facilities confirm that with proper design and operation the solar pond can supply thermal energy on an economical basis in suitable applications. Ponds can be operated seasonally or continuously, and at low, medium or high temperatures (up to 100°C), again depending on the chosen application and site. A wide variety of applications are practical, including aquaculture, industrial process heating, chemicals production, agricultural practices, electricity production and desalination.

1. What is a Solar Pond?

A solar pond is a large-area collector of solar energy resembling a pond that stores heat, which is then available to use for practical purposes. Researched designs include salt-water ponds, gel ponds, and others such as shallow ponds with covers, deep ponds with glass or plastic containment devices. Their common features are to store the energy in the incoming solar radiation in the heated depths of the pond, and to suppress the convection currents that would otherwise lead to heat loss to the surroundings.

The most common form of solar pond is a salt-water solar pond. Salt water ponds exist naturally in a variety of locations, the first ponds being discovered in Eastern Europe at the beginning of the 20th century at a natural salt lake in Transylvania. Most of the salt water ponds operated today, however, are artificial, simulating natural solar ponds but taking advantage of engineering technologies to advance their operation and application for practical purposes.

The key feature of a salt-water solar pond is that it has increasing amounts of salts dissolved in the water with depth (Figure 1). The salinity and hence density of each level of the pond thus increases with depth, so it is often called a ‘salt stabilised’ or ‘salinity-gradient’ solar ponds. Below this salinity-gradient zone there is a layer of near-saturated salt solution, the ‘storage zone’, and above it there is a thin layer of fresh or low-salinity water, the surface zone. The storage zone is typically one or two metres thick, and the overall pond two or more metres deep.

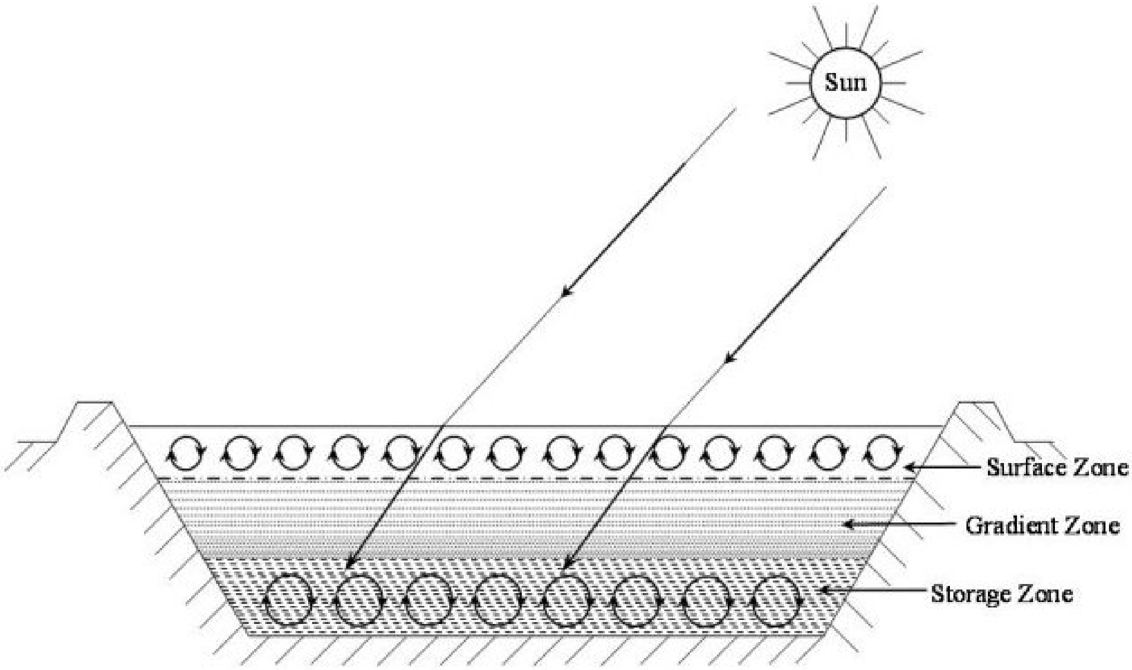

Figure 1. Schematic representation of a salinity-gradient solar pond

Much of the incoming solar radiation reaches the storage zone at the bottom of the pond where it heats up the concentrated salt solution there. Heat loss upwards in the pond from the storage zone is prevented since natural convection currents in the gradient zone are suppressed. This suppression and hence insulating effect occurs because of the density gradient present (Figure 2). As a particular layer of solution is heated from below its density is slightly reduced, but remains higher than that of the layer above. Hence there can be no movement upwards by the 'buoyancy' effect that drives natural convection in a normal body of water without such a density gradient.

The main process of heat loss from the storage zone has thus been halted, and while there are small heat losses by conduction through bottom and sides of the pond the storage zone heats up and retains this thermal energy until it is withdrawn for use. Temperatures above 80°C can be obtained in periods of high solar radiation, and elevated temperatures over ambient are maintained overnight and to some extent from summer to winter too (Figure 3).

The surface zone, with a thickness of typically half a metre, is mixed and kept cool by the winds blowing across the pond and heat loss by evaporation. This top zone requires continuous flushing with fresh water or low salinity water to compensate for evaporation and rinse away the salt rising to the top by the natural process of diffusion through the gradient zone.

Solid salt or saturated brine must be regularly added to the storage zone to make up for this loss of salt through upward movement to the surface zone. As long as these procedures are carried out, and waves that could cause mixing of the gradient layer are prevented, a salinity-gradient solar pond is a dynamically stable system.

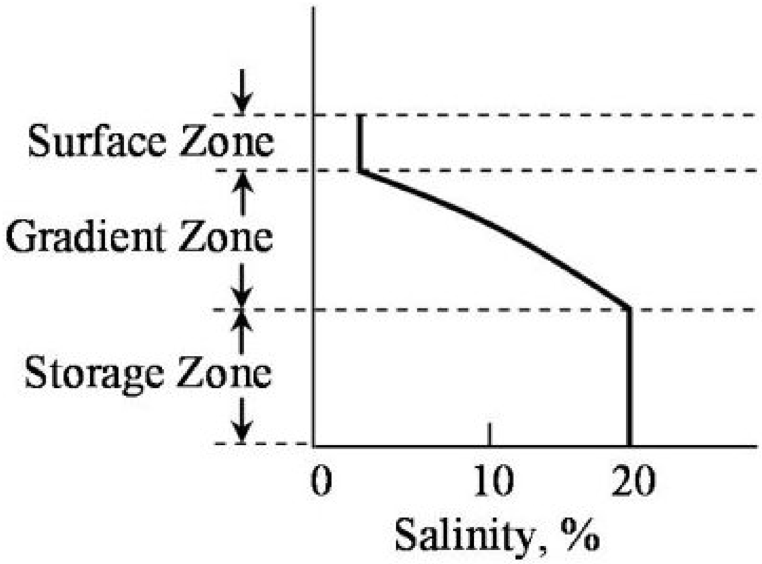

Figure 2. Salinity profile in a solar pond

Practical applications of solar ponds are many but direct use of the thermal energy for heating is most popular. The heat can also be used in a heat engine to drive a wide variety of mechanical technologies, including chemical and industrial heat processes, electricity production and desalination.

In this article, we will give some information on the design and performance of salt-water solar ponds (section 2), and some examples of experimental and demonstration solar ponds that have been constructed around the world (section 3). We will then survey the applications of solar ponds (section 4), and conclude with a review of the 'state of the art' of and future directions for solar pond technology.

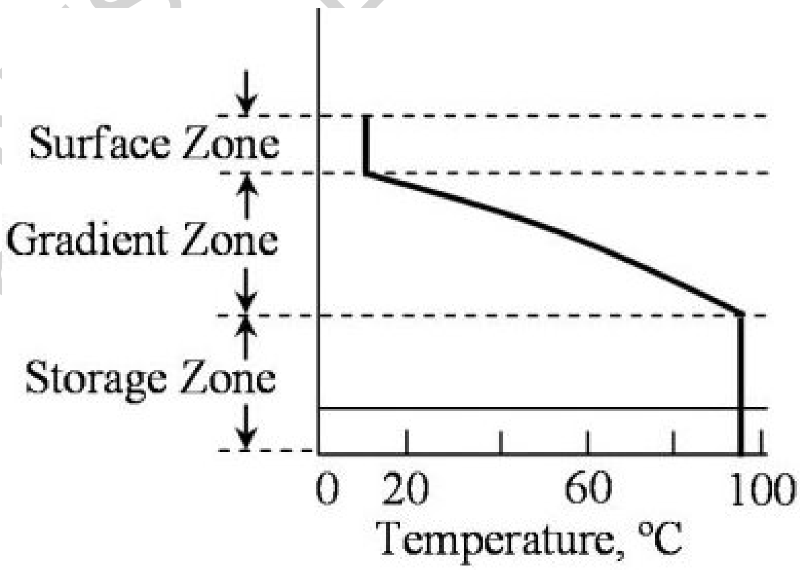

Figure 3. Temperature profile in a solar pond

2. The Design and Performance of Solar Ponds

2.1 Design Principles

2.1.1 Designing for an Application

An important first principle when designing a solar pond is to have a specific application in mind. This application may be heating for an industrial, commercial or agricultural enterprise. It is in this case crucial to know whether water, some other liquid or air is the medium to be heated. Also the temperature at which heat is to be supplied, whether up to say 80°C or as low as 35 or 40°C, is critical information for the solar pond designer. Alternatively the application may be electrical power generation or combined heat and power supply. When the desired application is known, the end-use energy requirements to be supplied by the solar pond can be identified, and the solar pond designed accordingly. In practice, for example, the characteristics of a solar pond to supply hot water at say 35°C to an aquaculture facility will be very different from that of a solar pond to be used to generate electricity where sustained performance at higher temperatures of 80°C or above is essential. Obviously the solar pond must be located as close to its application as possible.

2.1.2 Making Use of Local Resources

The economic viability and ecological benefits of employing a solar pond are always enhanced if maximum use of local material and human resources is made. A key requirement is to have locally available salt, or saline water (the saltier the better), and relatively fresh water too. Sufficient land area, the flatter the better, is also needed, and high level of annual solar radiation. Since construction of the solar pond basically involves earth moving and plumbing, it makes good sense to use local contractors.

2.1.3 Matching Thermal Output to End-Use Requirements

The aim is always to match the temperature of the hot brine in the storage zone of the solar pond with the desired heat delivery temperature for a proximate application. Clearly the storage temperature must be higher than the application to achieve the require heat transfer. But heat loss and economic penalties mount if the storage temperature is much higher than the delivery temperature than is necessary

2.2 Site Characteristics

Thoughtful sitting of a solar pond assists smooth installation and operability. Many of the site characteristics for a solar pond are similar to those for location of any artificial pond. Land that is amenable to forming banks, with soil that is cohesive and either structurally stable or compactable, within easy access to water and salt or brine supplies, and environmentally acceptable locations for managing salt recycling or disposal, are the ideal factors. In addition to geo-environmental considerations, the prevailing weather environment is also relevant. Locations where the wind is constantly strong would not be as ideal as calm locations. Clearly the annual solar radiation profile directly affects pond performance. However, it is still possible to build ponds that will operate well in high-latitudes, with increased area compensating for less available radiation per unit area of surface. A list of the ideal characteristics for a solar pond is given in Table 1, but please remember that some of these items are mutually exclusive.

o Free draining soil. o Free salt available nearby to reduce costs. o Easily compactable soil for structural stability. o Low prevailing wind speeds to minimize wave-induced mixing and the depth of the top mixed zone. o An environmentally acceptable disposal method or recycling ability for closed-salt inventory balancing. o Flat land to minimize earthmoving requirements.	o Dry soil for good thermal insulation. o Easy access to water supply for pond establishment and surface washing. o High incident solar radiation for good thermal performance. o Low evaporation to minimize the need for make-up water. o A method to withdraw heat readily; and a place where pond monitoring and control systems are locatable.	o A soil with good cohesion for forming stable walls (if not excavating). o A low amount of wind-borne debris to easily maintain cleanliness. o A stationary or deep groundwater table to minimize heat loss within the ground. o Most important some way in which to use the heat or power output usefully.

Table 1: Desirable characteristics for siting a solar pond

In reality, compromise is necessary. By way of example, in places where there is a high incidence of solar radiation, evaporation rates are usually substantial. Thermal leakage will be high and the pond will not perform as expected if the groundwater can remove heat from the bottom of the pond. If the water table at the site is shallow, and especially if there is water movement in the soil, consideration needs to be given to draining the area or insulating the pond, both of which add to construction costs.

2.3 Thermal Output and Sizing

The thermal performance of a solar pond largely depends on the nature of the absorption of solar radiation in the layers of the ponds. The water in the pond needs to be as clear as possible so that the maximum amount of solar radiation reaches the storage zone at the bottom. The more radiation that gets there, the higher the energy efficiency and operating temperature of the pond will be. In a well- designed and set up solar pond, upward heat losses from the storage zone are small.

Therefore most of the solar radiation that gets through to the storage zone is stored there, apart from the small amount lost by conduction to the ground. A typical solar pond with a depth of 3 metres and a storage zone 1 metre thick would receive around 20-25% of the radiation incident upon the pond’s surface. After accounting for losses to the ground, in practice around 15-20% of the incoming radiation is available for extraction to an application, with the heat delivered 40 to 50 degrees above the daily average temperature of the location.

The surface area and depth of the pond determine its operation and performance characteristics. A simple way to estimate the pond surface area required to meet any particular average annual thermal load is the following. Look up the annual solar energy incident on a square metre of horizontal surface at the location of the pond (say 7 GJ/m^2/year). Calculate the horizontal surface area on which the incoming solar radiation over a year is equal to the annual load to be supplied. If the annual load was say 2800 GJ, this area would be 400 m^2. Then multiply this surface area by a factor of 5 to 10 to estimate the surface area of a solar pond to meet this annual load. So in our example the solar pond would need to have an area of between 2000 and 4000 m^2 to supply an annual thermal load of 2800 GJ.

The actual design size will be impacted by the brine characteristics – most importantly water quality and transparency – and the operational strategy for the pond. A pond operated with steady withdrawal will be sized larger than a pond used for rapid, peak-heat extraction over a short periods. Thus operational dynamics impact on the final design. Important design parameters will include: ground thermal conductivity, requiring site specific figures for soil thermal conductivity and permeability; pond configuration requirements, requiring knowledge of pond site characteristics; local weather features, including long-term weather and solar data; and pond depth characteristics.

The temperature and quantity of the heat storage in a solar pond are determined by the available pond water characteristics, including transparency, and the pond depth. The depth determines such factors as maximum pond temperature, heat losses to the surrounding soil and air environments, and temperature decay time upon extraction from the storage zone. There are a lot of assumptions to be made, and the experience of practical solar pond operations provide a very useful guide for design sizing purposes.

A solar pond with a deep storage zone (typically of the order of 2 to 5 m) will store a large quantity of heat for a long time. Heat losses will be lower and the collection and storage efficiencies of the pond will be high. In contrast, a shallower storage zone (typically of the order of 1 to 2 m) can readily attain higher temperatures (since there is not so much thermal mass in storage), but will then have higher heat losses to the air and ground and a shorter storage capacity. Once again, the application impacts on the design.

2.4 Site Preparation, Excavation and Lining

The land chosen as the site for the solar pond should be as flat as possible. In order to minimise the heat losses to the ground it is desirable that the underground water table is 5 metres or more below the natural ground surface. If the water table is shallower, then insulating the bottom of the pond may be considered using insulation materials such as sheets of polystyrene. For large ponds (greater than about 1000 m^2), it is best to construct the pond by establishing the walls using the soil excavated from the periphery of the pond. The bottom of the pond will thus be below the surrounding ground level.

This arrangement provides the head required for gravity feeding of the surface water from the solar pond to adjacent evaporation ponds, as well as siphoning off brine samples from different depths in the pond for the required analysis.

Where unlined ponds can be operated effectively, the cost of solar ponds is lowered significantly since lining is one of the main cost components. However, in many locations pond lining is necessary, for both environmental as well as performance reasons.

Hot brine leaking out from a pond will carry away with it salt and heat, which in most places is not environmentally acceptable. The liner material should be able to withstand the anticipated maximum pond temperature, be resistant to ultraviolet radiation, should not react with salt. Above all it should be mechanically strong. Failure of liners has been one of the main problems encountered with working solar ponds.

2.5 Sources of Salt

The most common salts used in salinity-gradient solar pond are common salt (NaCl), as well as bittern, a magnesium-potassium rich salt solution remaining as a byproduct of salt production from salt water by evaporation and crystallisation. Aqueous solutions of sodium chloride can attain densities of 1200 kg/m^3.

However, this density can be increased to more than 1300 kg/m^3 if the salt used is mainly magnesium chloride. It would be possible to construct and maintain stable gradients with both salts. When setting up a solar pond as an integral part of a commercial salt production facility – an attractive proposition as we shall see later – it makes good economic and environmental sense to set up the solar pond using bittern, and save the more valuable sodium chloride for salt making.In order to operate a solar pond with minimum cost and minimum environmental impact, it is important to recycle the salt extracted from the pond by surface washing. For example, the salt solution flushed from the surface of the solar pond can be collected in an adjacent evaporation pond and there concentrated for later injection back into the storage or gradient zones of the pond. Such an evaporation pond needs to be at least equal if not twice the total area of the solar pond. Alternatively the flushed salt solution can enter a sequence of evaporation ponds in a salt production facility.

2.6 Source of Water

One of the most important criteria in determining the viability of a solar pond is the availability of fresh or low-salinity water (less than 50,000 ppm salt concentration or a density of less than 1050 kg/m^3). The amount of low-salinity water required to establish a pond is about the volume of the water in the pond measured from the surface to the middle of the gradient layer.The amount of water needed to maintain the gradient depends on evaporative losses, and the flow rate of the overflow system removing surface flushing water containing the salt that has diffused upwards. As a rule of thumb, a surface flushing water flow rate of two to three times the yearly average rate of evaporation is required. The rate of adding water to the surface zone must exceed the rate of removal through the overflow by the rate of evaporation.

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Bibliography

Akbarzadeh, A., Andrews J., and Golding P., (2005), Solar Pond Technologies: A Review and Future Directions, Chapter 7, Volume 16, Advances in Solar Energy, Edited by Goswami D. Y., Earth scan, USA. [A brief history and comprehensive review of worldwide developments in solar pond technology]

Hull,J. R., Nielsen C. E and Golding P., (1989), Salinity Gradient Solar Ponds (CRC Press, Boca Raton, Florida) . [A seminal text book on solar pond theory, design and operation]

Tabor, H. and Weinberger, Z., (1981), Non-Convecting Solar Ponds, Chapter 10, Solar Energy Handbook, Edited by Kreider, J.F. and Kreith, F., McGraw_Hill Book Company. [An introduction to solar pond principles and practice]

Biographical Sketches

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Prof. Akbarzadeh served as the chairman of the 1996 International Symposium on Heat Pipes and 1995 International Symposium on Energy, Environment and Economics.

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Peter Golding received his B.S. and Ph.D. from Monash University, Australia in 1977 and 1982 respectively. He is an Associate Professor in Metallurgical and Materials Engineering in the University of Texas at El Paso since 2000 where he also served in the Mechanical & Industrial Engineering department from 1989 to 1999. In the College of Engineering he is director of the Basic Engineering program, the Pre-Engineering program and Student Affairs / Success. Associate Professor Golding is the author/co-author of books and textbook chapters on solar energy technology, interdisciplinary technology and society, and fundamentals of Engineering, and has over 30 publications in the area of renewable energy. He has received federal Department of Education honours and awards for advancement of scholarship on

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