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Performance evaluation of single and double-basin solar stills in Las Vegas, Nevada

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PERFORMANCE EVALUATION OF SINGLE AND DOUBLE-BASIN SOLAR STILLS IN LAS VEGAS, NEVADA

by

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ABSTRACT

Performance Evaluation of Single and Double-Basin Solar Stills in Las Vegas, Nevada

by

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The objectives of this research were to conduct long-term testing of modified single-basin still designs, and to design, build and test an alternative double-basin still that may increase water production at the same or lower cost.

Performance of two commercial single-basin still designs, from different suppliers, was evaluated over a 14-month period in Las Vegas, Nevada. The average daily water yields of Sunwater® and SolAqua™ ranged from 1.1±0.7 L/m^2 and 0.9±0.5 L/m^2 (in winter) to 5.5±1.7 L/m^2 and 4.6±0.9 L/m^2 (in summer) respectively.

Different configurations of cover glass and water volume/depth were evaluated on Sunwater® single-basin stills. Low-e glass was found to produce 14.7% less water than standard clear glass. Water yield was generally not sensitive to operating water depth.

A double-basin prototype was constructed and tested. It had an average daily yield of 0.47 L/m^2, while the standard stills produced in the range of 1.8 - 2.9 L/m^2.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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My sincere thanks and best wishes to my family, and all my friends.

All of the world's water goes either into the ocean or into the rich's purse..

Anonymous

CHAPTER 1

INTRODUCTION & LITERATURE REVIEW

1.1 Introduction

Water is the essence of life. It is rightly said so because of the fact that our bodies are constituted of 70% water. The same proportion of the earth's surface is also water, of which 97% is present in the form of oceans. Out of the 2.5% estimated fresh water, roughly about 0.83% is in the form of groundwater/surface water (streams, lakes, and rivers). The rest is trapped in the glaciers and icebergs [earthobservatory, 2007]. Tremendous increases in population, industrialization and urbanization have put a lot of pressure on freshwater supplies. These same factors are causing pollution of such magnitude that it is becoming increasingly difficult to treat available fresh water to attain potability standards. Therefore, it is necessary to develop innovative methods to make water potable.

Desalination of sea and/or brackish water is an important alternative, since the only inexhaustible source of water is the ocean [Al-Kharabsheh, 2003]. Desalination can be defined as a process of reducing the salt content of water so as to make it potable. According to the World Health Organization (WHO) the permissible limit of salinity in drinking water is 500 ppm (or 500 mg/L) and for special cases up to 1000 ppm. Seawater and ocean water vary between 35,000-45,000 ppm in the form of total dissolved solids [Tiwari, 2003].

There are several methods for carrying out the desalination process. They are membrane filter techniques such as single and multiple stage nanofiltration and reverse osmosis, ion–exchange, phase change, electrodialysis, and vapor compression. Though these methods are very efficient, they are also very costly and require high maintenance. While they are economical for large-scale production, the non-renewable fuel usually needed for their operation could cause a lot of damage to our environment in the long run if these technologies were implemented on a large scale.

Solar stills offer a simple, clean and economical technology that replicates the hydrologic cycle, evaporation and condensation by utilizing solar energy. Many of the population centers in the world are located in the tropical or subtropical regions that usually have sufficient year-round sunlight to make solar distillation feasible. Hence, solar stills can be used effectively in underdeveloped and rural regions where there is no proper electricity supply and water demand is lower than 200 m^3/d [Fath, 1998]. A simple single basin solar still (SBSS), for example, can produce up to 2 $L/m^2/d$ in a mild winter and 4-6 $L/m^2/d$ in summer. In general, the average potable water requirement is 3-5 L/person/d, which can be, partially or fully met by commercial solar stills depending on still size.

The low yield, compared to other desalination processes, has overshadowed solar distillation's other attractive features, which is why the technology has not yet been accepted commercially in the global market. Another reason is economics, which depends on several factors such as, weather, proximity of suitable water supply, land costs (applicable in case of large stills for communities), availability of materials, labor, unit cost of energy (in case of active stills), interest rates, amortization rates, influent water quality, and social practices.

1.2 Research Objectives

The objectives of the research work were;

- To determine the long-term performance of the solar stills under varying climatic conditions.
- To observe the effects of changes of the still design on performance.
- To design, and fabricate a prototype which would give improved results compared to standard stills.

1.3 Literature Review

Use of solar energy in purifying water is a centuries' old practice. In the fourth century B.C., Aristotle described a way to evaporate impure water and then condense it to for potable applications [Tiwari, 2003]. Mouchot, a well-known French scientist, mentioned in his books that the earliest well-documented work on solar distillation was by Arab alchemists, who during medieval times carried out experiments with polished Damascus concave mirrors to focus solar radiation onto glass vessels containing saline water in order to produce fresh water [Delyannis, 2003]. Giovani Batista Della Porta wrote books on solar distillation during the 16th century that were translated in many different languages. He built and tested a unit that purified brackish water [Delyannis, 2003].

Nearly three centuries later, in 1872, Swedish engineer Carlos Wilson, constructed the first large industrial solar plant at Las Salinas, near Antofagasta in Northern Chile [Hirschmann, 1975]. The entire plant consisted of 64 bays having a total surface area of 4,450 m^2 and producing on an average 22.7 m^3/d [4.8 $L/m^2/d$] of distillate. For about 40 years it provided drinking water to the community near the silver and saltpeter mines.

Again for a few decades there was not much development in this field until World War II started. The US National Research Defense Committee (NRDC) funded solar research, resulting in many patents such as the practical individual small plastic solar apparatus, which served to distill water aboard a lifeboat. At the same time Maria Telkes, along with a team in MIT, came up with various glass-covered and multiple-effect solar still configurations [Delyannis, 2003]. Stills are broadly classified as active and passive. An active solar still is the one that is provided with an additional heating source such as a solar collector, heater, and/or partial or full recirculation of outgoing water in order to increase the basin water temperature, and in turn increase the evaporation rate. In contrast, a passive solar still does not require any additional energy, which means that heat collection and distillation processes take place in the same system. The most tested and proven solar still on the field is the passive single basin solar still (SBSS). A schematic SBSS cross section is as shown in the Figure 1.

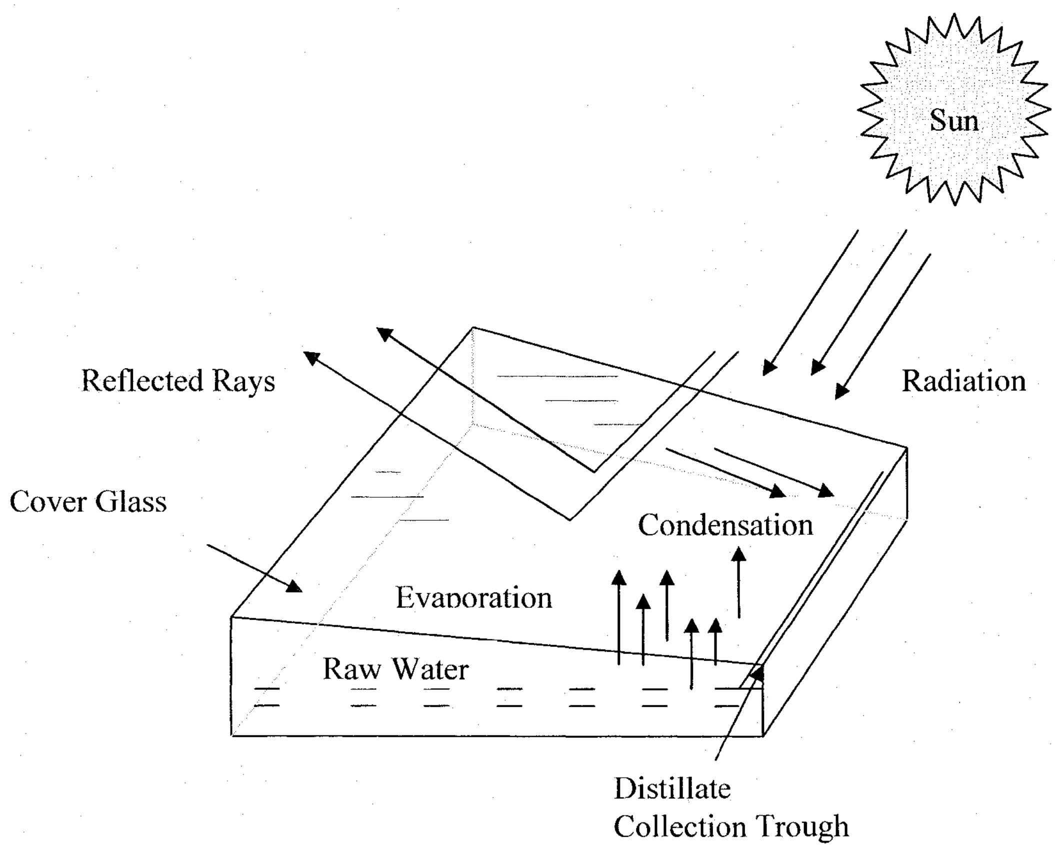

Figure 1: A Simple Single Basin Solar Still (SBSS)

A passive single basin solar still consists of a simple basin and a sloping cover. The basin can be made out of wood, metal, plastic or waterproof concrete. It is insulated with materials such as polyurethane, polystyrene, sawdust, or fiberglass to retain heat inside the basin by minimizing conductive and convective heat losses. The basin is constructed so that the cover, when laid on top, is set at a 2°-20° angle to the horizontal. The cover can be either glass or agricultural plastic. Glass is usually preferred because of its rigidity. Internally, the still is provided with a collection trough on the front end and externally it has inlet and outlet hose pipe connections for filling and drainage purposes respectively.

Several solar stills have been built based on innovative ideas with the purpose of increasing the product yield and reducing the cost per liter produced.

- Mutiple-effect basin still: This design consists of more than 1 basin, placed on top of each other. Here the latent heat of condensation in one basin is utilized to heat the water in the basin above it.
- Wick still: The SBSS is provided with a wick with one end in the feed tank and the other inside the still. Water is fed into the still by capillary action of the wick. At any time there is always only a film of water inside. Because of this there is a faster rate of temperature increase and a higher peak temperature of the distilland, resulting in a higher rate of water production.
- Hybrid still: An SBSS, in addition to distillation, can be used for other purposes such as;
    - Rainwater collection: A trough can be attached externally to the still to collect rainwater, which later can be used as feed.
    - Greenhouse heating: A solar still can be installed on top of the greenhouse with its roof serving as the cover of the still.

Research in this field has resulted in the improvement of quality and quantity of water produced from solar stills. The following published findings have been basically divided into two categories depending on the time period of analysis:

a. Short term: Experimental work lasting from a few days up to a month, and
b. Long term: Experimental work lasting anywhere from a month to a year(s).

1.3.1 Short Term Testing

a. Design Modification for improvement in quantity

Bahadori et al. [1971] did experimental work to improve the glazing of still glass covers, and thus the overall production. They found that etching the glass with either sodium metasilicate or hydrofluoric acid made them more wettable. Nine solar stills of 1 ft^2 area each, made of plastic, were tested with a water depth of 0.63 cm (0.25 inch) during March in Tempe, Arizona. Out of 9 stills, 3 had untreated glass covers. All the stills had covers at slope varying from 1.5° to 10°. The maximum production was that of the etched glass at a slope of 1.5° at nearly 8.2 $L/m^2/d$, though it is not mentioned for how many days the stills were run. It was concluded that etched glass could be used with a minimum slope of 1.5° which in turn improved the vapor path due to diffusion, thus improving the performance of the still.

Sodha et al. [1979] carried out a comparative study of double basin and single basin stills in New Delhi, India. Experimental stills of basin area 0.9m x 0.8m were built. Glass wool of 0.05m thickness was used as insulation and 3 mm thick glass covered the stills at a slope of 10°. Raw water was maintained at a depth of 6 cm in the single basin and the lower part of the double basin. The upper basin had water up to the inner surface of the cover glass. For a typical winter day (not exactly mentioned when), the double basin produced nearly 3.24 L/m^2 and single produced about 2.32 L/m^2. Although the minimum production rates of both stills occurred at around the same time (9 am), the peak production of double basin lagged that of single by almost 2 hours (around 7:30 pm for single, and 9 pm for double). The authors also performed numerical analysis and found out that the double basin still, by the use of latent heat, had produced 36% more water than the single basin.

The efficiency of different designs of solar stills was investigated by Tayeb [1991]. They all had the same evaporation area of 0.24 m^2 but varying condensation areas which was achieved by changing the way the cover material was laid over the basin. Plexiglas was used for three of the stills, while the fourth had glass. The lowest condensation area of 0.267 m^2 was that of the glass sloped flat on the still, and the highest at 0.565 m^2 was of the basin covered by Plexiglas in the shape of 2 half cylinders. The other stills had covers in the shape of half cylinder or slightly curved. The stills underwent 9 runs, from 31st May to 9th June 1990. It was found that the increasing the condensation area did not increase the water production by the same factor. The observation of basin, cover, and ambient temperature revealed that glass was the best material for this purpose as Plexiglas, due to its high surface tension, leads to beading of water droplets during daylight. However, after sunset when the production of glass drops sharply, the Plexiglas continues to produce. Also, at mid day (from 12-14:00 pm) when the cover temperature is highest, unlike the stills with covers of glass, the slightly curved Plexiglas cover stills produced at a higher rate because of their increased available condensation area. The overall efficiency was found to vary between 14.9 to 21.8%, glass being the most efficient, followed by double half cylinder still, half cylinder, and finally the slightly curved Plexiglas.

Hamdan et al. in 1997 carried out some experimental work on single, double, and triple basin solar stills in Amman, Jordan. All the stills had the same base area of 0.96 m x 0.96 m. Four glass covers were inclined at 45° in order to form a pyramid. Data was reported for a single day's operation. During daytime, single basin used to give the maximum production followed by double and triple. This process would reverse as the day progressed, as the latent of heat of condensation was also being utilized in multistage basins, hence increasing their production. Operating water depth was not mentioned. The triple basin had the highest output of 4.9 L/m^2 followed by double with 4.6 L/m^2, and single basin with 3.7 L/m^2. Hence, the triple basin was calculated to be 32% and 6.5% more efficient than the single and double basins respectively. Whereas, double basin was 24% more efficient than the single basin still.

Elkader [1998] analyzed the effects of base slope angle, cover slope angle, and air gap on the efficiency of an SBSS with inclined jute. Three still models, were constructed each having a basin area of 1 m^2, front-end height of 18 cm but different back-end (H) heights. During the course of the experimental work, carried out in Port Said, Egypt, the still base slope and the cover glass slope angles were varied from 10° to 35° and 30° to 45° respectively to get maximum production. The glass and jute temperatures were measured regularly. Elkader showed that varying the angles brought about very small change in the cover glass temperature but noticeable changes in the jute temperature. The best results were observed for the still with front and back heights of 18 cm and 57 cm, having the cover glass mounted at an angle of 35° and the still base at 15°. This still produced 5.5 $L/m^2/d$.

The effect of using different absorbing materials in an SBSS and thus enhancing its efficiency was studied by Akash et al. [1998]. The experimental still had a basin area of 3 m^2 with the cover glass mounted in an inverted V shape at an angle of 25°. The raw water volume was 120 L (water depth of 4 cm). Three different absorbing materials were used, black rubber mat, black ink-in-water solution, and black dye-in-water solution. The experiment was carried out in Amman, Jordan. The standard still, without any absorbing material, produced the least amount of water. Black dye produced the greatest amount, nearly 3.45 L/d. The peak point of distillation was at 2:30 pm for all the stills. The black dye, black ink, and black rubber mat showed 60%, 45%, and 38% improved results, respectively, compared to the standard still.

Khalifa et al. [1999] modified several basin type solar stills in order to improve its performance. Basically there were 3 groups of stills, A, B, and C. Group A consisted of A1 (simple still), A2 (simple still with a parabolic collector solar heater), and A3 (simple still with 2 external condensers made of glass). Group B also consisted of 3 stills, where B1 and B2 were simple double-slope and single-slope stills, and B3 was a combination of B2 and an 8 pass internal condenser. Still C was a single slope still that was tested with and without a double pass internal condenser. The purposes served by these modifications were preheating of raw water by a solar collector and additional vapor condensation by internal and external condensers. The stills were operated with different water mass flow rates and volume flow rates on clear days in Baghdad, Iraq. Group B stills were run for five days while, still C was experimented with and without the internal condenser for four and two days respectively. It was evident from the results that efficiency of A3 was 14% greater than A1 and that of A2 was 4% more than A1. The internal condenser in B3 increased the efficiency of the single slope still by 33.8%. It was also found to be better than double slope still by 57.6%. Still C was more efficient in the presence of the internal condenser as it enhanced the performance by 8.7%. It was observed that an 8 pass condenser (used in B3) was much better than a double pass (used in C).

Along the same lines as above, Nafey et al. in 2001 tried increasing the still efficiency by introducing black rubber and black gravel in the basin as storage materials. Four identical stills, each having dimensions of 0.5m x 0.5m, were constructed. The units were insulated with 4 cm thick foam, and covered with 3 mm window glass at a 15° slope. Effects of varying storage material dimensions (rubber mat-2, 6, 10 mm thick and gravel-7-12, 12-20, 20-30 mm) and distilland volume (20, 30, 40, 50, and 60 L/m^2) were observed. Results from six experimental runs carried out in Egypt in September 1998 were reported. The positive effect of the rubber mat was found to be directly proportional to its thickness and to the volume of water in the basin. A 10 mm mat placed in the basin containing 60 L/m^2 distilland resulted in 20% increased efficiency. But in the case of gravel, the efficiency was highest for the maximum size (as it increased the evaporation area) and minimum water volume; 20-30 mm gravels along with raw water volume of 20 L/m^2 enhanced the still productivity by 19% compared to the standard still.

Naim et al. [2002] demonstrated the use of an energy storage material (ESM) in increasing the production of solar stills. The ESM in this case were distilled water, and a mixture of paraffin wax, paraffin oil, water and aluminum turnings. The latter was called a phase change energy storage material (PCM), which stores heat in daytime and releases it in the night, by melting, hence resulting in improved nighttime production. The effects of varying factors such as the concentration, flow rate, inlet temperature of the saline water and duration of the experiments on the stills' performance were studied. A total of eight experimental runs were reported in Alexandria, Egypt. Under good conditions viz.

longer experimental duration (7 hours) and higher ambient air temperature, the still in the absence of ESM produced a mere 0.21 L and 0.09 L during daytime and overnight operation respectively. On the other hand, under similar conditions, in the presence of PCM, the still produced o.44 L and 0.08 L during daytime and overnight operation respectively. It was observed that ESM worked much efficiently with increased saline water flowrate. The highest production of 0.86 L (0.66 L-daytime, 0.2 L-overnight) was obtained at a flowrate of 40 mL/min

Bouchekima [2003] conducted experiments to determine the efficiency of a capillary film solar distiller. A DIFICAP (distiller with a film in capillary motion) attached to a flat plate collector was run with geothermal water rich in Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, $CO_3{}^{2-}$, SO_2^-, and CO_2^- found abundantly near Touggourt, South Algeria. In this type of still, a very thin layer of tissue with fine mesh, saturated with water, is maintained in close contact with a metal plate due to surface tension, which is much greater than the gravitational forces. The author claimed production rates of 15-20 L/m^2/d.

Solar desalination not only is a cheap method of purifying saline water but also an environmentally friendly one. One hurdle can be the cost. But if stills are made out waste or recyclable material, then that problem will be solved too. This aspect was studied by Toyama et al. [2004]. Three different designs were tested.

- A small polyethylene terephthalate (PET) bottle was placed inside a big one.
- A flower pot was covered by a transparent plastic cap in the shape of a dome.
- A washing bowl, of diameter 300 mm, covered with a transparent shopping bag. The polyethylene sheet was wrapped in such a way so as to form two cones, above and below the bowl. This arrangement was tested in the laboratory where

the solar beam was replaced by infrared lamps. The beam strength was matched with the data from the meteorological agency. The maximum water production volume was found to be 3.54 L/m^2.

Tunisia, being in "Sun Belt", has 350 sunny days per year [Bouguecha et al., 2005]. The authors tried to identify the potential of solar and geothermal energy in purifying brackish water. Performance of Multiple Effect Solar Still (MESS), Reverse Osmosis driven by Photovoltaic (RO-PV), and Membrane Distillation powered by Geothermal resources (MD-GW) were compared with each other. The prototype MESS had a basin dimension of 1m x 0.5m. It is similar to the DIFICAP mentioned earlier [Bouchekima, 2003] except that the former had 3 stages, and the MESS had 4 stages. Testing was carried out in Tunisia, Algeria and Libya. Presence of a mirror along with the cover glass enhanced the water production by 39% to reach 7-8 L/m^2/d. The efficiency was found to decrease with increase in stages (56%-1st stage, 29%-2nd stage, and 15%-3rd stage). Hence, it was recommended that a MESS should have 3 or lesser stages. Even though the energy consumption was highest, at 1500 kJ/kg, economic analysis revealed that the cost of product water was the lowest at \$0.05/kg.

b Quality Analysis

The efficiency of a Concrete Cascade Solar Still in improving the quality of raw water was studied in comparison with an electrically heated conventional solar still [Balladin et al., 1999]. Both the stills were operated continuously for five days with the same tap water. The water quality index (WQI) of the output from the cascade and electric stills were 4.50, and 3.76 respectively, while that of the raw stored tap water was as high as 29.35. However, the microbiological assay test revealed that cascade water had

420-1400 CFU/ml, which could have been due to air-borne microbial contamination. The economic analysis showed that for small-scale purposes, it was more feasible to have a solar cascade still than an electrical one.

1.3.2 Long Term Testing

a. Efficiency Analysis

Onyegegbu [1986] studied the nocturnal behavior of solar stills in Nsukka (6.78° N latitude, 7.28° E longitude), Nigeria. An SBSS with the glass cover in the inverted V-shape was run for 3 months, from mid December 1983 to mid March 1984. The still had dimensions of 2.44 m x 1.22 m and was tested with water depths, 17.8 cm and 7.6 cm. Results showed that the peak production of deep basin lagged that of shallow by almost 3 hours. However peak production of both stills took place only after sunset, as at that time the temperature difference between the distilland and the cover was the greatest. Because the deep basin has the capability to retain heat for a longer time, its overall production was greater than the shallow basin, even though the peak production rate of the shallow still was greater than deep basin. Nocturnal distillation accounted for 78% and 50% of the total daily output of deep and shallow basin respectively.

The performance of a simple single basin solar still (SBSS), manufactured by SolAqua with modification from the Sandia National Laboratory, was studied in the border colonias of New Mexico (Foster et al., 2002). Two hundred families in this region are getting their major share of potable water solar stills since 1996. Two still sizes were installed, 1.39 m^2 and 1.17 m^2. They were found to be very efficient in reducing the salt content and bacteria from contaminated water. Test results showed only 4-5 viable cells/L survived out of an original count of 10,000 cells/Liter. It was established that the stills were able to remove (coliform) bacteria more than 99.65% and *E. Coli* 100%. New Mexico State University (NMSU) also conducted water quality tests at regular intervals to check for conductivity, salts, fluoride concentration, and pH. Everything except pH, which seemed to increase a bit, was well within drinking water standards. The increase in pH was due to the natural bicarbonate buffering occurring within the still. A survey conducted at the end of the test period showed 85% of the respondents were happy with the stills performance and it was concluded that a 1.39 m^2 still was more suitable to meet the potable water requirements of a family.

Efficiency of a SBSS in the removal of a selected group of inorganic, bacteriological, and organic contaminants was evaluated by Hanson et al. (2004) in Southern New Mexico. Six stills having a basin area of 1.94 m^2, each were run with different inputs, i.e., local tap water, brackish groundwater, geothermal groundwater, fluoride-spiked tap water, high salinity spiked water, fluoride & nitrate spiked water, diluted raw sewage, and organochlorine pesticide mixture, over a period of nearly 60 days (stills had one input at the same time). Irrespective of the salinity, hardness, fluoride, and nitrate concentration in the raw water, the stills' output had nearly none of these contaminants. Bacteria were removed with an efficiency of more than 99.9% when there was no cross contamination. Three out of seven pesticides Alachlor, Lindane, and Endrin, were detected in the brine and distillate sample. The rest, Aldrin, Dieldrin, Heptachlor, and Meth-Oxychlor were too volatile to have remained in the brine. Hence, Hanson et al. found that although the stills were not very efficient in removing VOC's, their concentration was brought under the maximum allowable limit.

A simple SBSS with an area of 0.54 m^2 and cover glass inclination of 33.3° was designed and checked for overall performance in the city of Islamabad, Pakistan at latitude of 33.3° N. The still was run for 8 days in the month of July 2004 with the raw water coming from Simly dam filtration plant (Samee et al., 2004). The daily average output was 1.7 L (i.e. about 3.14 $L/m^2/d$) though neither the initial volume nor depth of distilland is mentioned. Quality analysis revealed that the still was very efficient in bringing TDS and conductivity within the recommended limits. Hourly water production was monitored for one day, which showed that the maximum distillate production lagged solar noon by an hour.

b. Design Modification for improvement in quantity

Investigations were carried out by Qasim in Texas in 1975 to determine the efficiency of solar stills in treating raw sewage. Two 2-story greenhouse type solar stills were built. Both were made up of wooden frame, Plexiglas, and covered by polyethylene film (10 mil and 4 mil). The upper section was the solar still while the lower section worked as a greenhouse. In one still (A), the trough present in the upper section, which worked as a basin for sewage, was of dimensions 27" x 5.75" x 3" and in the other (B) 23" x 57" x 4". The evaporation trough in still A was lined with black plastic sheet and contained 1.5L of sewage. The condensate collection was made in bottles, which were attached below the condensation troughs. Greenhouse section of both the stills housed several types of plants. In still B, the lower part, though provided with many openings for ventilation, was completely cut off from the upper part and was placed with 2.5L of treated sewage. Still A was operated from February to May of 1975. Regular temperature and distillate measurements were made. On an average, the daytime temperature of the solar still was

38°F more than the ambient air, whereas, average temperature in greenhouse was nearly 12°F lower than that in the solar still. The average condensate rate was 3.6 $L/m^2/d$ (0.09 $gal/ft^2/d$). The still effectively reduced ammonia nitrogen and completely removed coliform and odor. But the greenhouse did not seem to work properly, as the species of *Asiatic Jasmine* and *Liriope* grass could not survive. Out of 50 plants of *Hardy* grass only 2 survived. This is because extremely high temperatures of exceeding 120°F occurred inside the greenhouse. Still B was operated from July to September starting of the same year. The distillate production rate was about 2.4 $L/m^2/d$ (0.06 $gal/ft^2/d$), which was because of low temperature inside the still resulting due to leaks. The condensate quality was similar to that obtained from still A. All the plants in this still survived and remained healthy, as during the daytime the doors and windows were opened, hence the temperature never exceeded 100°F. It was concluded solar distillation is a viable method of not only treating sewage but also growing plants.

Steenderen [1977] tested various kinds of solar stills such as inclined tray stills, semi-inclined roof stills, and double inclined roof stills, with several modifications to select a particular design for further study. The double-inclined roof still was selected because of its high efficiency, construction cost, local availability of materials and ease of maintenance and operation. The floor of the experimental model was compacted with sand treated with weed killer and insecticide. The evaporation basin had an area 4.95 m^2. Six sheets of 2.94 mm thick glasses were inclined at 15° on both sides. The author conducted an experiment with glasses of thicknesses varying from 2.15 to 6.70 mm to determine the one best suited for maximum solar radiation absorption. The 2.15 mm glass turned out to be the most efficient, but because of its weakness, 2.94 mm glass was chosen. The raw water was maintained at a constant depth of 2.5 cm. This model was run for the whole year of 1970 in five different locations of South West Africa, Windhoek, Aroab, Ondangua, Möwe Bay, and Rössing. Here the summer is from November to March and winter lasts from June till August. Average water production of around 27 L/d (5.5 $L/m^2/d$) was recorded for November in Aroab, Ondangua, and Rössing. Windhoek and Möwe Bay had the highest average production of nearly 18 L/d (3.6 $L/m^2/d$) in December. The least that these places recorded was about 6 L/d (1.2 $L/m^2/d$) in June, and Aroab got the same quantity in July. Rössing had its minimum of around 8 L/d (1.6 $L/m^2/d$) and Ondangua had a production of approximately 11 L/d (2.2 $L/m^2/d$) in June. Based on these results, it was concluded that there was not considerable adverse effect of wind speeds on the efficiency of the still.

A SBSS was tested for its performance in Nag Hammadi, Egypt at latitude 26°14' N and longitude 32° E [Morcos, 1993]. The solar still of area 1 m^2 was placed at an angle of 26° facing south with a flat plate solar collector, having an area of 0.5 m^2, located 0.5m below it. Experimental work was carried out during March and April of 1993 by changing;

- Water mass: The water mass was varied from 2 to 29 kg at constant salinity.
- Salinity: The salinity was varied from 2 to 17% at constant water mass.
- Effect of film distillation: Spacing between the water surface and jute cloth mounted on a wooden frame was varied from 2 to 18 cm at optimum basin water mass of 20 kg and salinity of 5%. This was repeated by adding 0.5% black dye.
- Thermosyphon circulation: For this, the solar collector was coupled to the still in such a way that the outlet of the collector was slightly higher than the water level

in the basin. All other parameters viz. water mass, salinity, and black dye concentrations were kept at their optimum values. Here also the distance between the jute cloth and the water surface was varied and its effects observed. This experiment was repeated for simple film and simple film with black dye.

The most favorable spacing was found to be 10 cm for all cases. For this optimum distance, the simple film and simple film with black dye produced approximately 1.8 $L/m^2/d$ and 2.1 $L/m^2/d$ respectively. But the highest production of 3.55 $L/m^2/d$ was observed by the thermosyphon with film distillation and black dye arrangement, resulting in an overall efficiency of 21.3%.

Minasian et al., in 1994, made a successful attempt at improving the efficiency of a SBSS and a wick-type solar still by simply combining them. The resulting still allowed direct entry of the hot waste brine water into the SBSS. The experimental work, comprising one each of SBSS, wick-type, and wick-basin type solar still, was conducted for the whole year of 1992 at the Solar Energy Research Center in Baghdad, Iraq at latitude 33.33° N. It was found that the test model gave enhanced production all through the year. The maximum distillate, for all the stills, was produced in June. The year round performance of the combined wick-basin type still indicated that its efficiency was 85% more than that of the basin type still and 43% more than the single wick type still. The authors also performed economic analysis that showed the wick-basin type solar still to be the most cost –effective.

The main expenses of a large scale solar still come from its fabrication and on-site construction, which includes land preparation, basin and cover construction [Madani et al., 1995]. The basin is usually made of concrete and lined with brackish water resistant black paint or rubber sheets etc. In this paper a conceptual design was proposed and a prototype was tested by building still using galvanized steel and placing it in shallow seawater bed. An inverted V-type aluminum cover was put over the glass cover. This arrangement was tested from May-January of 1994, 1995 in the city of Jeddah, Saudi Arabia at latitude 21°45' N for three different conditions when still basin was: painted black, covered by 2.5 cm thick layer of soot (carbon powder of particle size 40-50 μm) , and covered with soot but no thermal insulation. The daily yield of these modifications varied between 1-4 L/m^2. Results showed that the presence of soot increased the daily yield production by 50% when average daily solar flux was low, but there was not much of a difference for the higher values of solar flux. On average, soot increased production by 35%, and absence of insulation decreased the production by about 13-17%. Avoiding the construction of a concrete base and usage of freely available soot brought the life cycle water production cost to US$2.4/$m^3$.

Performance enhancement by using different absorber materials and integration of the still with a solar collector was studied by Tiris et al. in 1995 in Turkey. Two identical SBSS of 0.96 m^2, with cover glass at an angle of 17°, were tested for two months from August till September under varying water depths of 1 and 3 cm along with different absorbing materials, charcoal, blackened rock-bed, and black paint. Charcoal seemed to increase the yield by 11-18%, and 23-92% more than black paint, and blackened rock-bed respectively. Also charcoal and black paint's productivity improved with an increase in the water depth whereas; strangely it was the opposite for blackened rock-bed. The still, when attached to two flat plate collectors and a 200 L hot water storage tank showed a claimed yield improvement of 194%.

The effect of adding a suspended absorber in an SBSS was studied by El-Sebaii et al. in Tanta, Egypt at latitude of 30° 47' N [1998]. A conventional solar still, having a 1 m^2 basin area, was provided with a suspended absorber plate of thickness 2 mm. This plate acted like a wall dividing the water horizontally. It could be moved up and down. Different plates made up of stainless steel, aluminum, copper, and mica were tested. Experiments were also done by making vents in the plates. The September and October of 1997 results showed that it was best to not provide vents and keep the absorber in the middle of the still and have a shallow depth of water above it. The efficiency of copper, aluminum, and stainless steel plates were found to be 15-20% greater than SBSS where mica plates gave an improved efficiency of 42%.

The advantage of using an outside condenser was studied by El-Bahi et al. in 1999 in Ankara, Turkey (39°57' N). The still basin had an area of 1 m^2, with the cover glass inclined at 4°. It was provided with a stainless steel reflector, which acted as a cover for the additional external condenser. The still was operated from June to November of 1998. During early daytime, as the inner surface of the glass was cool, condensation took place inside the still. As the day would proceed, with the glass becoming hotter, vapors used to condense in the condenser (its temperature was lesser than the inner surface of glass as it was shaded by the reflector). They observed the peak in water production to lag the solar peak by 2 hours. An efficiency enhancement of 70% along with a maximum yield of 7 $L/m^2/d$ was reported, though the daily average production over the 6 months period was not described.

The effects of climate on the performance of an SBSS and an active still were determined in the arid region of Adrar, Algeria [Boukar et al., 2001]. The still of area

1.04 m^2 had two glass covers in the shape of an inverted V, and the collector had an inclination of 28°. They were run for a few days in winter and summer and full time from starting of January to end of March, 2000. Distilland was maintained at a depth of 2.5 cm. The SBSS produced 4.01 $L/m^2/d$, whereas the coupled still produced exactly the double at 8.02 $L/m^2/d$. When the distilland depth was increased by a centimeter, the output of SBSS increased by 300 mL, but there was hardly any difference in the production of coupled still as it had improved by just 50 mL. The authors also found that the wind speed had a very little effect on the yield.

Cappelletti, in 2001, tested a double basin still made out of Plexiglas insulated by polystyrene. He built two hermetically sealed single basin stills and superimposed one on top of the other. As it was clear transparent plastic, solar radiation entered from not just the top, but also the vertical sides. The area of individual basins were 0.165 m^2 and the total quantity of raw water was 6 L. Observation of the experimental work done from July of 1995 to February of 1996, in Foggia (Italy), revealed that the maximum water production occurred during the third week of July, when solar radiation was between 27 and 28 $MJ/m^2/d$, as 1.7-1.8 $L/m^2/d$. The author says that this low production or low efficiency of 16% is due to the low basin temperature of around 50°C. The maximum basin temperature was 81.4°C.

The role of charcoal in increasing the efficiency of a solar still was studied in a paper by Naim et al. [2002]. The non-conventional still, made of Perspex (or Plexiglas, as in the previous paper), was insulated with sawdust. The optimum cover glass angle was calculated to be 17° for the Alexandria, Egypt. The still was tested under two conditions: underlining the bed of charcoal (for three different particle sizes, viz. 0.0015, 0.005, and

0.007m) with a layer of jute, and with just the jute material (so as to let the still work as a wick type). The flowrate of the brine was varied between 40 and 160 mL/min. It was found that use of charcoal gave better results than the wick still by 15%. The efficiency of coarser granules increased with the flowrate. Charcoal was also effective in removing chlorides completely.

Kumar et al. (2002) carried out experimental analysis of an active still (SBSS connected to a flat plate solar collector) over a year in New Delhi, India with a latitude of 28°35' N and longitude of 77°12' E. The still and the collector had areas of 1 and 2 m^2 respectively. The still was operated with different depths of distilland varying between 0.03 and 0.12 m. The yield was found to be inversely proportional to the depth. The depth of 0.06 m produced nearly 3.33 $L/m^2/day$.

Maximum production was observed in May, April, and October (in this order) because of a larger number of clear days in May. Experiments performed to find the ideal inclination angle for the collector (varied from 5°-60°) and still cover (varied from 5°-30°), to get the maximum output, suggested that the collector and still inclination angles should be 20° and 15° respectively.

CHAPTER 2

MATERIALS & METHODS

The performance of two types of single basin solar still (SBSS), one made by SolAqua, three by Sunwater, and one triple basin prototype still were investigated. The test site was located on the roof of the Howard R. Hughes College of Engineering Building of University of Nevada, Las Vegas (latitude 36° 06.587'N, longitude 115° 08.518'W). Table-2.1 lists the monthly average air temperature for the National Weather Service gauge at the McCarran airport.

Table 2.1: 2006-2007 weather data for McCarran International, Las Vegas, NV

Month	Average high, °F	Average low, °F	Average wind, mph	Total rain, inches	Average gust wind, mph
Jan 06	60	40	6	0.03	25
Feb-06	65	43	6	0.05	24
Mar-06	64	46	9	0.19	24
Apr-06	78	55	9	0	23
May-06	93	69	8	0	23
Jun-06	103	78	8	0.07	22
Jul-06	106	84	8	0.13	22
Aug-06	102	80	8	0.04	21
Sep-06	92	70	7	0	25
Oct-06	78	58	6	1.07	21
Nov-06	69	48	6	0	26
Dec-06	57	38	6	0.12	26
Jan-07	56	36	7	0.06	26
Feb-07	65	44	8	0.16	24
Mar-07	76	52	7	0	24

Source: www.wunderground.com

The four seasons are well defined. During summer, daily high temperatures usually exceed 100° F and lows remain in 80s. Except for July and August, the rest of the months are bearable because of very low relative humidity. Winters are quite pleasant. During afternoons, the average temperature is about 60° F. There are the occasional rains, and rare snowfall. Spring and fall are generally ideal, but sometimes have sharp temperature shifts. Extreme winds of speed over 50 mph can occur occasionally.

2.1 Materials

Four Sunwater® stills were shipped from Woodruff, Arizona. The Sunwater® still has a rectangular basin of area 0.976 m^2 (46.75" x 32.31").

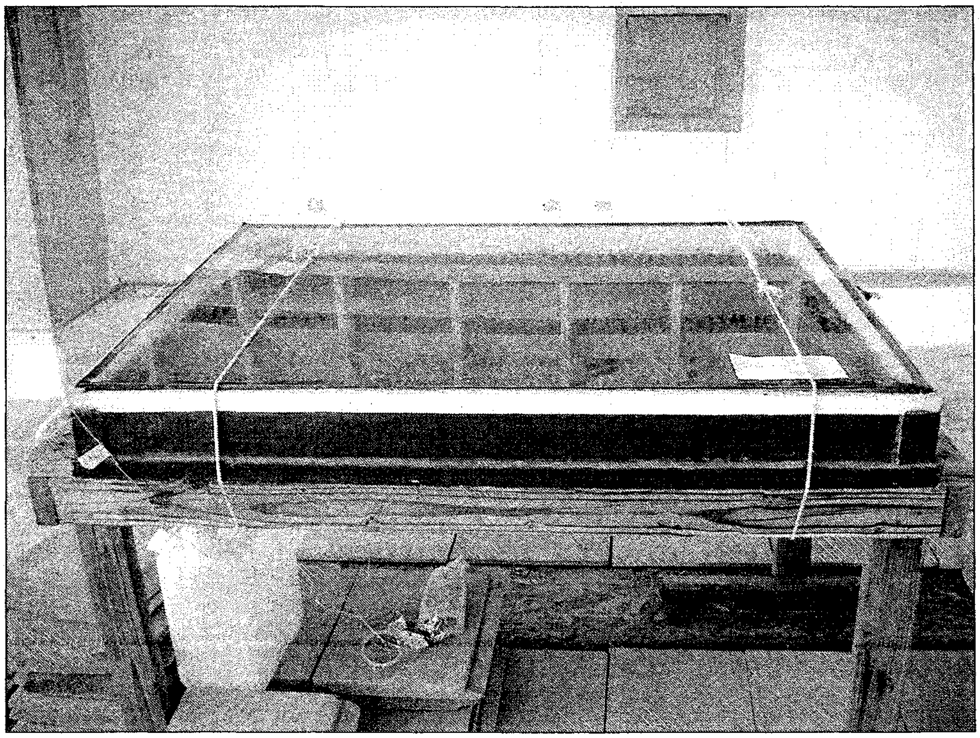

Figure 2.1: Sunwater® simple single basin solar still

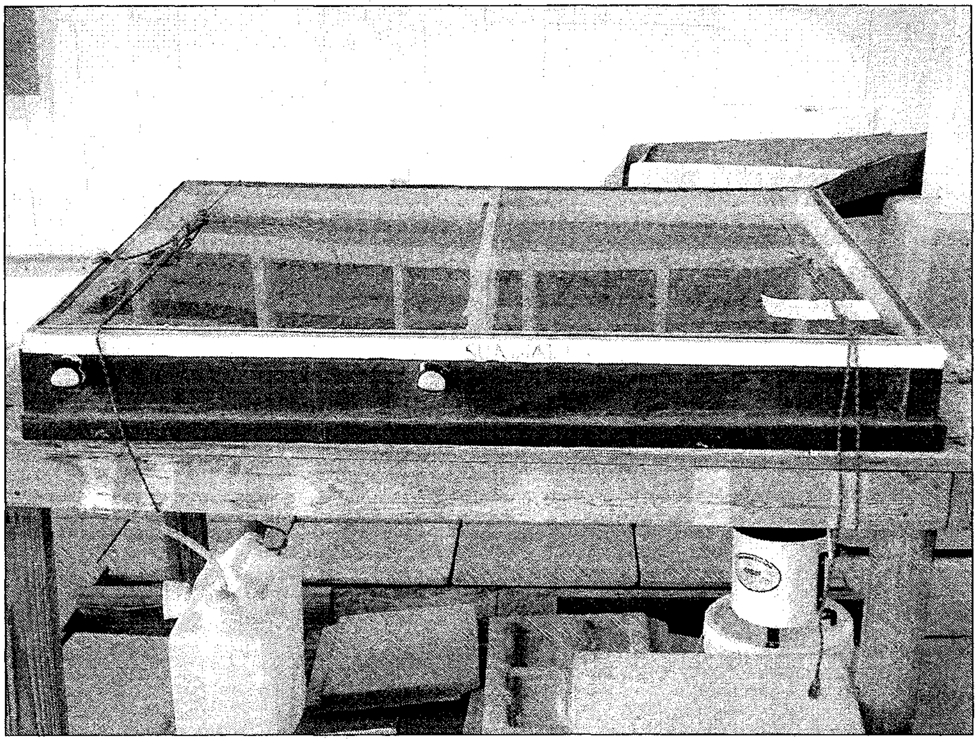

Figure 2.2: Sunwater® double-basin solar still

The still body is made of sheet aluminum. Insulation is provided by 1" thick polyisocyanurate foam board, coated with FDA-approved silicone sealant, in layers with un-bonded glass fiber cloth. The inside and outside are also coated with silicone. The collection trough in the front end of the still is also made out of aluminum and painted white. They are provided with glass cover of slope of 2°. Each still has 2 inlets, 1 delivery, and 1 drainage tube. Two models of Sunwater® stills were used, single-basin (Figure 2.1) and double-basin (Figure 2.2). The double-basin still was bifurcated along the width to divide it into two equal basins of area 0.48 m^2.

The SolAqua, Rainmaker^{tm} 550 (Figure 2.3), is made of a fiberglass exterior box with foamed in-place insulation. The sealing is in the form of a U-channel molding which wraps around the perimeter of the still clamping the glass against a D-section seal that is bonded to the fiberglass box. The still comes with two large diameter fill tubes, one having a hose connection attached to a screen for filling and one unscreened for drainage, and two small tubes are provided for delivery of condensate. The SolAqua has a basin area of 0.767 m^2 (45.75cm x 26cm) and a clear cover glass slope of 9°. The still comes with its own clear tempered cover glass and a detachable support frame made of PVC pipe.

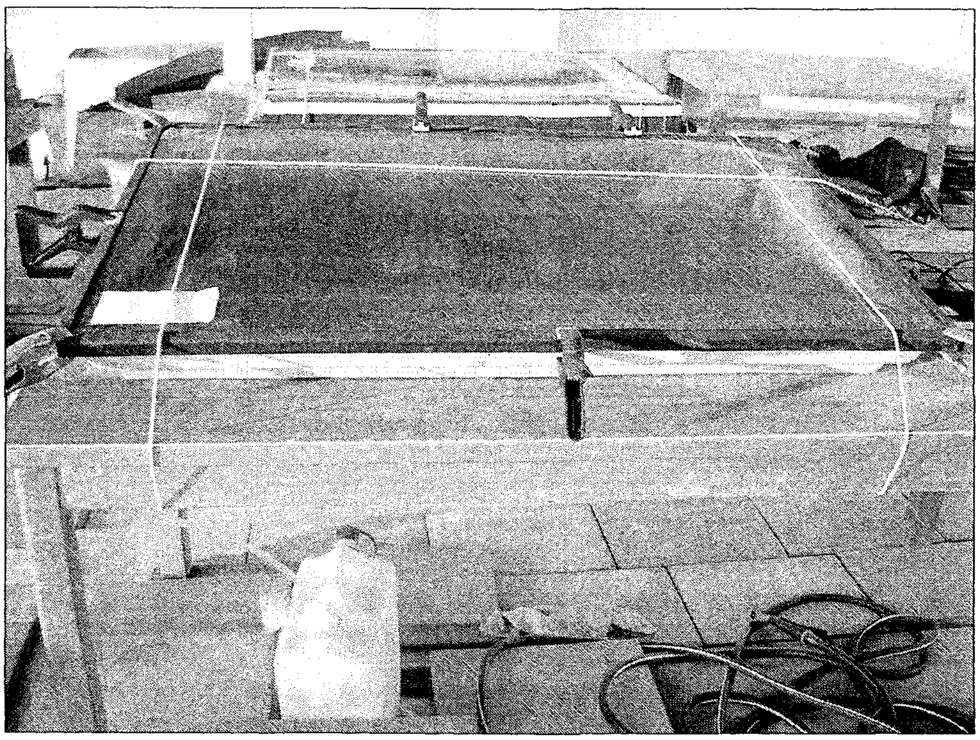

Figure 2.3: SolAqua^{tm} simple single basin solar still

Table 2.2 lists the stills used, and their supplier. Table 2.3 gives a description of different cover glasses, their suppliers and the various combinations in which they were used till now. The still name column in both the tables give the abbreviated names by which the stills and glasses would be referred in this thesis.

Table 2.2: Solar Still identification table

Still Name	Maker	Still Type
A	Sunwater®	Simple single-basin
B1	Sunwater®	Double-basin
B2	Sunwater®	Double-basin
C	Sunwater®	Simple single-basin
S	SolAqua™	Simple single-basin
P	Prototype	Single basin with increased condenser area

Table 2.3: Various combinations of stills and cover glasses used in this research

Still Name	Glass Type and Supplier				
	Sunwater® Clear Tempered (as-supplied) **SSG**	**BJ Clear Tempered** **BJTG**	**PPG Sungate 500 Low-E** **LEG**	**SolAqua™ Clear Tempered (as-supplied)** **STG**	**Best Clear Tempered** **BTG**
Sunwater® Single-Basin, A	A-SSG	A-BJTG	A-LEG	-	A-BTG
Sunwater® Double-Basin, B1	B1-SSG	B1-BJTG	B1-LEG	-	B1-BTG
Sunwater® Double-Basin, B2	B2-SSG	B2-BJTG	B2-LEG	-	B2-BTG
Sunwater® Single-Basin, C	C-SSG	C-BJTG	C-LEG	-	C-BTG
SolAqua™, S	-	-	-	S-STG	S-BTG

The stills were fixed to individual wooden tables made of plywood (2 x 4 inch boards) of dimensions 4' x 6' and installed on the TBE building roof facing geographic south. Stills are secured to the tables by means of ropes. The building roof has a low parapet and unobstructed southern exposure from geographic east to geographic west. All the stills were provided with a Nalgene® jerricans of 20L capacity for collection of product water. The jerricans were fitted with Nalgene® fitting/venting closure, which housed Nalgene® carboy vent filters. This filter allowed air to be displaced as the container filled with water, while reducing risk of contamination by air borne particles. The arrangement is as shown in Figure 2.4.

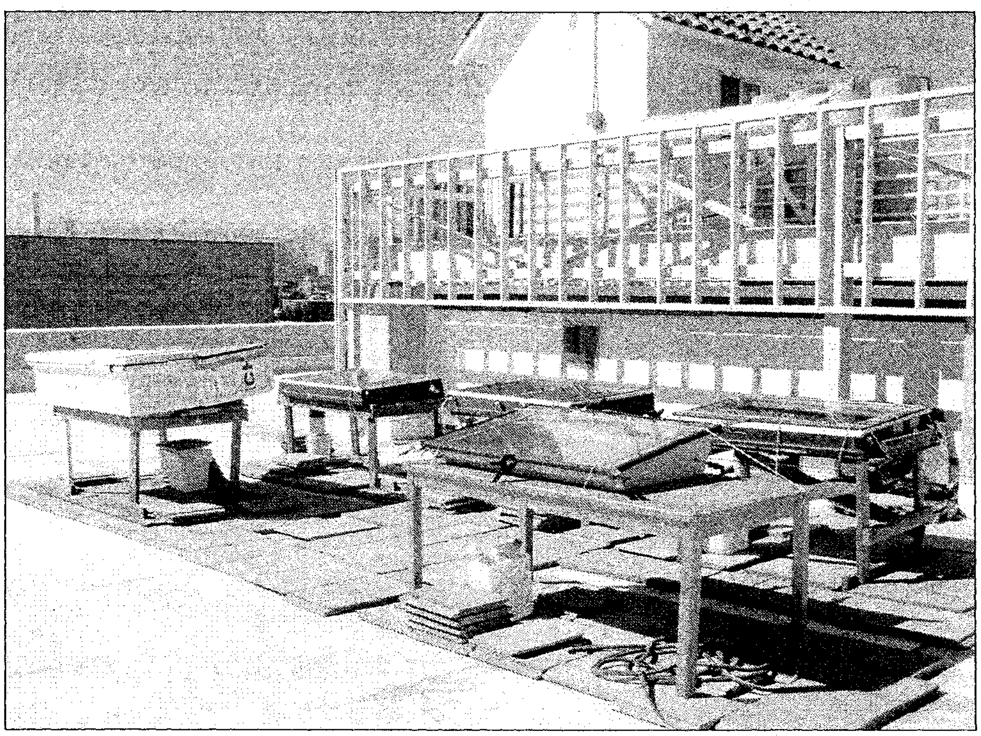

Figure 2.4: Test site on the roof of TBE B building, UNLV, Las Vegas, NV

2.2 Methodology

2.2.1 General Procedure:

Each still was filled with the same quantity of raw water (LVVWD tap water). The quality of water, for major contaminants, has been tabulated in Table 2.4. From November 2005 until November 2006 distilland temperature was measured from morning 9am till evening 5pm at a regular interval of 2 hours. A Fluke 51 K/J thermometer and Fluke K-type thermocouple were used for this purpose.

Table 2.4: Typical composition of Municipal tap water delivered by LVVWD in 2006

Constituent	Average, mg/L	MCL, mg/L
Potassium	5.4	N/A
Calcium	66	N/A
Magnesium	27	150
Sodium	89	N/A
Alkalinity	132	N/A
Sulfate	265	500
Chloride	98	400
Silica	7.8	N/A
Total Dissolved Solids	652	1000

Source: www.lvvwd.com

After November-2006 the stills were instrumented with HOBO® pendant light/temperature data loggers. Every morning around 8–8:30am, the distillate was measured, by Nalgene® 1L plastic graduated cylinder, and put back into the still. This was done to reinitialize the water volume, so that every morning all the stills had the same volume. This procedure did not alter the temperature of the still water as the distillate and distilland are nearly at the same temperature just after sunrise. All the stills were flushed and cleaned regularly every 2-3 weeks to remove the collected salt. They were assessed by varying the distilland volume, distilland depth, and cover glass.

2.2.2 Equal Volume:

The distilland volume in all the similar type of stills (single-basin and double-basin) were kept the same. This was done in order to determine the most efficient still for the same mass of water. In course of this, cover materials were also changed (as listed in Table 2.3) to investigate the effect of glass cover on performance and hence choose the best type of glass.

2.2.3 Equal Depth:

Here the volume of water was adjusted in order to have same depth in all the stills (different for single-basin and double-basin stills), as shown in Table 2.5. The cover materials were again changed just like in the previous description.

Summary of the above events are given in Appendix A.

2.3 Design and Fabrication of Three-Basin Solar Still Prototype

The design concept of the prototype was proposed by Mr. Harold R. Hay, in July of 2006. The unit consists of three-basins; an outer box with a hot insulated insert, and a cold condenser, as shown schematically in Figure 2.5.

The idea behind the prototype was that the water in the still would get heated and produce vapors. The vapors being hot would rise and travel across to the condenser via the hot vapor slot, some of it will condense there as the temperature is much lower and

Table2.5: Details on constant volume and constant depth experiments for all the stills

Date	Experiment Name	Stills Used	Water Volume, L			Water Depth, cm			Night Cover	Weekend Operation
			Single-basin	**Deep-basin**	**Shallow-basin**	**Single-basin**	**Deep-basin**	**Shallow-basin**		
2/1/06-3/30/06	Constant volume	A, B2, S	20	10	10				Yes	No
3/31/06-4/25/06	Constant volume	B2, S, A (on alternate days)	23	11.5	11.5				No	Yes
6/16/06-6/26/06	Constant volume	A, B1, B2, S	26.6	13.3	13.3				"	"
6/30/06-7/20/06	Constant depth	A, S				3.9			"	"
7/3/06-8/20/06	Constant volume/depth	B1, B2		27.5	11		5.7	2.3	"	"
11/4/06-3/31/06	Constant depth	A, C, S				3.2			"	"

the rest of the vapors would return back into the still through the cold vapor return slot. This cycle then repeats as long as temperature differences exist to drive the circulation.

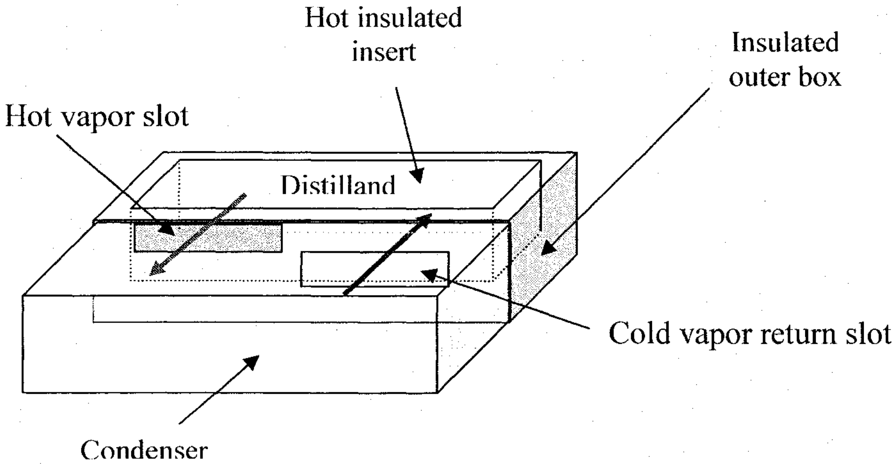

Figure 2.5: Schematic of the Prototype

The outer box of the still, having a dimension of 1.8 m x 0.6 m x 0.3 m (6 ft x 2 ft x 1 ft), refer to Figure 2.6, was made from 2" thick Styrofoam/polystyrene panel with an R-value of 8. Hot vapor and cold vapor return slots, of size 0.9 m x 0.1 m were provided in the box. Sealing was done using General Electric Heavy Duty construction purpose Silicone Sealant. The 1.6 m x 0.5 m x 0.3 m insert (Figure 2.7) acting as the hot solar still was made out of galvanized steel sheets. It had flanges in order to hang on the box. Two-inch thick styrofoam was cut to size and placed inside, so that it was completely insulated.

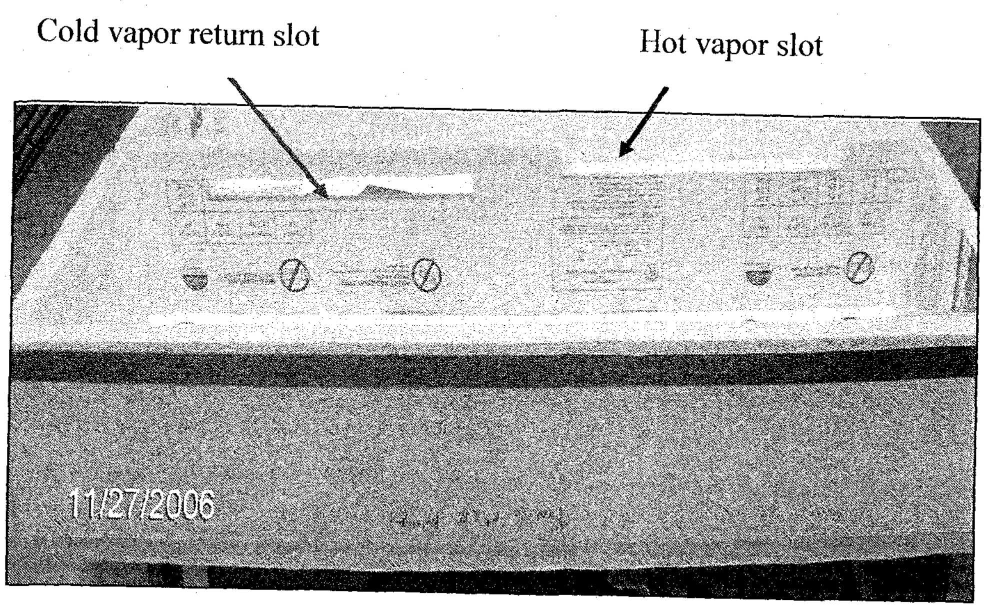

Figure 2.6: Insulated outer box for the still

This insert was also provided with a bag made from 6 mil thick black agricultural grade low density polythene plastic liner which would hold the distilland. An impulse sealer was initially used to create seams for the liner. The condenser was made out of 24 gauge galvanized steel sheet. Having the same dimensions as that of the outer box, slots were cut so as to mate the two them when kept side by side. The condenser was primed with Rust Oleum® Latex Primer for Aluminum or Galvanized Metal and painted white with Rust Oleum® white paint in order to reflect light. It was provided with a 2.22 cm, diameter drain and fitted with a # 6 rubber cork, which could be removed for fresh water collection.

Two glass sheets of dimensions 1.8 m x 0.6 m each were laid as cover. They were sealed using the low compression Frost King® rubber foam weatherseal of thickness 3/16”, 5/16”, and 7/16” and D shape rubber seals.

Figure 2.7: Insert placed inside the insulated hot still (without insulation and liner.

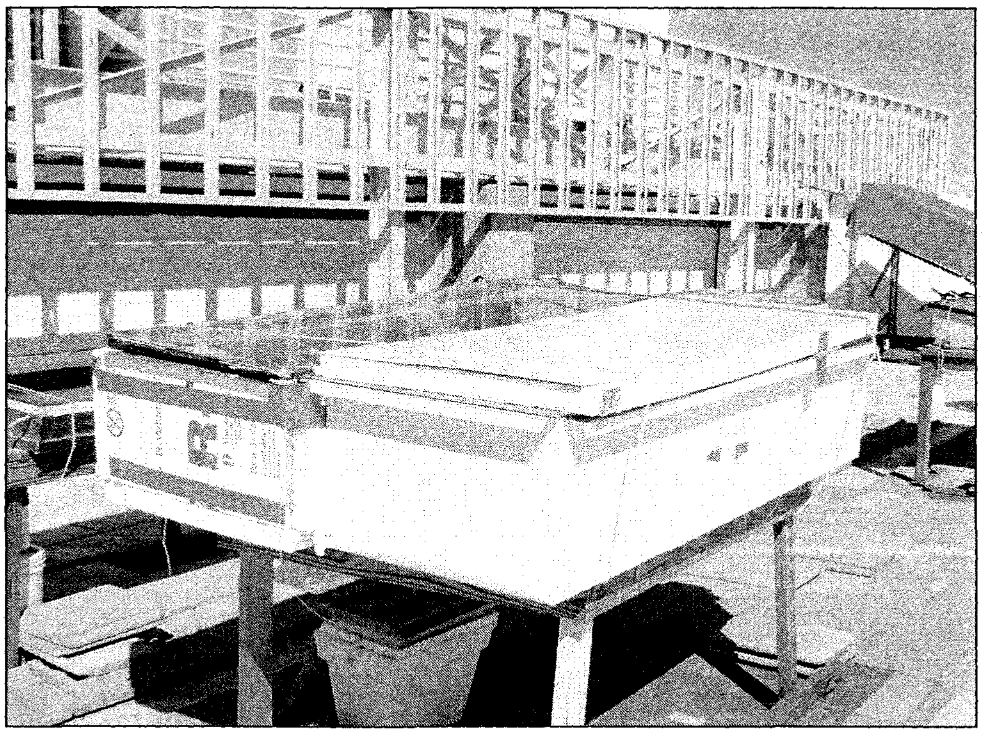

Figure 2.8: Prototype in operation

On the condenser side, the glass was covered by 20 gauge galvanized sheet metal (white painted) of the same size. Eighteen liters of tap water was filled into the still. The whole arrangement was placed on the 1.8 m x 0.6 m (6 ft x 2 ft) wooden table, secured in place by pavers. The still, like all others, was tied to the table using rope (Figure 2.8).

The next morning, the liner was found to be leaking. A new bag was prepared. But this also did not work as the weight of the water was exerting extra pressure on the plastic seals and causing them to fail. Considerable amount of damage was also done by the heat as the liner was probably being exposed to more than the rated temperature (as seen in Figure 2.9a and 2.9b).

Figure 2.9a: Material failure of liner

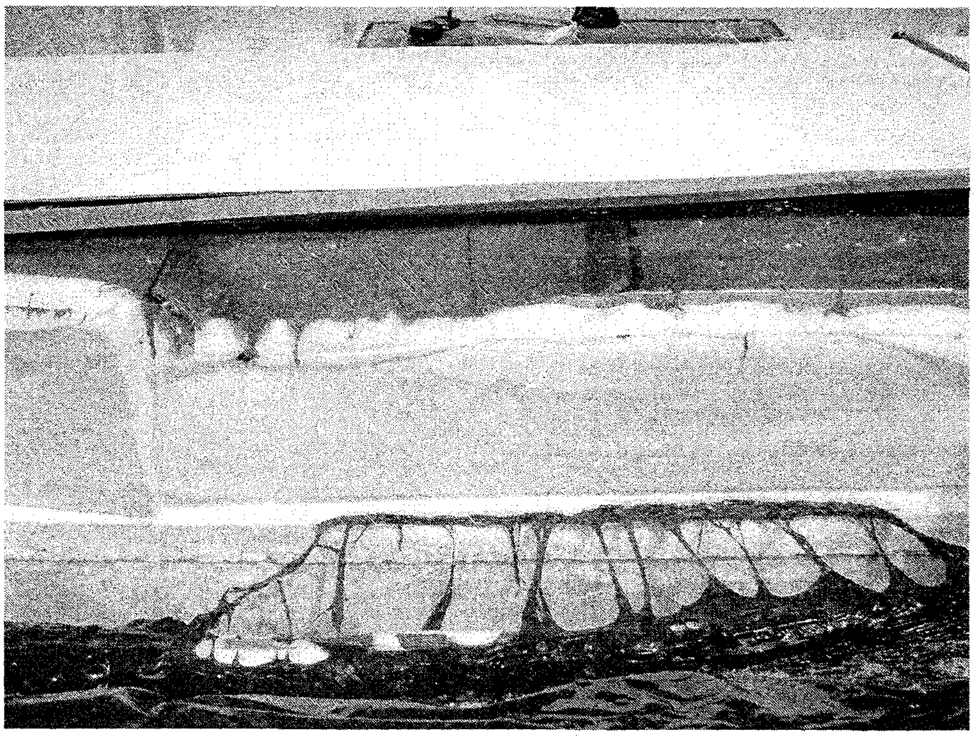

Figure 2.9b: Material failure of liner

Hence, the 6 mil liner was double folded and simply laid in the insert in the "shape" of a bag. Duct tape was used to tape the ends of the plastic together with the insert. A two-inch thick Styrofoam panel was cut to size to insulate the condenser at night and still during daytime on alternate days. The unit facing south (condenser first) was tilted by wooden shimming to a slope of 3.4° and operated with 18L of raw water.

To monitor temperatures a HOBO® pendant temperature/light data logger (part # UA-002-XX) and Saelig data logger were launched with a 10 minute recording interval. The thermometer recorded the still headspace, hot vapor, condenser headspace, and cold vapor return temperatures, while the HOBO data logger recorded the distilland temperature and incident light.

This arrangement did not result in any collection of water, even though there was some condensation taking place. Hence, on 3/6/07 the unit was rotated 180° such that the hot still faces the geographic South. A new bag of the same material was laid, and filled with 26L of tap water. The condenser was tilted with support of wooden shimmings to have a slope of 3.5°. The cycle of externally insulating the condenser at night and still during daytime, on alternate days, was repeated.

After 14 days, the liner failed once again along with the Styrofoam within the insert, hence the prototype still was removed from service. It was repaired and brought back to service on the 28th of March. This time 16 L of distilland was filled in. The liner started showing signs of failure after three days and had to be taken out of service on 4/10/07.

The experimental history of the commercial stills are shown in Tables A 2 to A 6 in Appendix A.

CHAPTER 3

RESULTS & DISCUSSION

This chapter presents the experimental results. A series of experiments were carried out to determine the performance of different stills under several different operating conditions;

- Constant volume
- Constant depth
- Different glass covers
- Same glass covers
- Additional insulation

The results have been divided into two major sections: Single-basin Stills, and Double-basin Stills. These stills were both operated on a short-term (few days to a few weeks) and long-term basis (Several months up to a year). Cover glass codes are shown in Table 2.3 on page 28.

3.1 Single-Basin Solar Stills (Short-term and Long-term Results)

Experiment 1: Different basins and different cover glasses

Stills A and S were operated, with 1/8" BJTG and STG respectively, from 2/1/06-3/31/06. Figure 3.1a and 3.1b depict the regression plot of water yield of stills A and S on global solar radiation. The coefficient of determinates (R^2) for dependence of yield on insolation is 0.45 for still A and 0.5 for still S. Few data points are missing which were for weekends. Because it was winter and early spring, with sometimes heavy gust of winds, the stills were initially covered, by a sheet of cardboard, at night on weekdays and during the weekends. Hence, the quantity of distillate collected on every Monday consisted of three days production, Friday, Saturday, and Sunday.

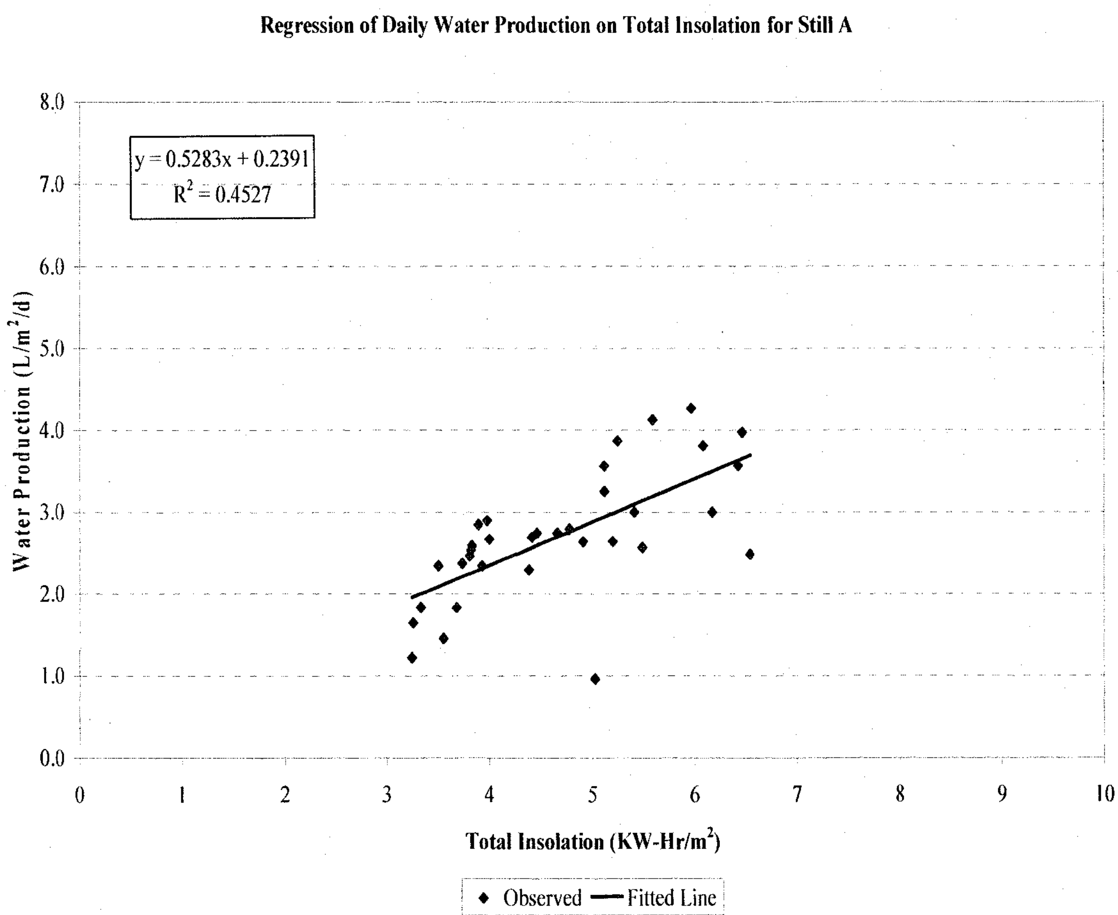

Figure 3.1a: Regression of water yield of still A and global insolation for BJTG clear glass

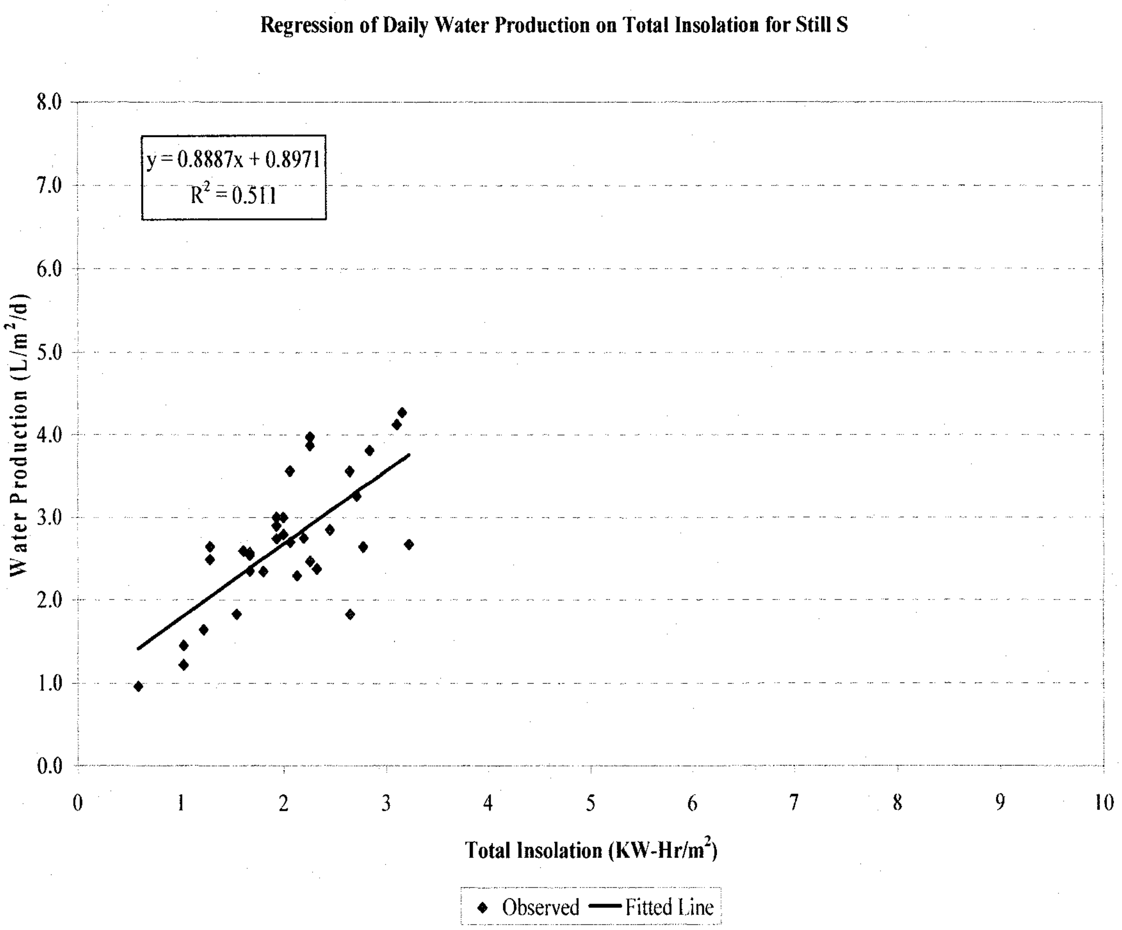

Figure 3.1b: Regression of water yield of still S and global insolation for STG clear glass

The efficiency of a still is measured by the quantity of distillate it produces. It can be calculated in the following way:

1. Water production is normalized by dividing it by respective still basin area on a daily basis.
2. This normalized yield (L/m^2) is multiplied by the density of water (0.996 kg/L) to obtain kg/m^2.

3. Then it is further multiplied by the heat of vaporization (Joules/kg) at 60°C, the amount of heat required to vaporize one kg of water, to get the energy captured by the water in Joules/m^2.
4. Finally this term is divided by the daily total incident insolation (Joules/m^2), obtained from the UNLV solar site, to determine efficiency.

Figure 3.1b compares the still efficiency of stills A and S. It can be observed that unlike the water production, which was lower in the beginning and higher in the end of the experiment, the efficiency followed the complete opposite pattern. It was noticeable from the graph that the overall performance of still A was better than still S.

As it can be seen from Figure 3.1c, with increase in global insolation increased in the latter part of March, the peak distilland temperatures of both the stills did not increase considerably. This lower March efficiency could be because of a larger number of cloudy days in March (14) than in February (9) [weatherunderground, 2007].

Experiment 2:Different basins and different cover glasses

Figures 3.2a and 3.2b compare a longer-term water yields between still A and S. Still S had the same cover as earlier, whereas, still A had SSG. The experiment was run for more than four months (From 6/23-10/30/06). From summer through the fall, as insolation declined by nearly 50.7% (Figure 3.2a, 3.2b), the water yield of stills A and S declined by 59.6% and 53.4% respectively.

However the relative decline in efficiency (Figure 3.2c) was nearly 16.2% (from 52% to 43.6%) for still A and about 24.4% (from 41% to 31%) for still S.

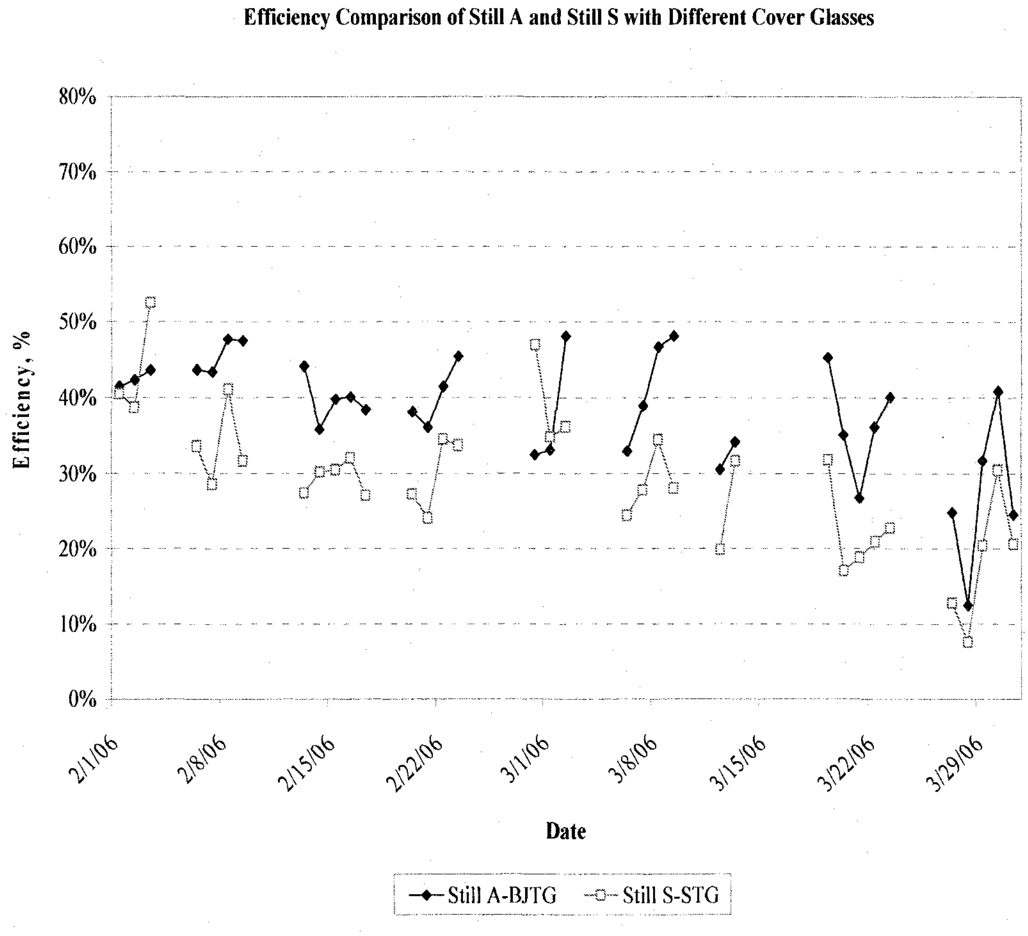

Figure 3.1c: Efficiency comparison of stills A and S for BJTG and STG clear glasses

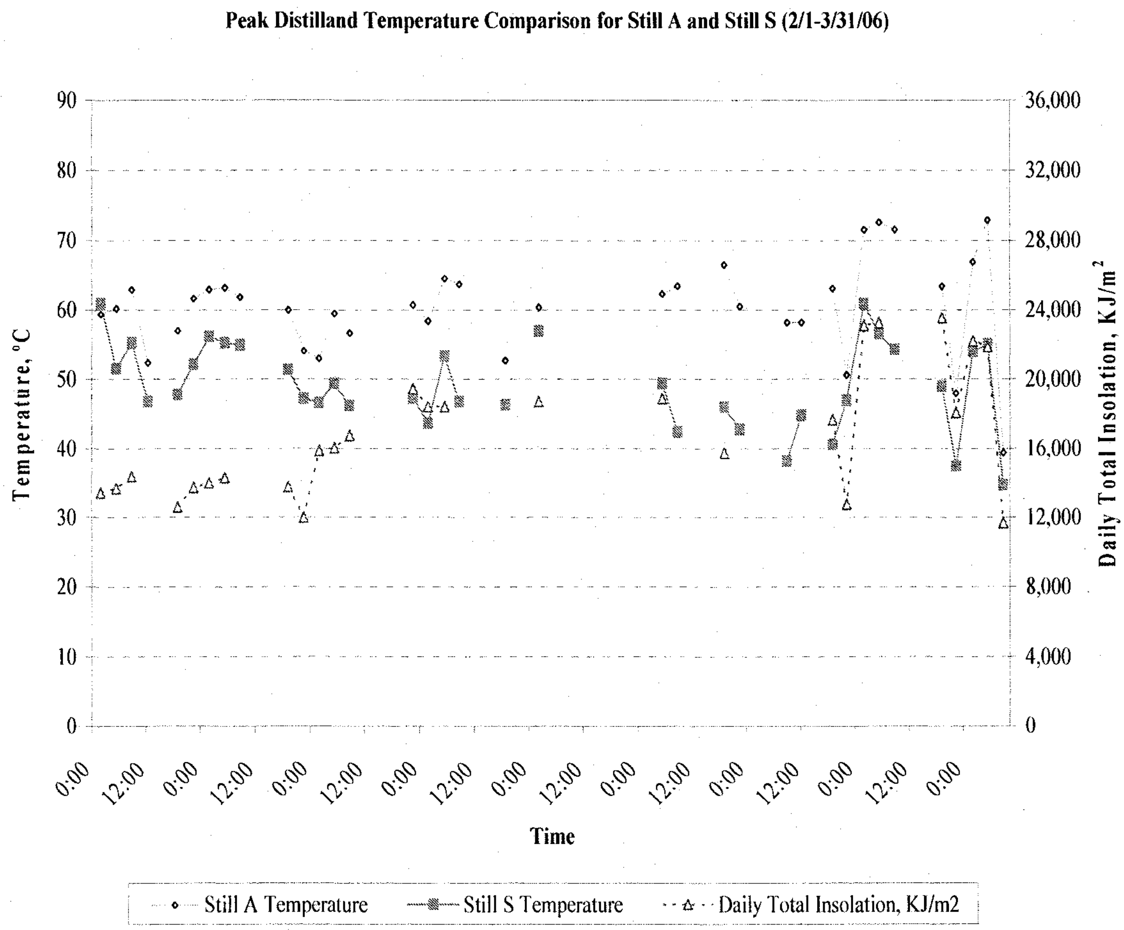

Figure 3.1d: Peak distilland temperature comparison in stills A and S for BJTG and STG clear glasses

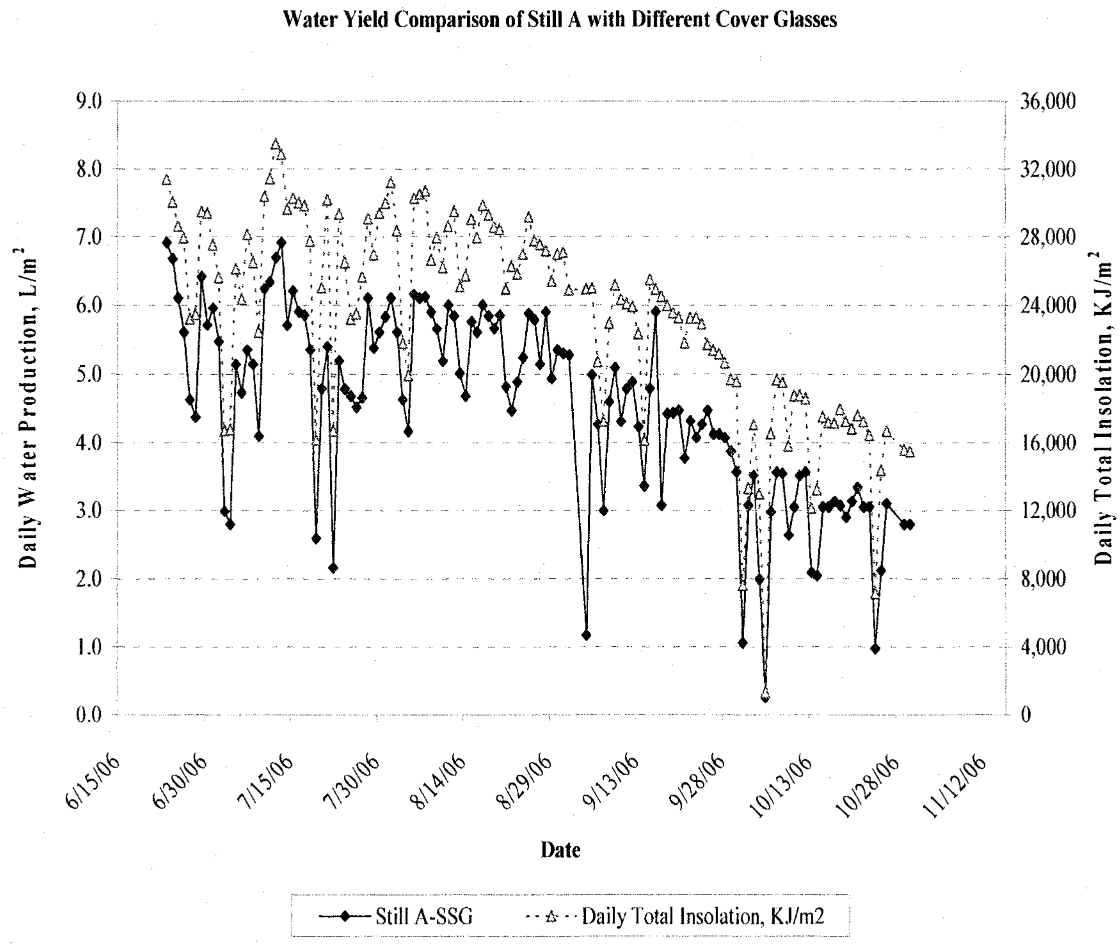

Figure 3.2a: Long-term water yield of still A for (as-supplied) SSG clear cover glass

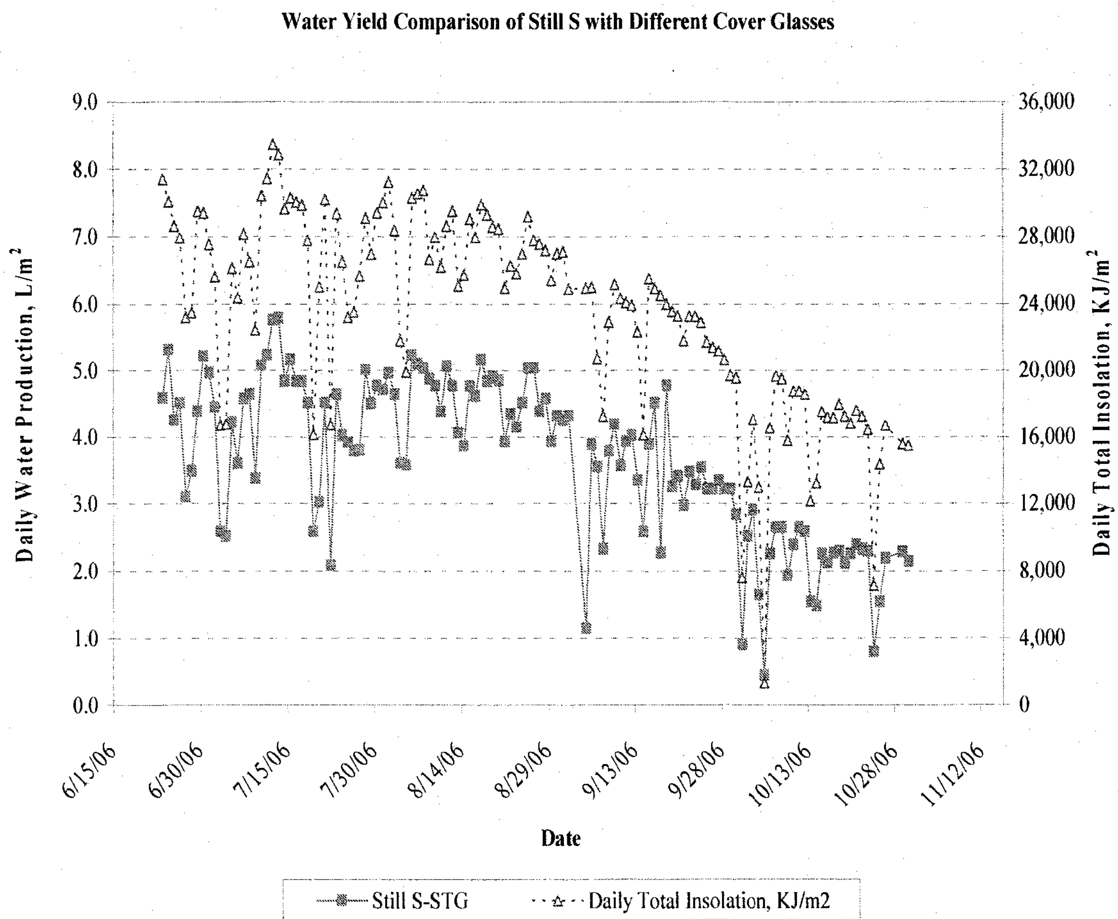

Figure 3.2b: Long-term water yield of still S for (as-supplied) STG clear cover glass

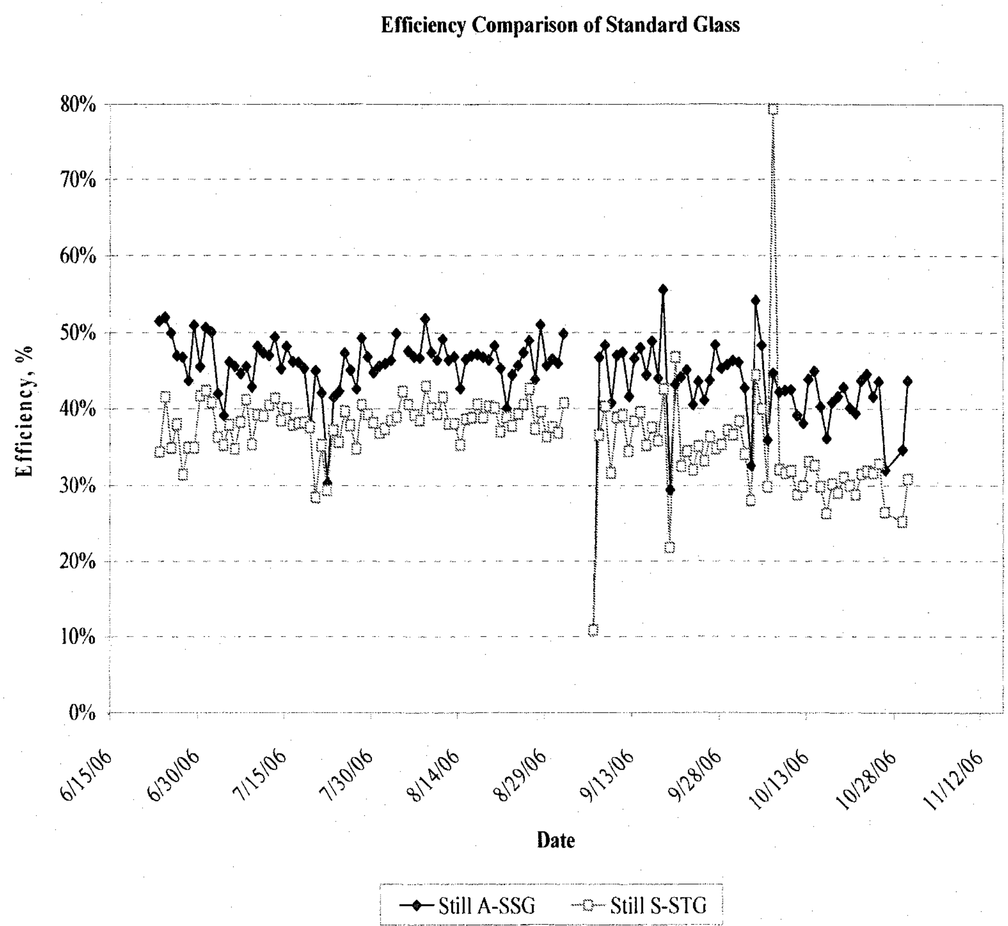

Figure 3.2c: Efficiency comparison of stills A and S for their as-supplied covers

Experiment 3: Different basins and same cover glasses

In the previous two graphs, still A and S were compared for efficiency for different glass covers. In Figure 3.3, results of a test conducted for five months, from November-06 to March-07, can be seen where still A and S both had BTG clear glass covers. Water depth was kept constant for both the stills.

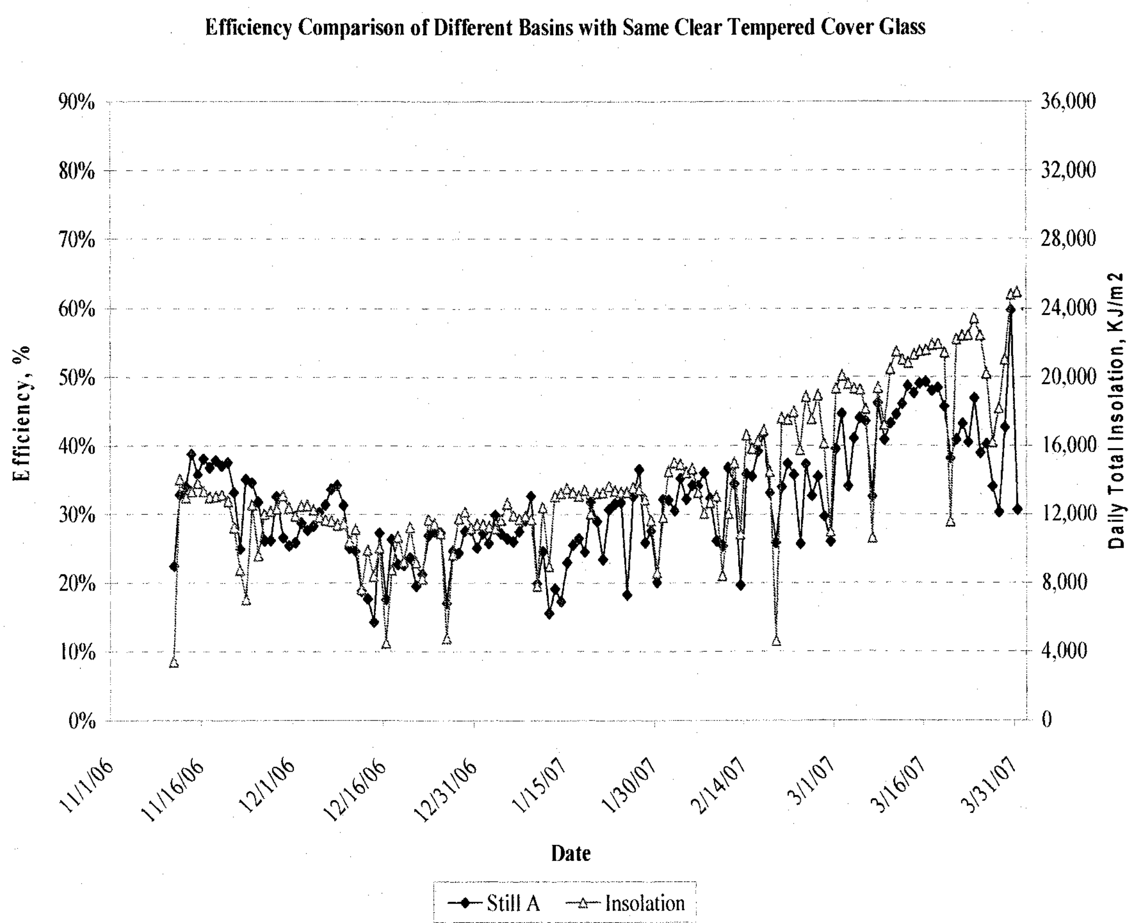

Figure 3.3a: Late fall and winter global insolation and corresponding efficiency of still A with BTG (clear)

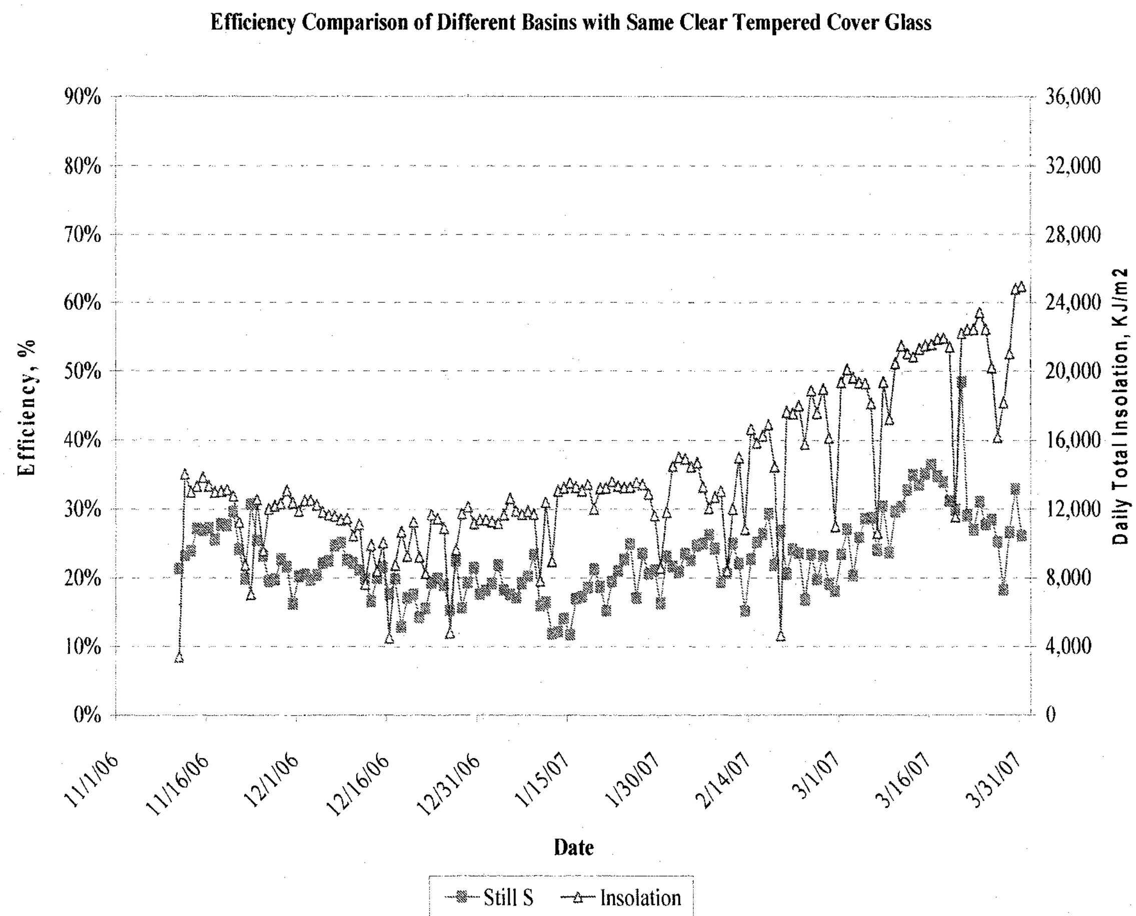

Figure 3.3b: Late fall and winter global insolation and corresponding efficiency of still S with BTG

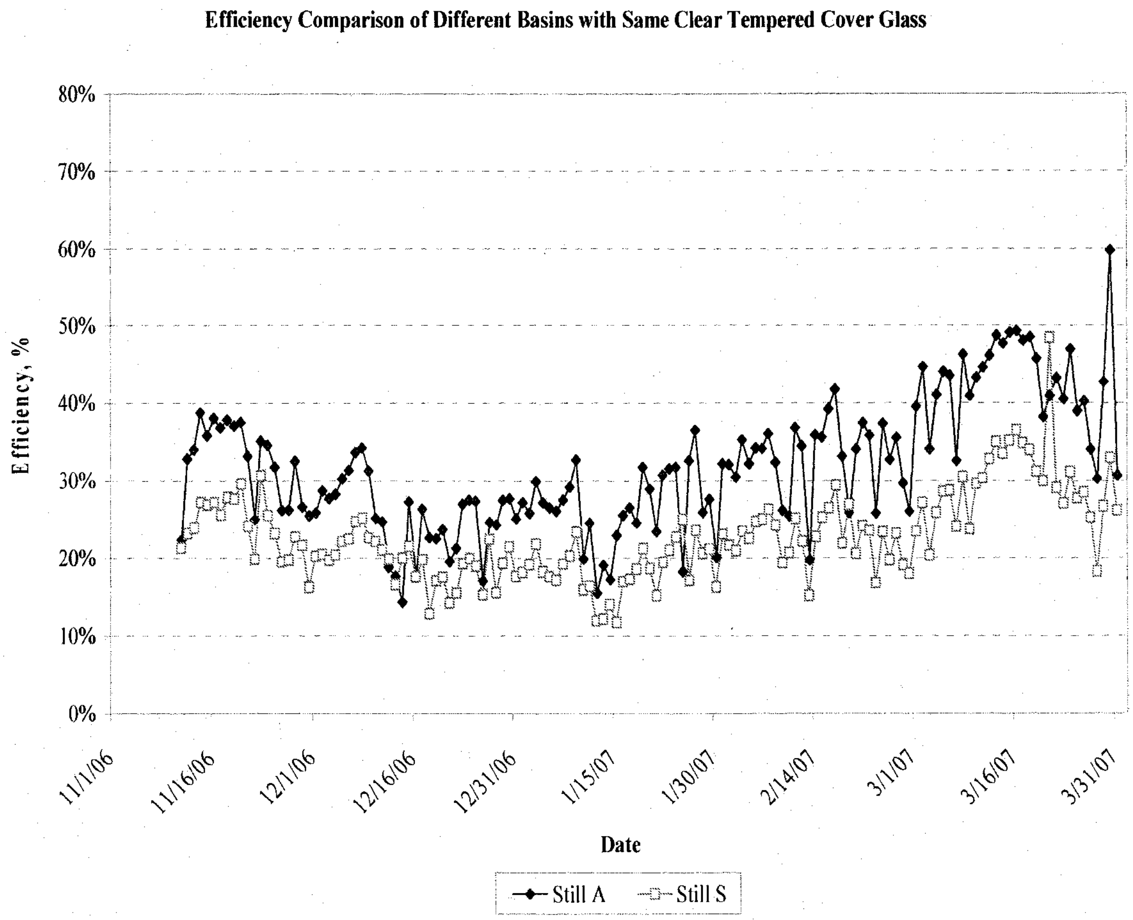

Figure 3.3c: Late fall and winter efficiency comparison of identical BTG covers for stills A and S

Both stills showed minimum efficiency during December 15 2006 to January 15 2007. Efficiency then steadily increased through late winter and into spring as insolation rose steadily. The mean efficiency of still A was 32% ± 8.4% and that of still S was 23% ± 5.6%. A one-way ANOVA showed that over this period these values were significantly different at the 5% confidence level (Calculated p of 1.98E-22). Even though the glass covers were same, the production pattern was the same as in Experiment 2, with still A out producing still S.

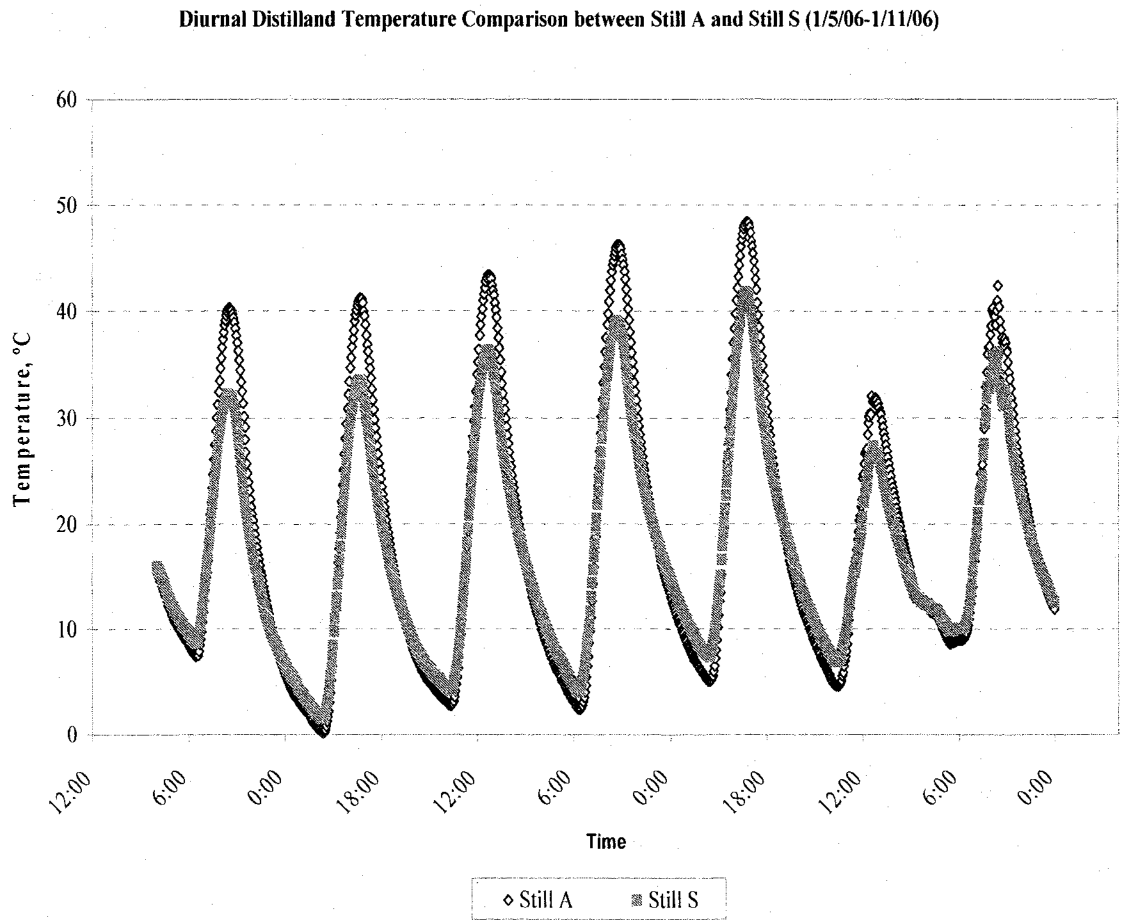

Figure 3.2d: Comparison of distilland temperature between stills A and S

This is because basin still A is insulated with polyisocyanurate foam whose R-value is nearly twice the R-value of fiberglass, which constitutes the body of still S. And this is evident from Figure 3.2d as the peak distilland temperature in still A was greater than that of still S by approximately 6°C.

<u>Experiment 4</u>: <u>Similar basins and different cover glasses</u>

A comparison of different clear cover glasses was performed for stills A and C. In this case the still basins were of the same make (Sunwater®), but had different clear cover glasses (BTG and BJTG respectively). Production efficiencies were very similar, as shown in Figure 3.4.

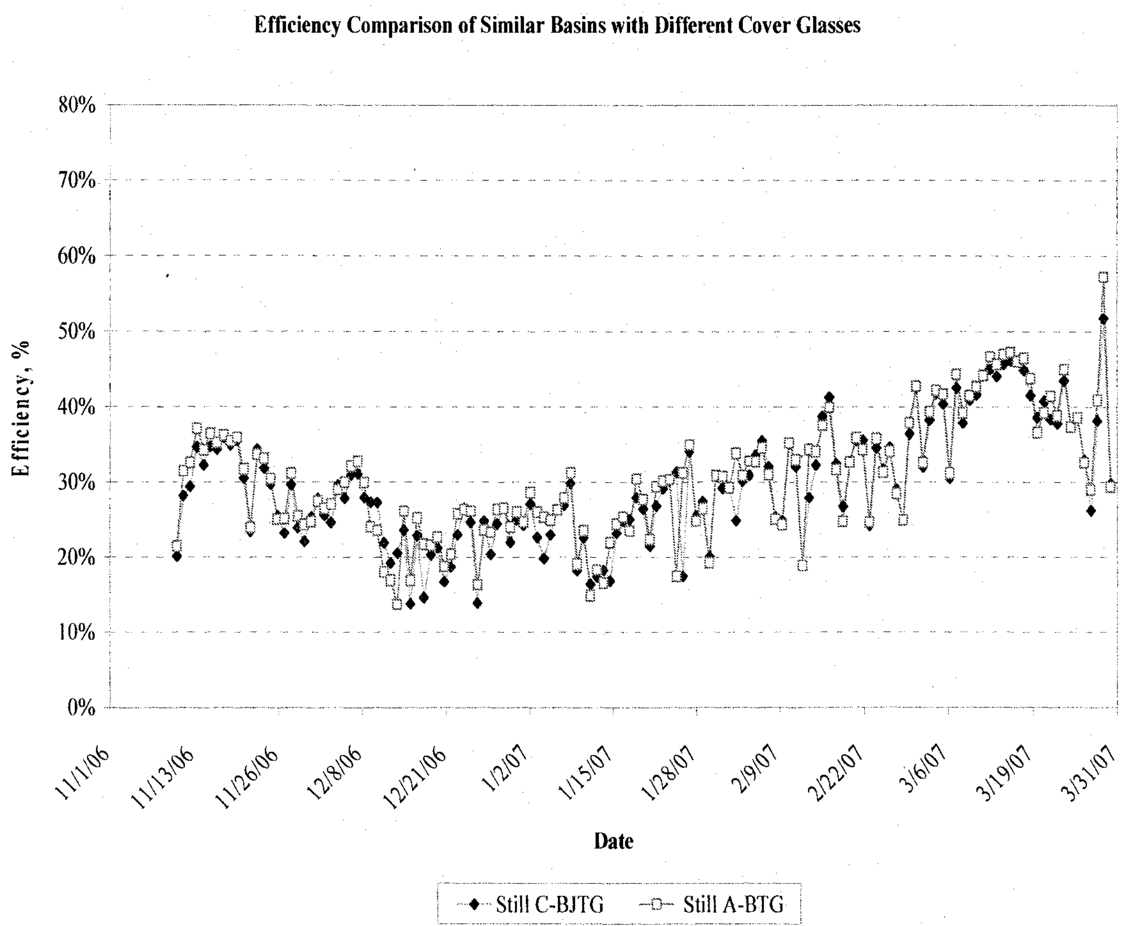

Figure 3.4: Efficiency comparison of different clear cover glasses for identical still basins A and C

The average efficiency for still A was 31% ± 8.2%. Over this time period, the average efficiency of still C was 32% ± 8.4%. One way ANOVA showed these two stills to be not significantly different with a calculated p-value of 0.37.

3.2 Double-Basin Solar Stills (Short-term and Long-term Results)

Experiment 5: First short-term comparison of low-e and clear cover glasses

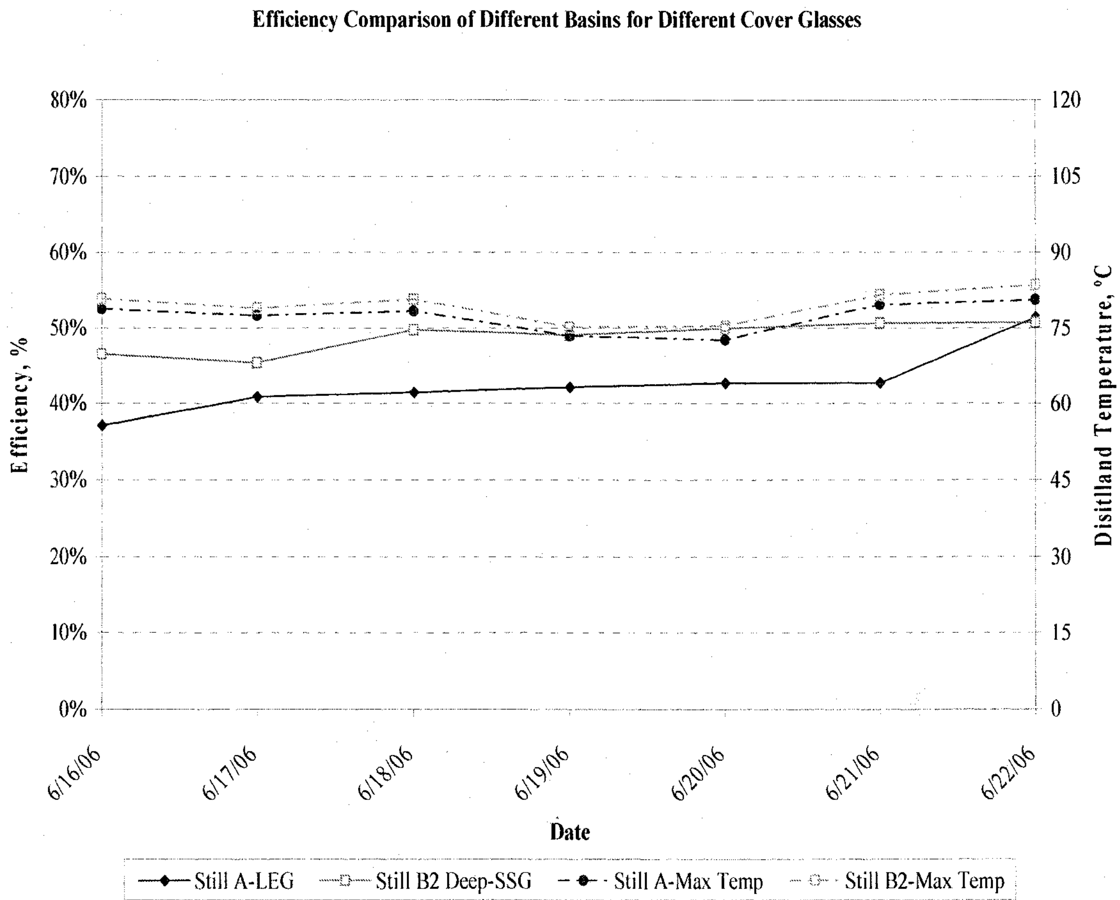

Figure 3.5a: Efficiency and maximum distilland temperature comparison of stills A and B2 for LEG (low-e) and SSG (clear) respectively

Figure 3.5a shows the efficiency of stills A and deep-basin of still B2 for seven experimental days. Stills A and B2 had LEG (low-e) and SSG (clear) respectively. The plot also contains the maximum observed distilland temperatures of the days corresponding to the given efficiency. The average efficiencies were 43% ± 4.3% (still

A) and 49% ± 2.1% (still B2). ANOVA showed that even though there was the peak temperatures did not vary significantly (calculated p- value = 0.21). there was no significant difference between the two efficiencies (calculated p- value = 0.005) for an α of 0.05.

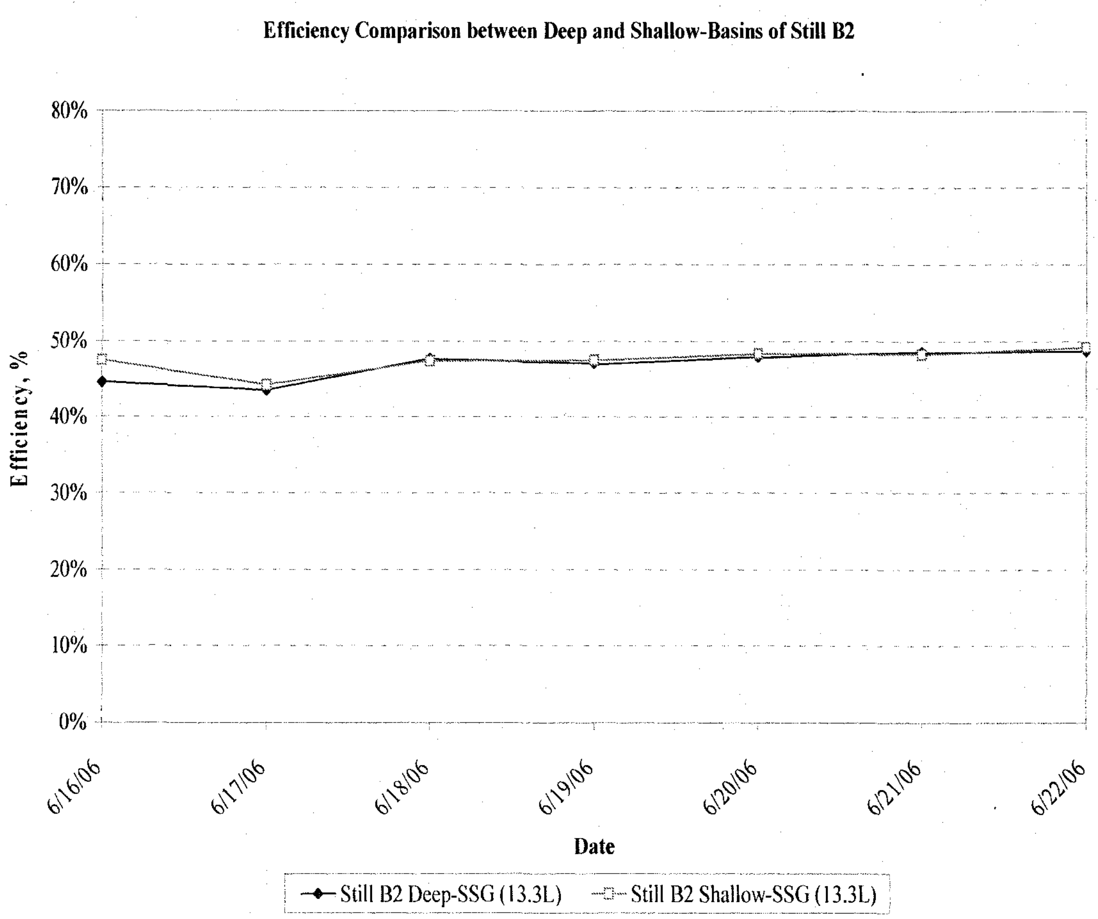

Figure 3.5: Efficiency comparison between deep and shallow-basins of still B2 having same distilland volume and glass cover

Figure 3.5b depicts the performance of both deep and shallow-basins of still B2 at the same water volume. Their average efficiencies were 49% ± 2.1% and 50% ± 1.6%. No significant difference was noticed between them (p-value = 0.52).

Experiment 6: Second short-term comparison of clear and low-e cover glasses

Experiment 6 is a repeat of experiment 4 with the cover glasses exchanged on stills A and B2. still A's efficiency was higher than that of B2 (Figure 3.6)

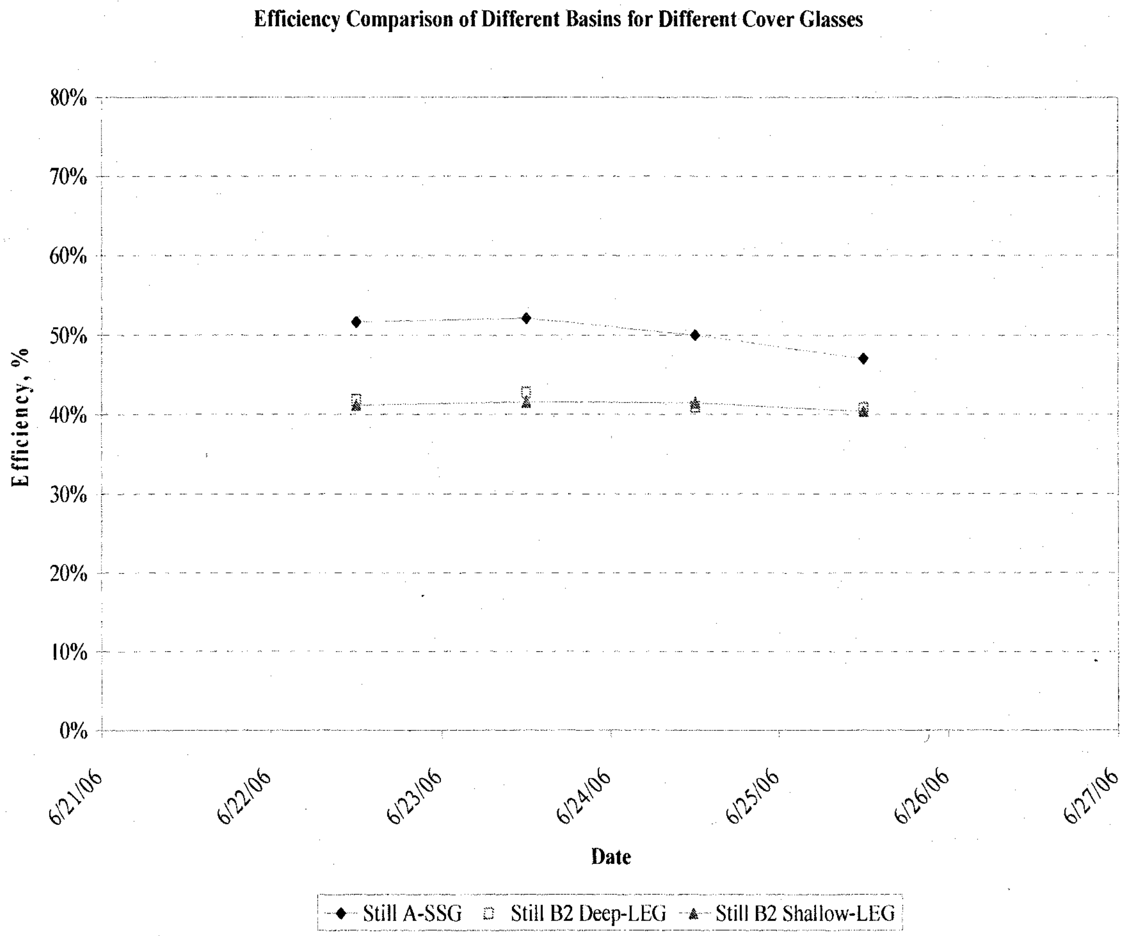

Figure 3.6: Efficiency comparison of stills A and B2 with SSG (clear) and LEG (low-e) respectively

The efficiency differences between still A and deep-basin of still B2 and still A and shallow-basin were found to be statistically significant, with p- value of 4.2E-04, and 2.5E-04 respectively. However p-value for comparing deep-shallow efficiency of still B2 was 0.48. LEG efficiencies were lower than SSG (just like in Figure 3.5a), and in case of still B2 deep and shallow-basin efficiencies were similar.

Experiment 7:Longer-term comparison of clear and low-e cover glasses

Stills B1 and B2 were run for almost two months with the same mass and depth of water. The former had BJTG and the latter had LEG. Occasional dips in the B1 still can be noticed in Figure 3.7a, some of which were known to be caused due to leaks and kinking of the delivery tube. For some other data points, reasons for the yield reductions are not known. Since their previous and following data points were higher than still B2, hence several days can be considered as outliers. Including, all outliers, still B1 had a daily mean yield of 4.3 $L/m^2 \pm 1.3$ L/m^2 whereas still B2 had 4.2 $L/m^2 \pm 0.9$ L/m^2. The calculated p-value was 0.07 for one-way ANOVA, indicating that there was no significant difference in the two stills' production.

Referring to Figure 3.7b, calculated efficiencies also showed no significant differences as still B1 had a mean efficiency of 38% ± 7.6% whereas still B2 had 37% ± 5%. Again due to high p-value of 0.55, the null hypothesis could not be rejected.

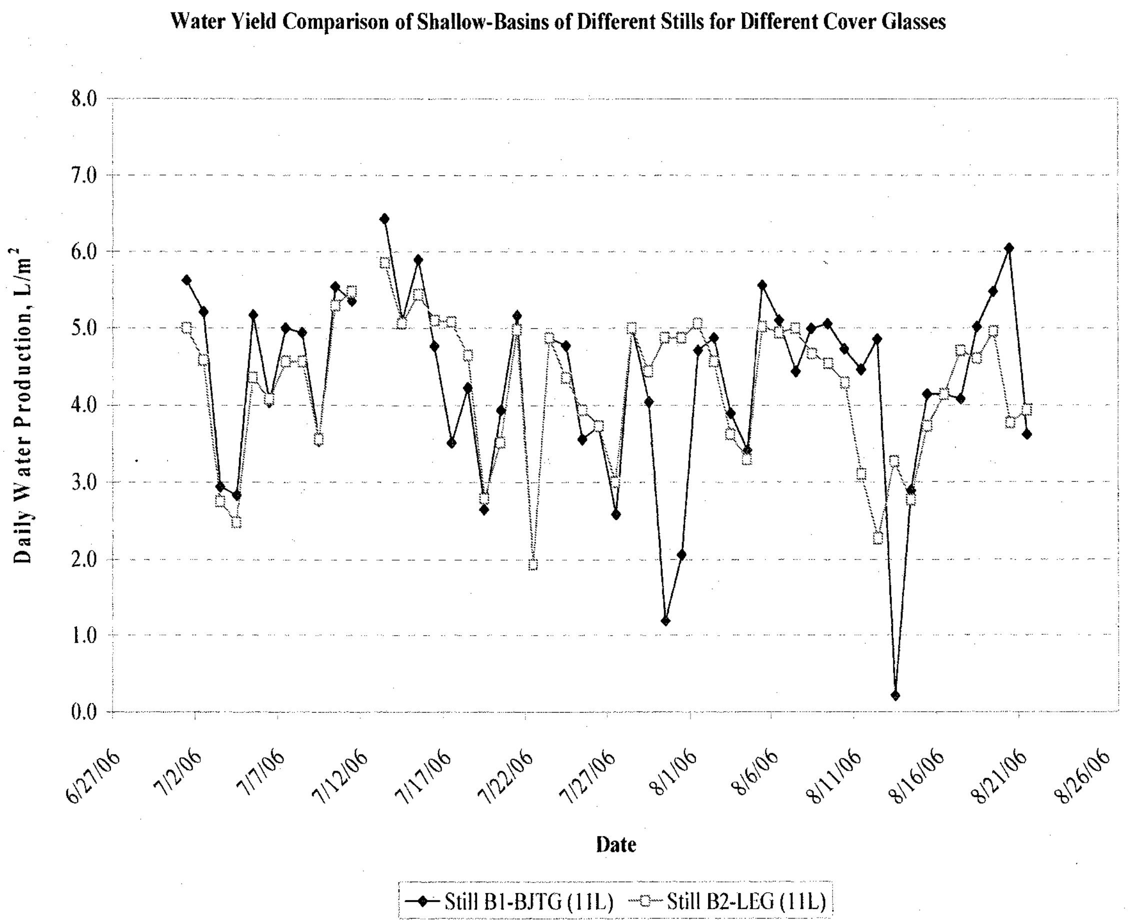

Figure 3.7a: Water yield comparison of BJTG (clear) with LEG (low-e) for identical stills B1 and B2

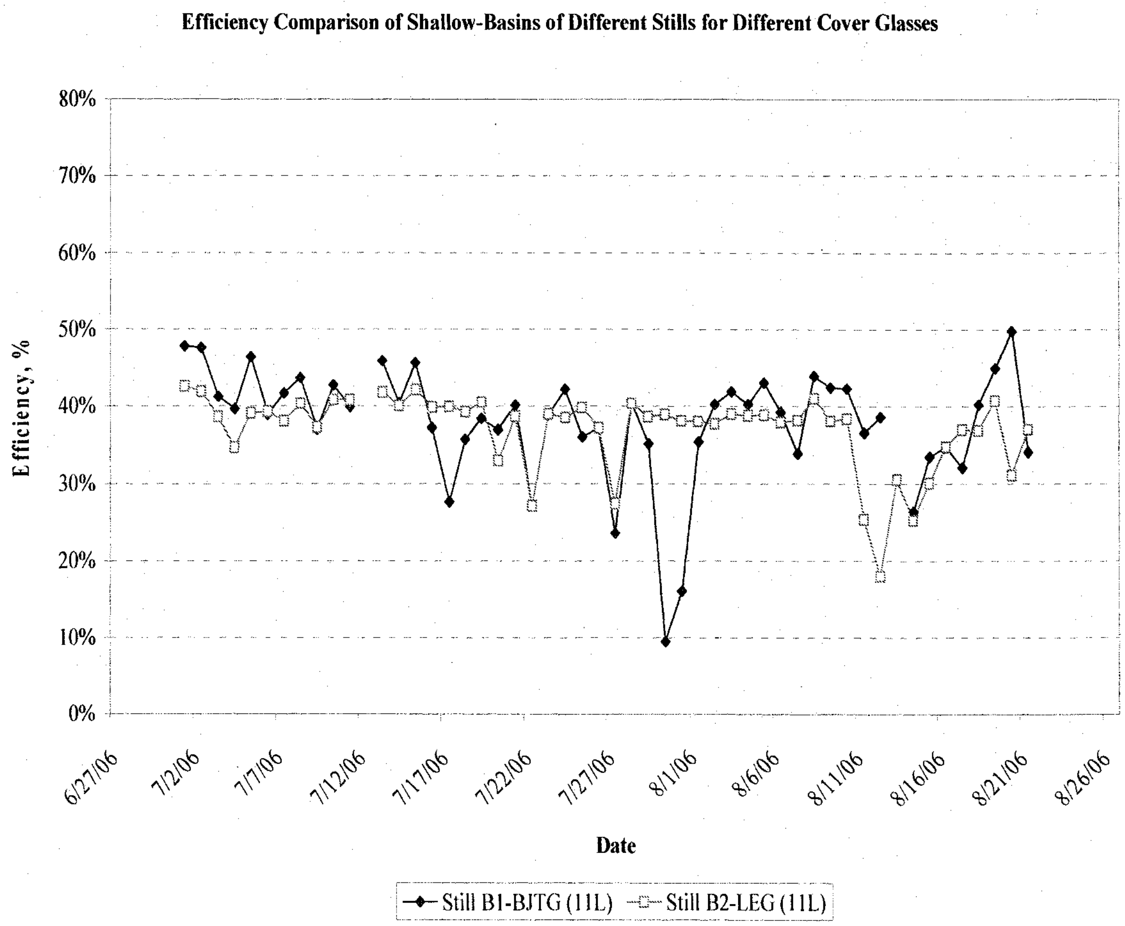

Figure 3.7b: Efficiency comparison of BJTG (clear) with LEG (low-e) for identical stills B1 and B2 with a distilland volume of 11L

Experiment 8: Second long-term comparison of clear and low-e cover glasses For deep basins

The Experiment 7 results were for shallow-basins of stills B1 and B2. This section presents the same results for their deep-basins with a distilland volume of 27.5L. It can be observed from Figure 3.8a and 3.8b that unlike earlier, still B1 consistently performed better consistently. The mean water yield for stills B1 and B2 were 4.4 L/m^2 ± 0.82 L/m^2

and 4.1 $L/m^2 \pm 0.79$ L/m^2. One-way ANOVA gave a p-value of 0.046 indicating that the null hypothesis of no difference in water production can be rejected.

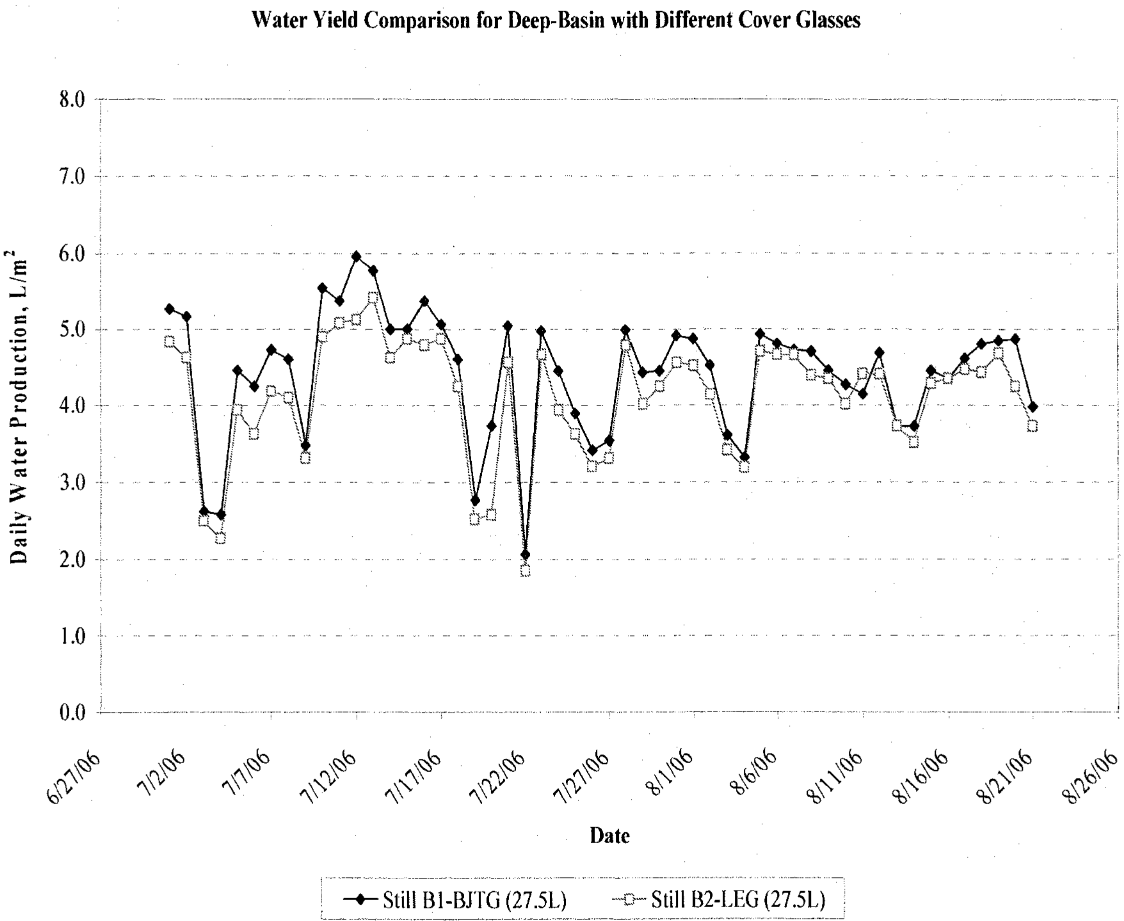

Figure 3.8a: Water yield comparison of BJTG (clear) with LEG (low-e) for identical stills B1 and B2 with a distilland volume of 27.5L

ANOVA for the efficiencies of stills B1 and B2 (Figure 3.8b) gave their mean as 38.3% ± 3% and 35.6% ± 3% respectively. The difference was also confirmed to be highly significant with a p-value of 9.15E-06. For deep-basins, clear glass (BJTG) outperformed low-e glass (LEG).

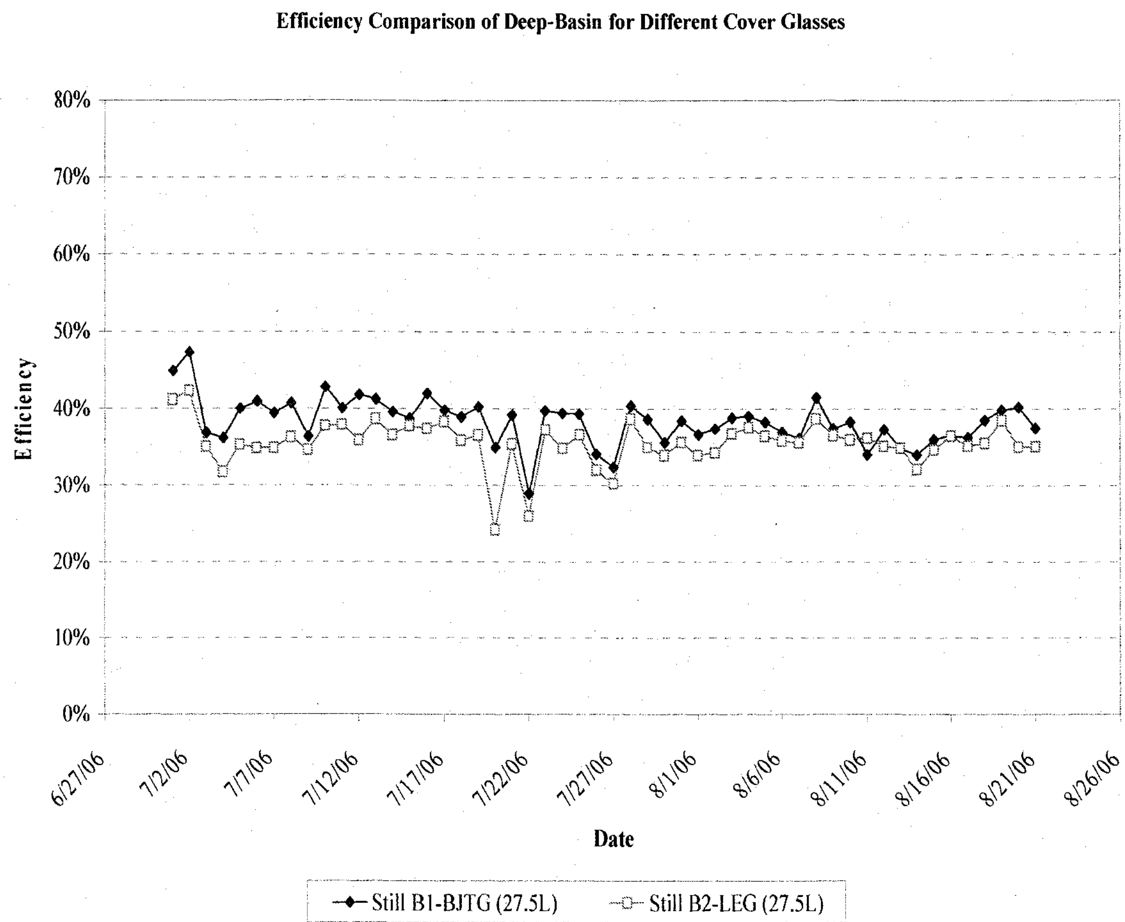

Figure 3.8b: Efficiency comparison of BJTG (clear) with LEG (low-e) for identical stills B1 and B2 with a distilland volume of 27.5L

<u>Experiment 9</u>: <u>Nighttime production in solar stills</u>

In experiment 9, the tipping bucket rain gauge was shifted between deep and shallow-basins over a period of two months, 7/1/2006-8/30/2006. From Figure 3.9 it can be observed that a still behaves diurnal in nature. It not only produces condensate during daytime but continues to do so even after sunset. This is because at night the basin water releases the heat trapped by it during the daytime. The amount of energy trapped depends upon the water depth in the basin. For the data shown, night-time production was 9.2 cm^3

± 29 cm^3 in shallow-basin and 60 cm^3 ± 55 cm^3 in the deep-basin. ANOVA showed that they were significantly different with a calculated p-value of 1.86E-08.

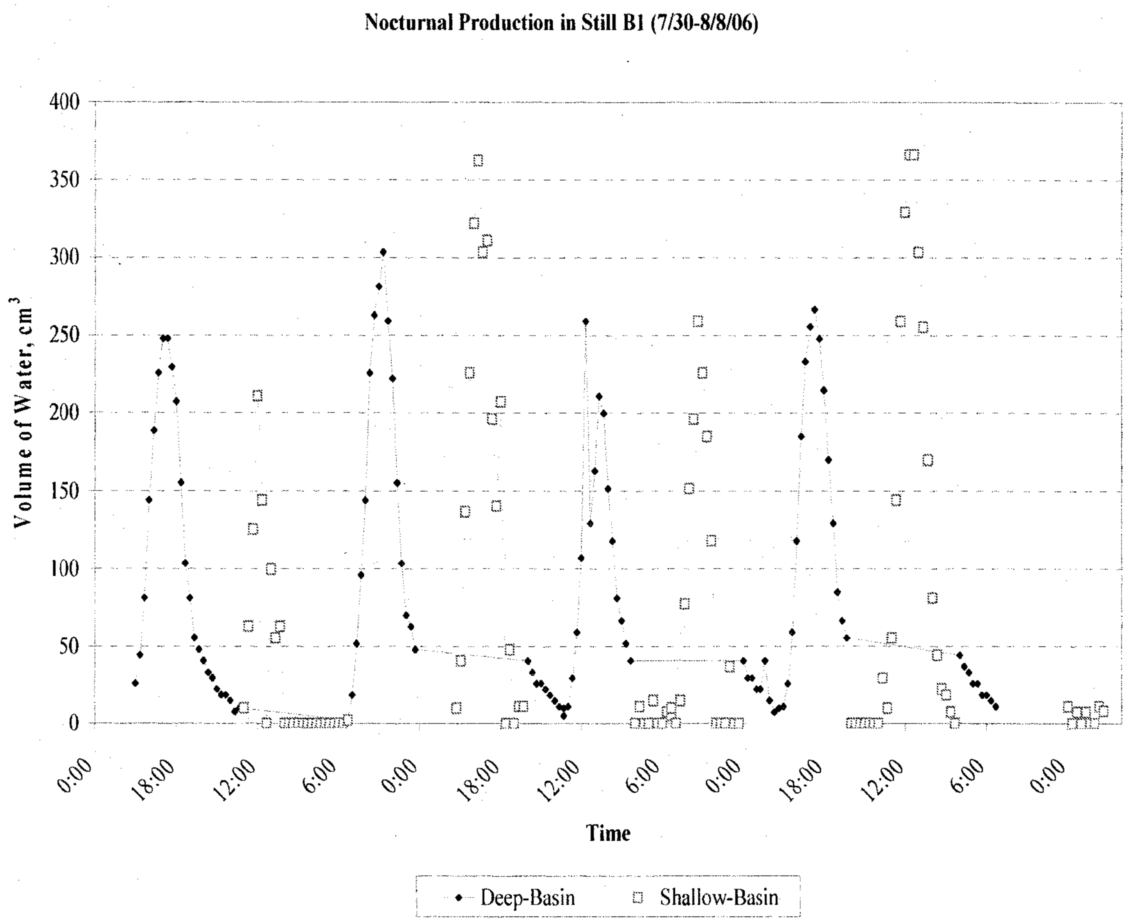

Figure 3.9: Example depiction of deep and shallow night-time production on alternate days

<u>Experiment 10</u>: <u>First long-term deep and shallow-basin comparison for same water mass</u>

One of the research hypotheses was that nocturnal production can be enhanced by increasing the amount of distilland in the basin. In Experiment 10, the principle of nigh-time deep-basin water production was tested. For this purpose, the deep and shallow-basin distilland volumes were varied and their performance was observed. These results are presented in the following sections.

For two months, in late winter and early spring, deep and shallow-basins of still B2 was maintained with the same distilland volume of 10L. It had SSG cover glass.

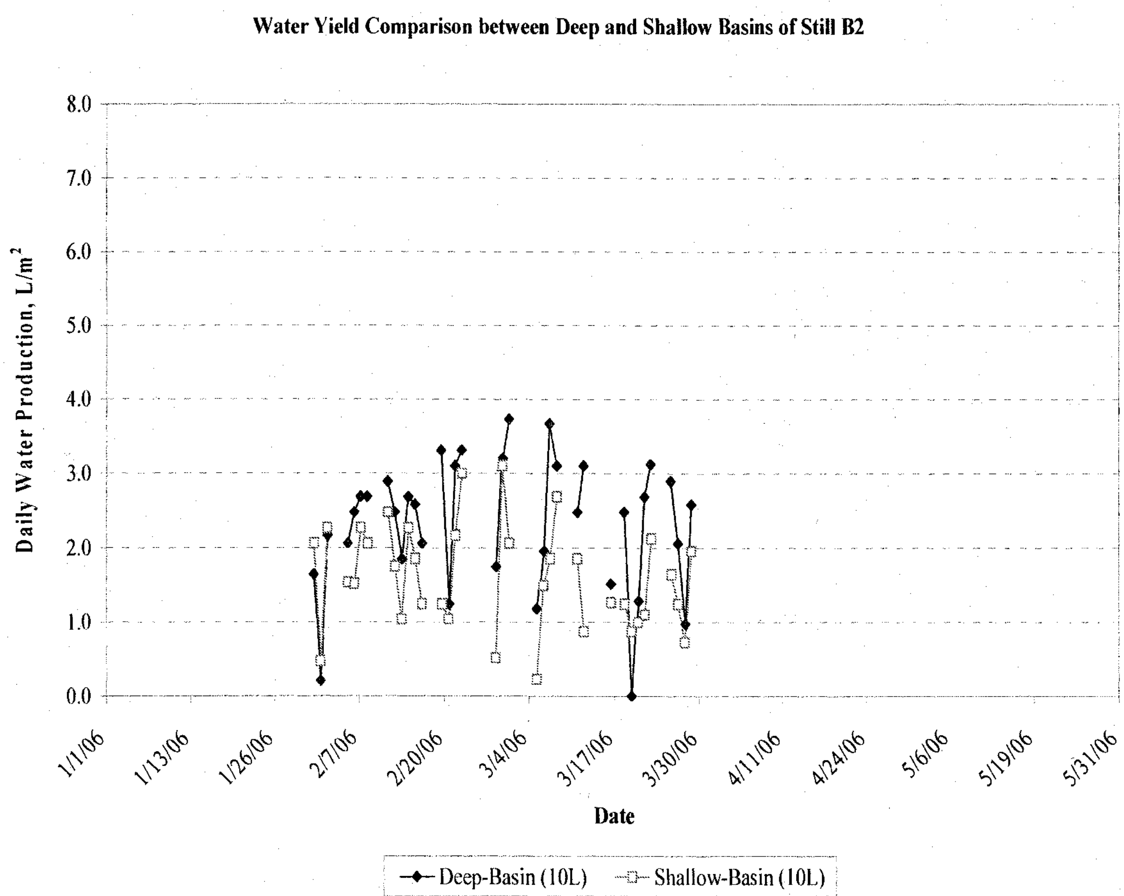

Figure 3.10a: Water yield comparison of SSG (clear) for the deep and shallow-basins of still B2

Figure3.10a shows the water yield of both the basins of still B2. Their mean yields were 2.3 L/m^2 ± 0.8 L/m^2 (deep-basin) and 1.6 L/m^2 ± 0.5 L/m^2 (shallow-basin), whose difference were found to be highly significant with a calculated P-value of 4.3E-04.

Figure3.10b depicts the efficiencies of deep and shallow-basins of still B2. The mean efficiencies for the deep and shallow-basins were 33.4% ± 10.4% and .23.2% ± 10.1% respectively. One-way ANOVA gave a highly significant difference value of 8.42E-05.

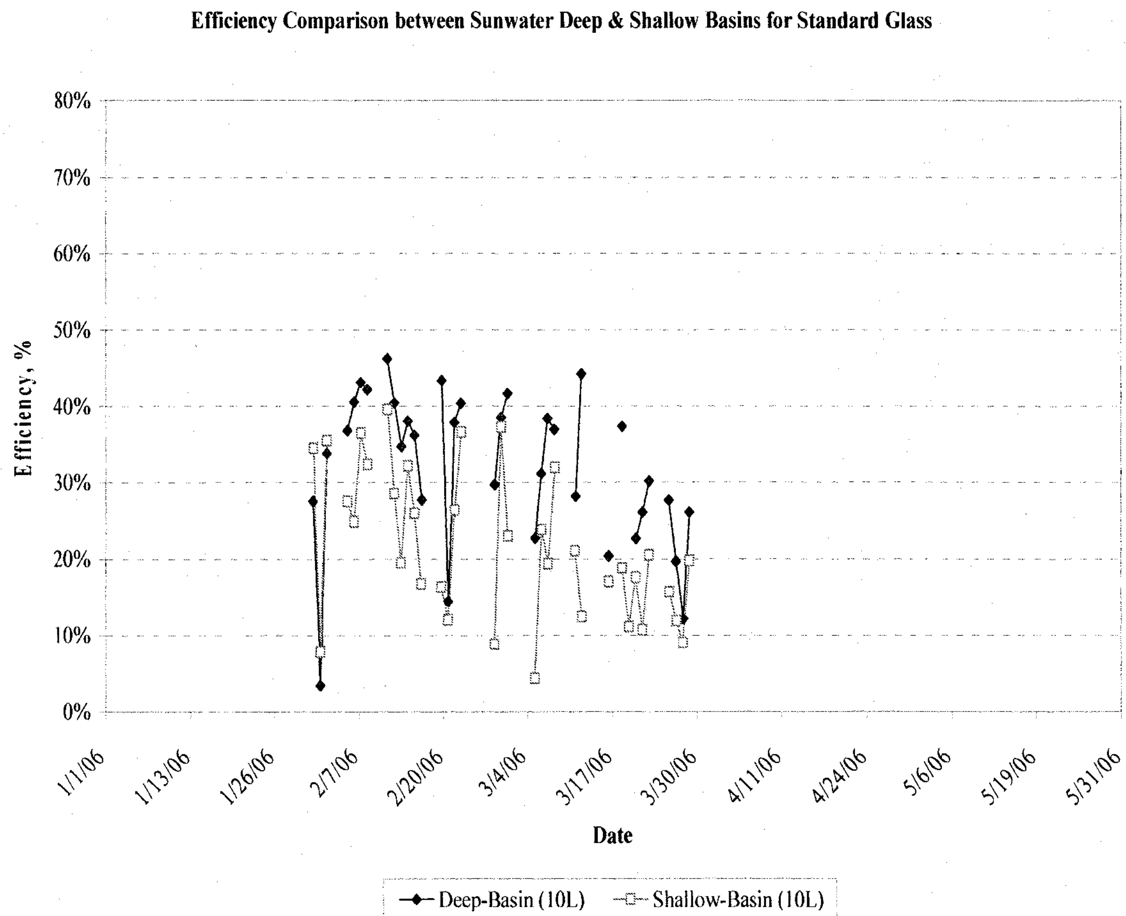

Figure 3.10b: Efficiency comparison of SSG (clear) for the deep and shallow-basins of still B2

This high discrepancy in water production and corresponding efficiency may be because of manual errors. As the test was carried out in the starting stages of the research, we were still getting to know how to operate the stills in terms of collection, and reintialization procedures. There could also have been some unnoticed air gaps on either side of the basin, causing one to produce less than the other inspite of all attempts to create identical conditions.

Experiment 11: Short-term deep and shallow-basin comparison with different water mass

In Figure 3.11, test results of still B2 with two different water masses has been plotted. The deep-shallow distilland ratio was almost 2:1 in the first and 1:1 in the second stages of the experiment.

The difference in the two sets is clearly visible as when the volumes were different, the shallow-basin was more efficient. When the volumes were same, the efficiencies became similar too.

The mean efficiencies for deep and shallow-basins were 42.4% ± 4.7% and 44.3% ± 8.6% (first case) and 48.8% ± 2.1% and 49.5% ± 1.6% (second case) respectively. But the efficiency differences in both the sets were not found to be highly significant as they had P-values of 0.61 and 0.52 respectively.

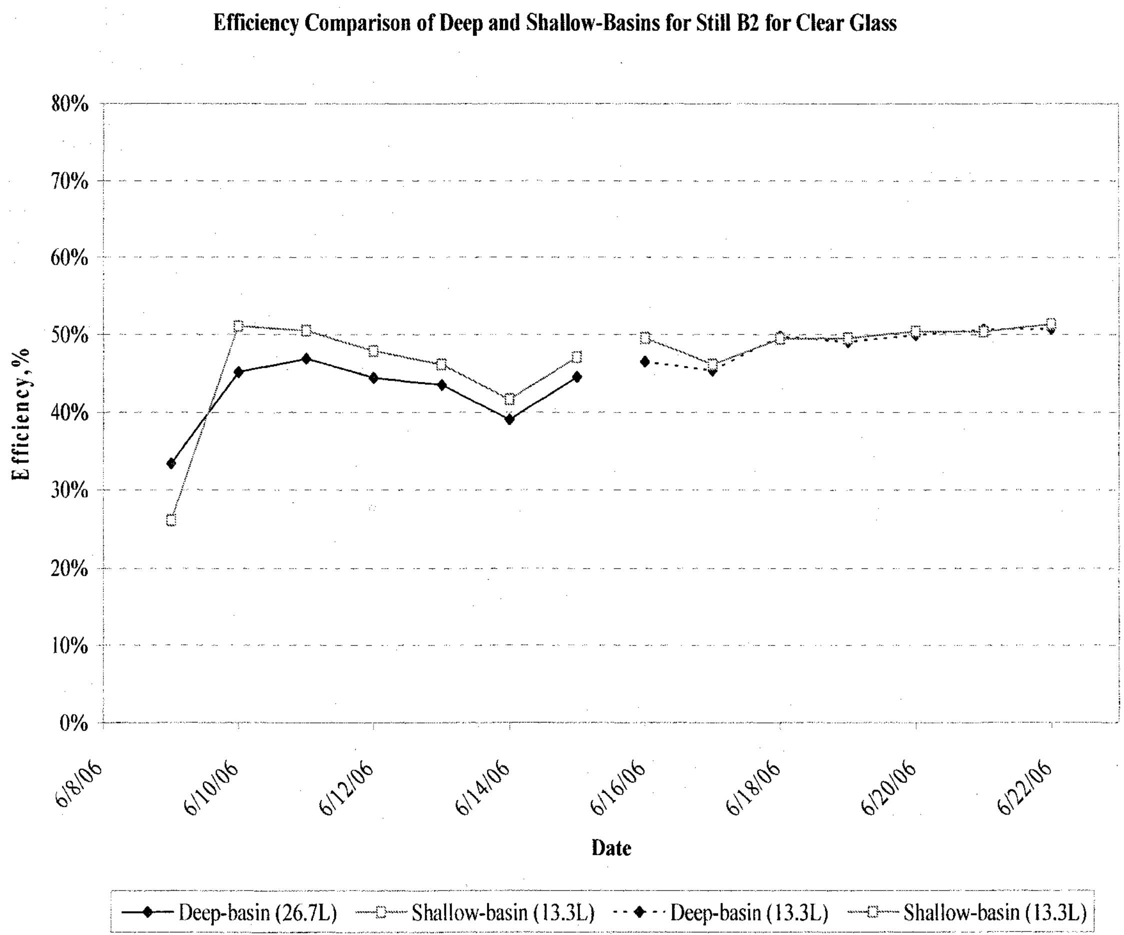

Figure 3.11: Efficiency comparison of SSG (clear) for the deep and shallow basins of stills B1 and B2

Experiment 12: Second long-term deep and shallow-basin comparison for different water mass

In this experiment, the volume in deep-basin was made two and a half times that of shallow-basin and still B2 was using LEG (low-e). Figure 3.12a compares the water productions of these two basins. The still was operated for almost two months during late summer and early fall. The mean yields were 4.1 $L/m^2 \pm 0.8$ L/m^2 (deep-basin) and 4.3 $L/m^2 \pm 0.9$ L/m^2 (shallow-basin). With a calculated p-value of 0.36, the null hypothesis could not be rejected.

Figure 3.12b depicts the efficiencies of deep and shallow-basins of still B2 with LEG (low-e) cover glass. The mean efficiencies of deep and shallow-basins were found to be 35.6% ± 3% and 37% ± 5% respectively. ANOVA gave a calculated p-value of 0.08, hence the null hypothesis could be not be rejected. .

It was found that there was no use of increasing the distilland mass as the extra water (compared to the shallow-basin) was not being utilized as the heat storage element.

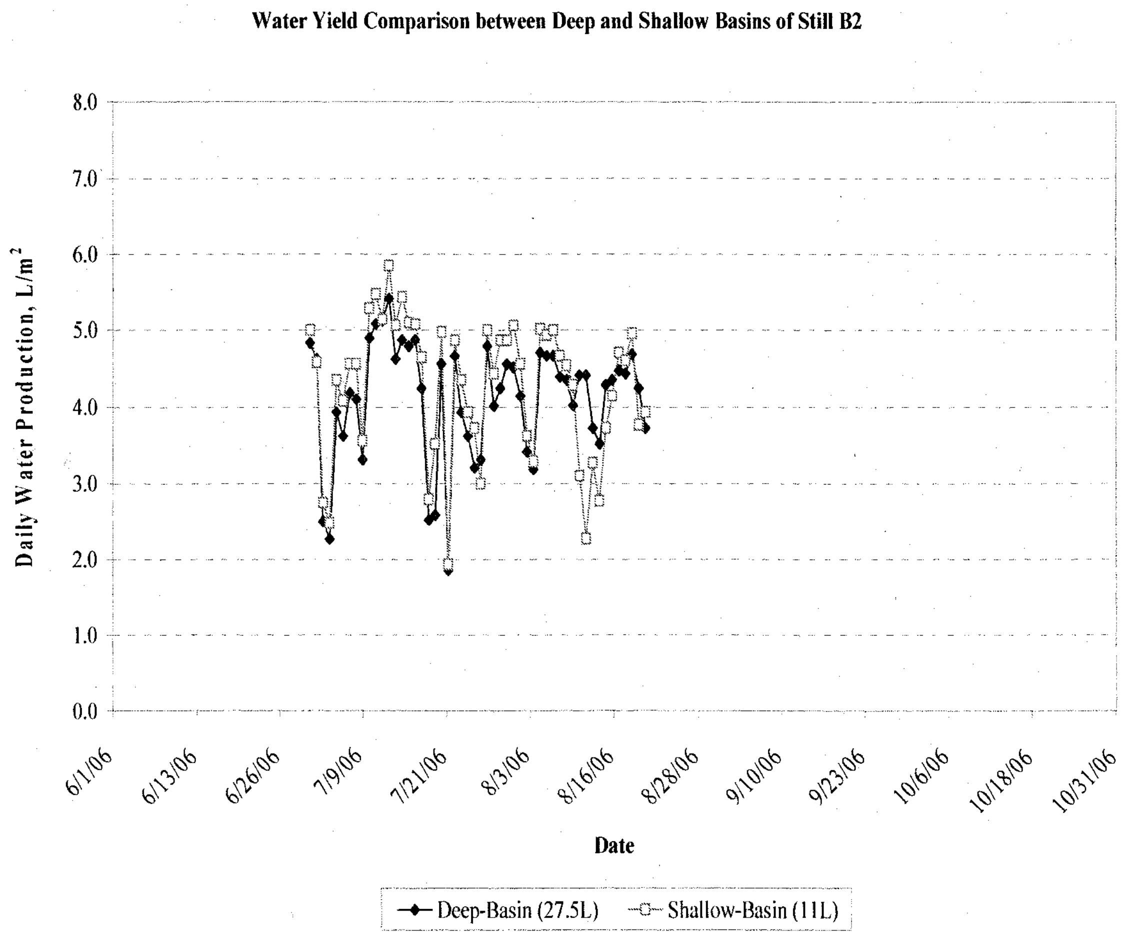

Figure 3.12a: Water yield comparison of LEG (low-e) for deep and shallow-basins of still B2

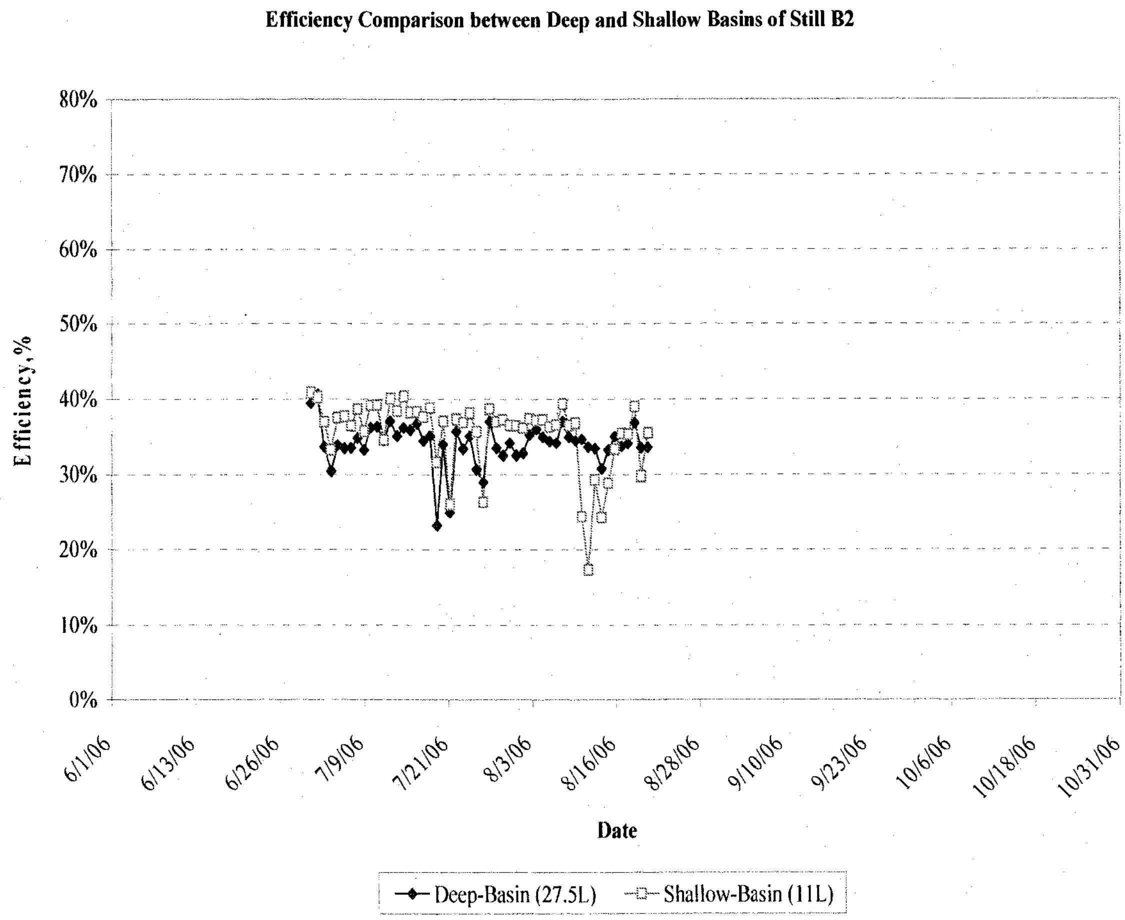

Figure 12b: Efficiency comparison of LEG (low-e) for the deep and shallow-basins of still B2

Experiment 13: <u>Third long-term deep and shallow-basin comparison with different water mass</u>

This test was run for a long duration of five months, from Nov-06 to Mar-07. The distilland ratio in terms of deep to shallow-basins was 2:1. The still was covered with BTG. The mean yields of deep and shallow-basins were found to be 1.8 $L/m^2 \pm 0.97$ L/m^2 and 1.8 $L/m^2 \pm 0.98$ L/m^2 respectively. During this time, ANOVA showed no significant difference as calculated P-value was 1.

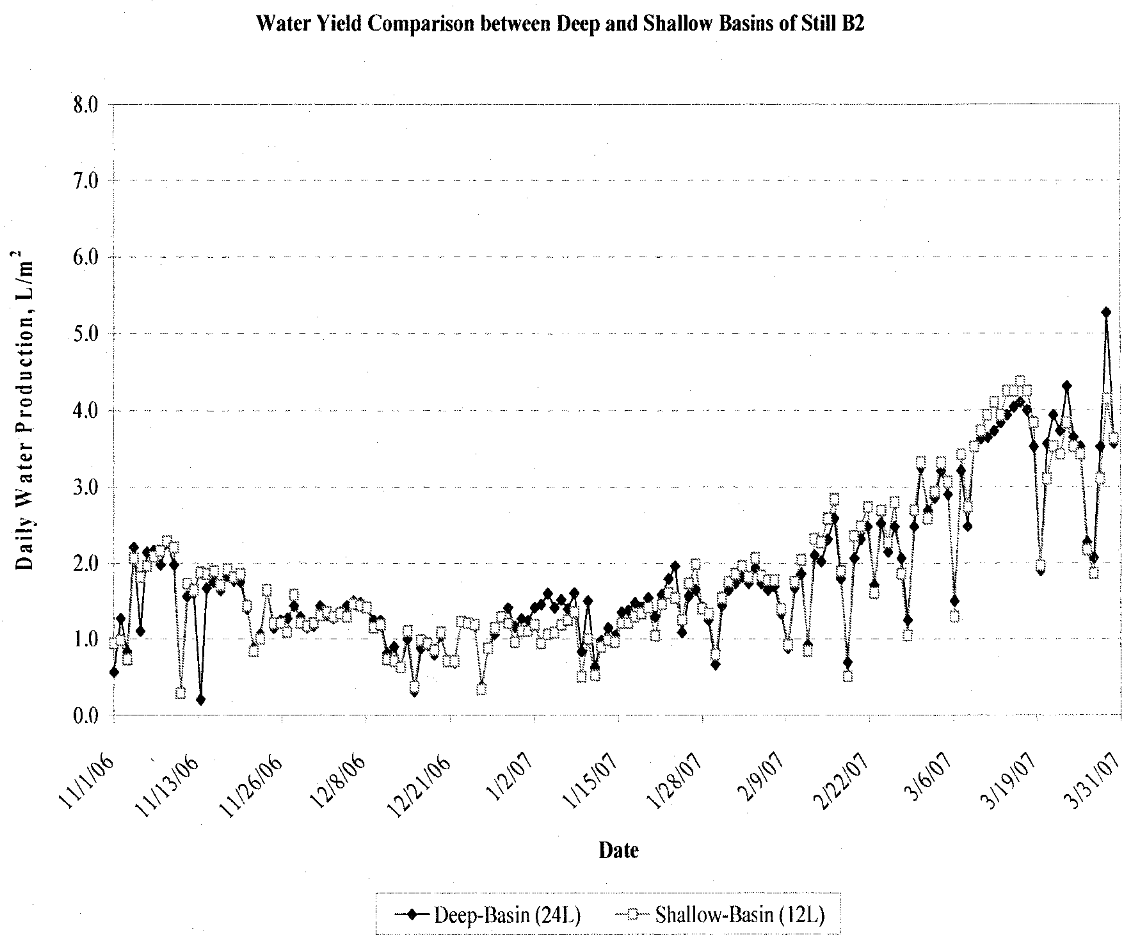

Figure 3.13a: Water yield comparison of BTG (clear) or deep and shallow basins of still B2

The efficiencies of deep and shallow-basins were plotted as shown in Figure 3.13b. With the mean efficiencies of 29% ± 7.5% and 8.7% ± 8% for the deep and shallow-basins respectively. ANOVA gave a p-value of 0.84, again indicating no significant differences.

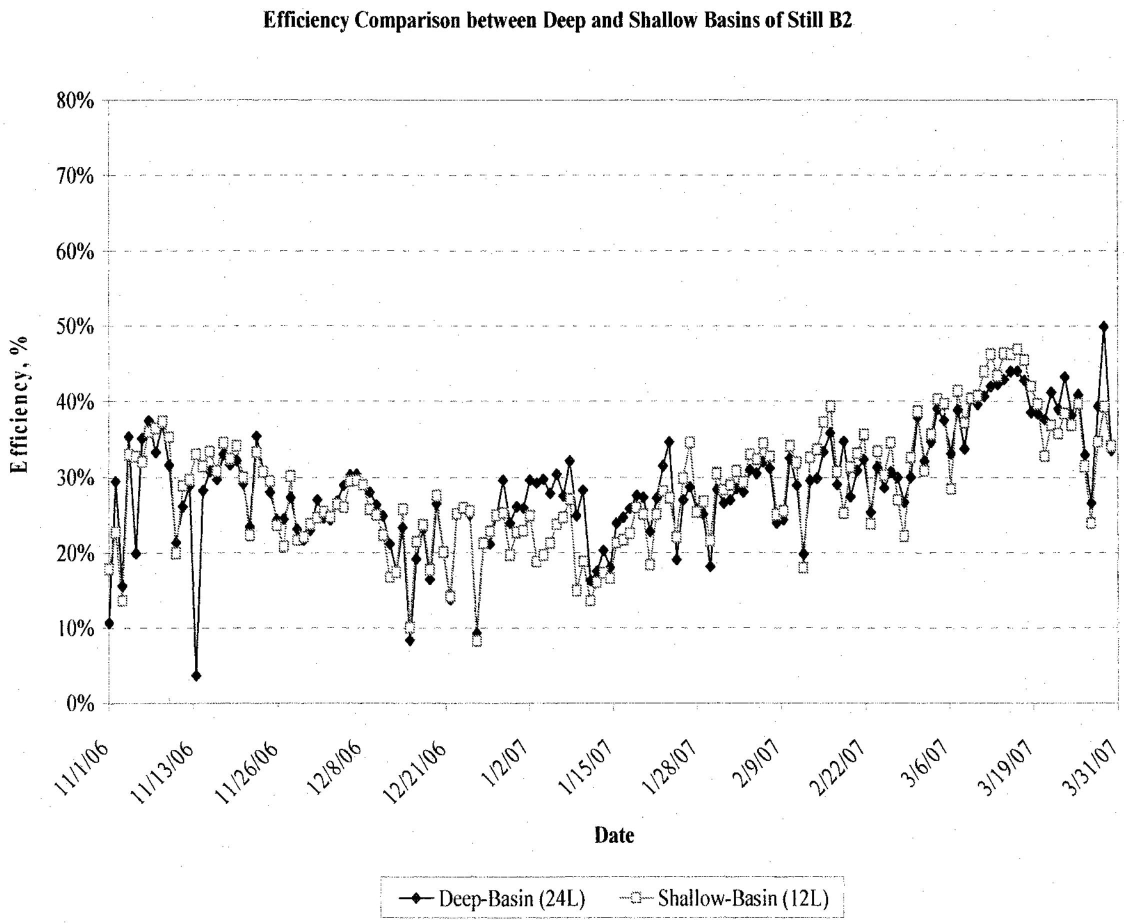

Figure 3.13b: Efficiency comparison of BJTG (clear) for deep and shallow basins of still B2

As in the previous two experiments, the concept of higher yields from a "deep-basin" could not be validated. To observe that effect, may be we should have made the deep-shallow ratio much larger. One limitation with the Sunwater® still was that near to 27.5L was the maximum in the deep-basin that could be reached without spilling into the collection trough and near to 10L was the minimum. Any quantity less than 10L would dry the upper region of the shallow-basin. Results of the deep-shallow comparison experiments are shown in Table3

Table 3.1: Summary of results obtained from all the deep-shallow comparison analysis

Experiment Number	Test Duration	Cover Glass	Deep-Shallow Distilland ratio	Time of the Year	Result
9	Medium	SSG	1:1	Winter-Spring 06	Highly significant
10	Short	SSG	2:1, and 1:1	Fall 06	Not significant
11	Medium	LEG	2.5:1	Fall 06	Not significant
12	Long	BTG	2:1	Winter 06-Spring 07	Not significant

Results show that, in general operating water depth did not significantly affect performance in a commercial single-basin still.

3.3 Effect of Global Insolation

Experiment 14:Impact of insolation on still performance for different cover glasses

Figures 3.14, 3.15, and 3.16 depict the amount of water produced as a function of total global insolation received by still A with LEG, BJTG, and BTG covers. Global insolation in kilo joules was converted to kW-hr to allow comparison with other published results. The observed data points were fit with a linear least-squares regression line.

In Figure 3.14, 82.4% of the variation in the water production is accounted for by global insolation. The remaining 17.6% can be explained by outliers. Also the null hypothesis that the relationship occurred due to chance can be rejected at 0.01 level as ANOVA gave a calculated P-value of 4.05E-23. The change in yield was 0.73 L/kW-hr insolation.

When the intercept of the regression lines were set at zero, two out three times, the correlation coefficient decreased. A possible reason assumed which caused this drop in R^2 was that a minimum amount of energy is needed before a still produces a measurable quantity of water.

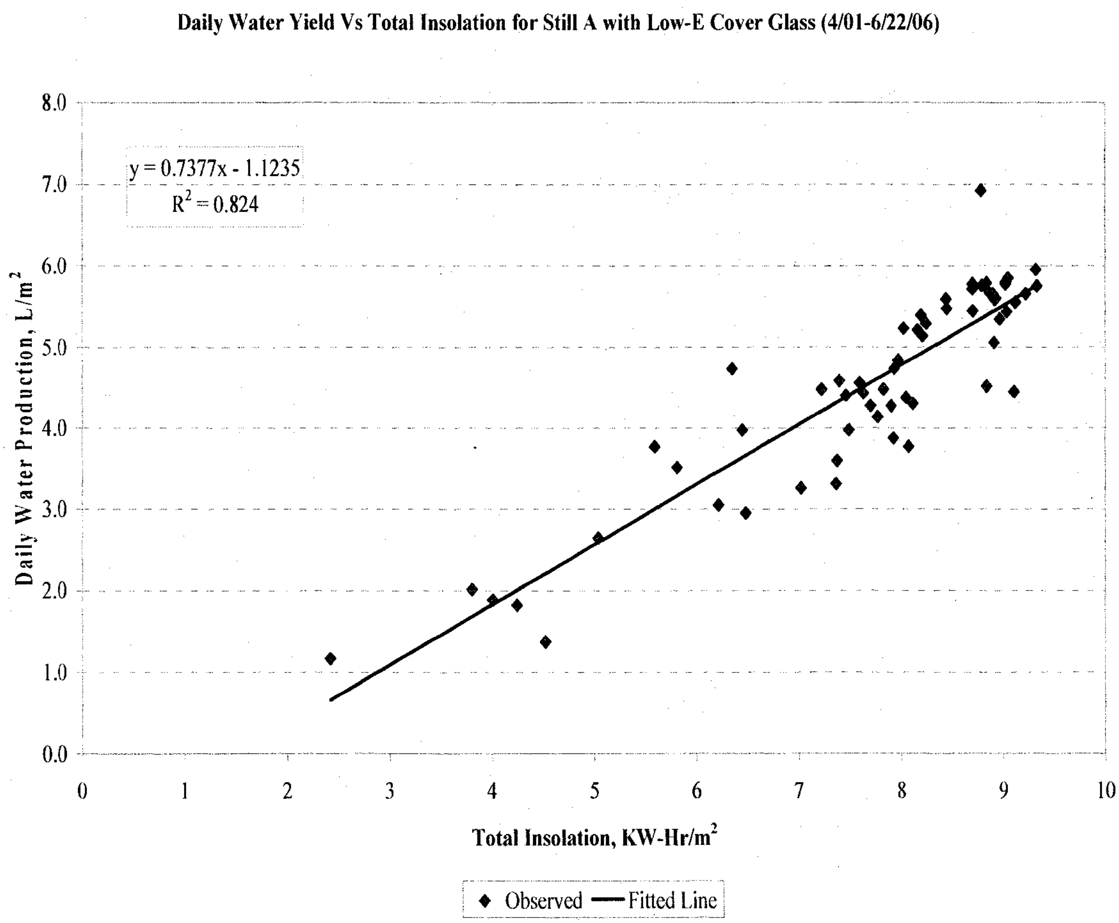

Figure 3.14: Water yield capacity of LEG (low-e) as a factor of global insolation for still A.

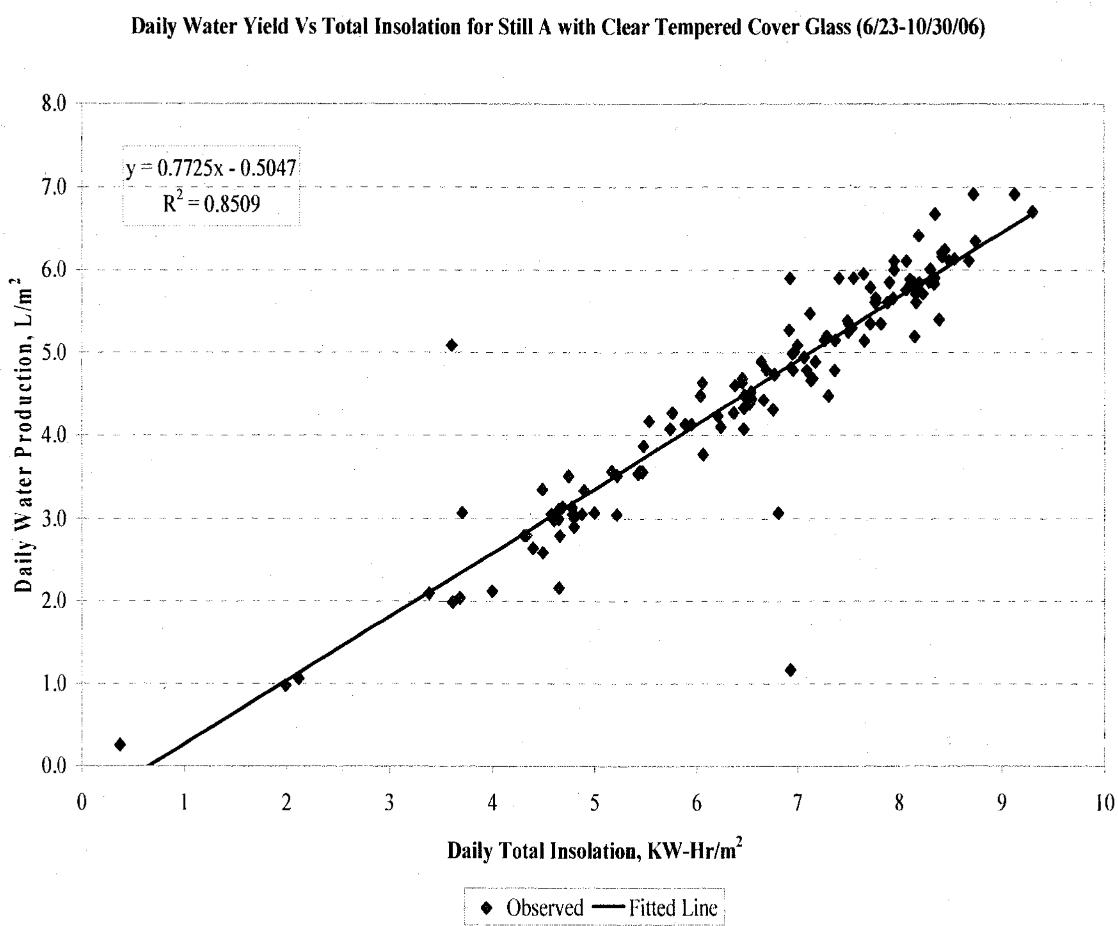

Figure 3.15: Water production capacity of BJTG clear glass as a factor of global insolation for still A

Figure 3.15 shows data for still A with BJTG (clear) in summer and fall-2006. The slope was a little higher than that with LEG (low-e). The null hypothesis was rejected at 0.01 level with a calculated P-value of 8.78E-53. The change in yield was 0.77 L/KWh of insolation

Figure 3.16 shows data for still A with BTG (clear). It can be observed that 88.4% of the variation of water production can be explained by the insolation. ANOVA calculated for the regression showed that it was significant at $P < 0.05$ level. The change in yield was 0.87 L per KWh of insolation.

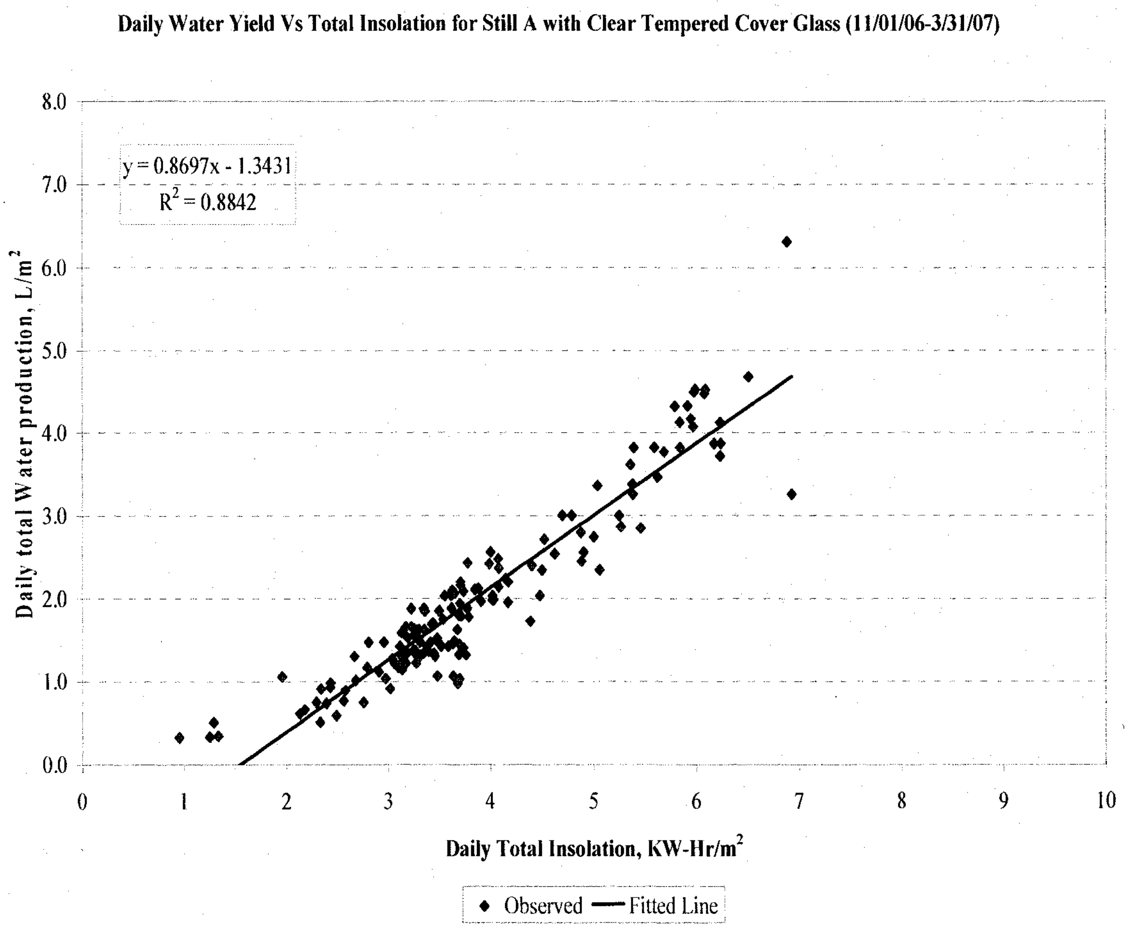

Figure 3.16: Water production capacity of BTG clear glass as a function of global insolation for still A

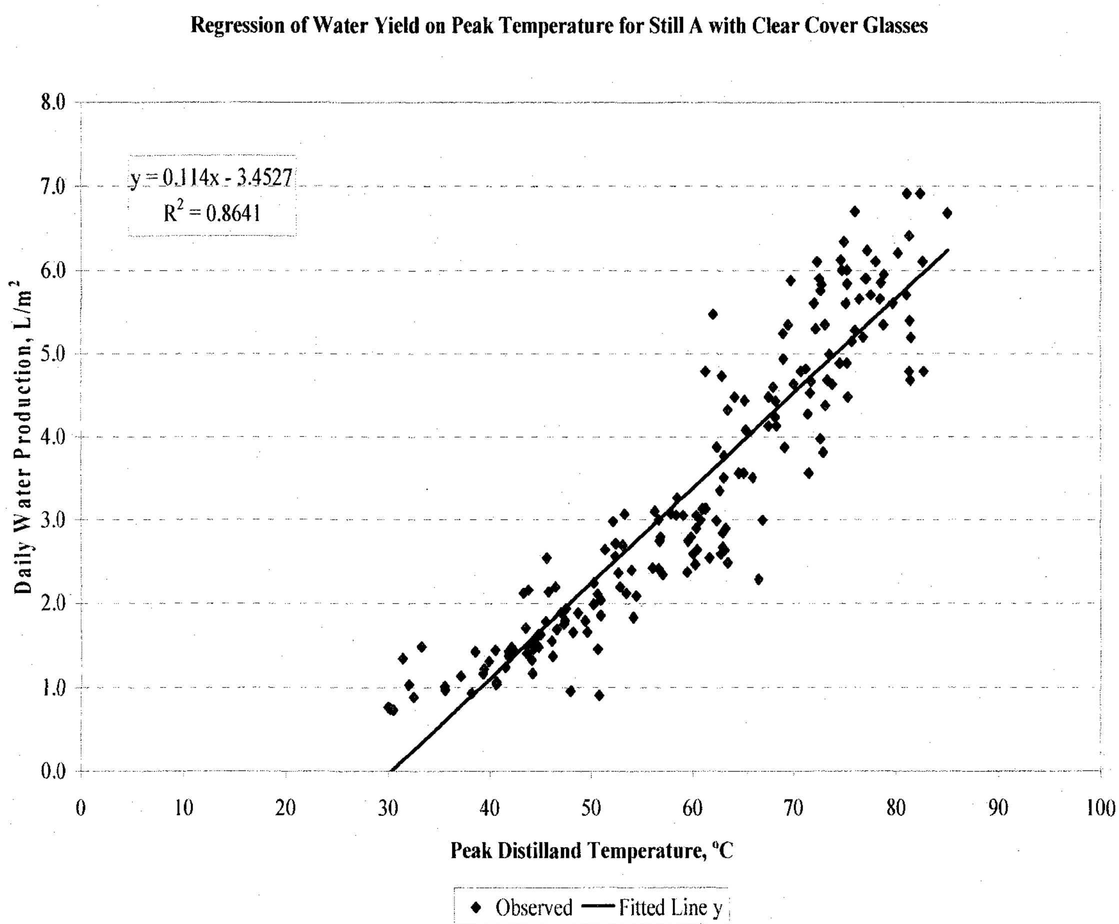

Figure 3.17: Variation in water yield as a function of maximum distilland temperature for still A

Figure 3.17 gives a plot of the variation in water production as a function of maximum distilland temperature for still A. It can be observed from the line equation that a minimum of 39.2°C of distilland temperature is required to produce a Liter of fresh water. Also to even start the process of evaporation, the distilland should be heated to a peak temperature of at least 30°C. It can also be clearly observed that maximum yield of 7 L/m^2 was attained at the maximum temperature 85°C. The regression analysis showed the dependence of yield on peak temperature to be highly significant with p-value of 1.28E-95.

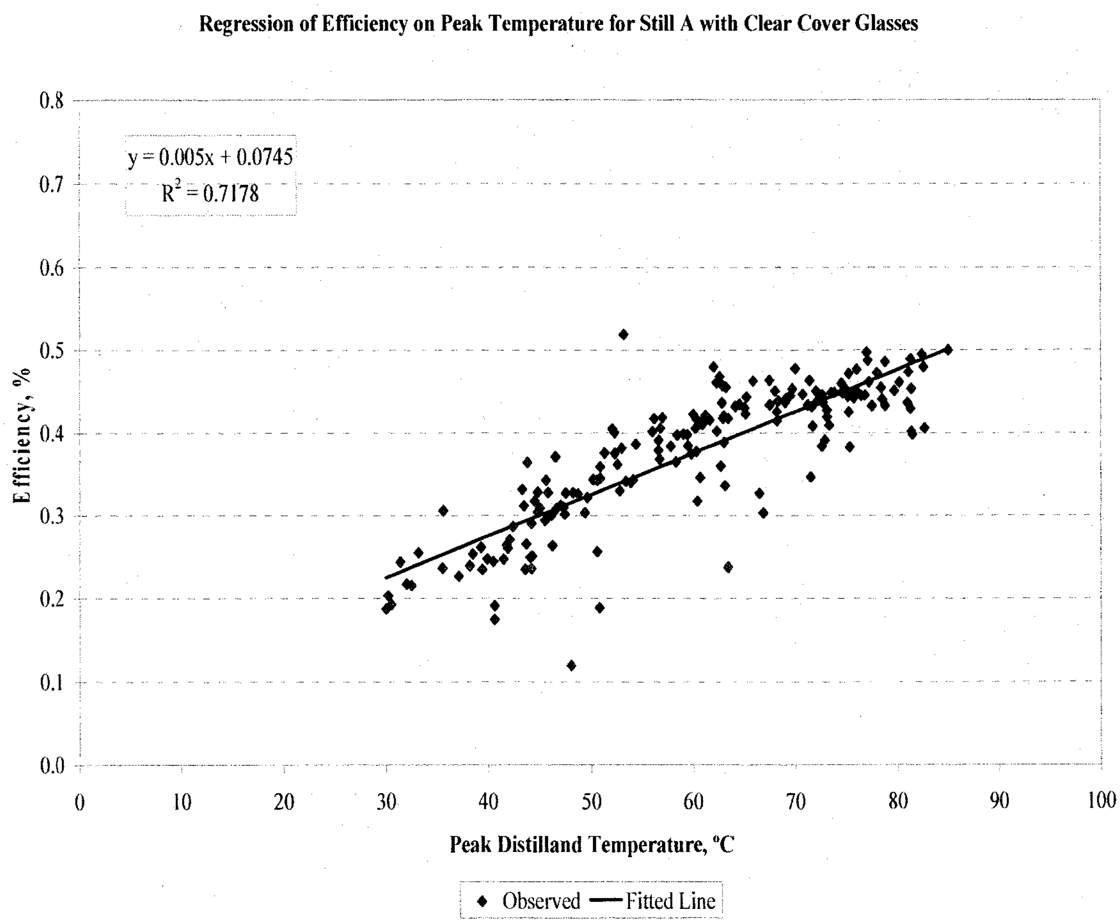

Figure 3.18: Variation in efficiency as a function of maximum distilland temperature for still A

The linear regression of efficiency on peak distilland temperature (Figure 3.18) gave a highly significant P-value of 8.63E-50 for the rejection of the null hypothesis.

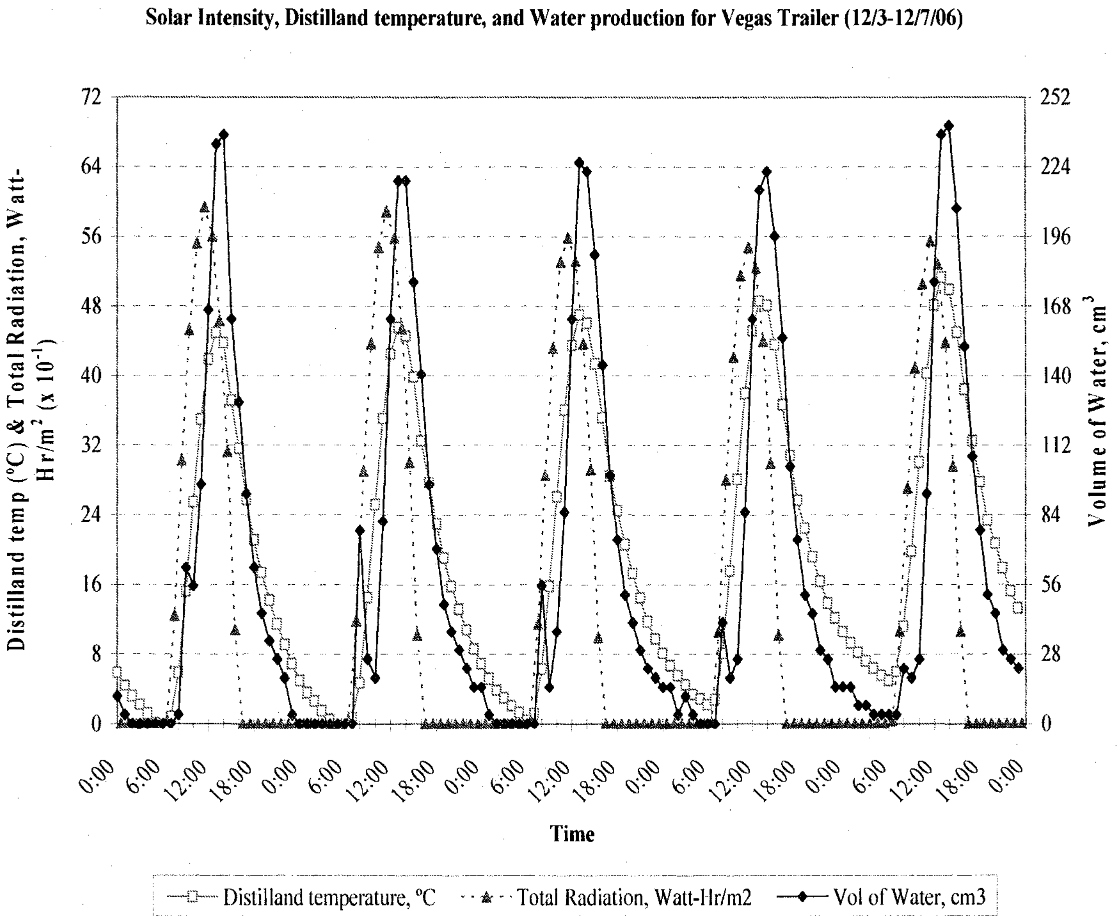

Figure 3.19: Dependence of water production on distilland temperature and solar insolation for still A

In Figure 3.9, the concept of nocturnal production was introduced. In Figure 3.17 dependence of yield on distilland temperature was depicted. In Figure 3.19, hourly yield, temperature, and solar radiation were plotted for still A for five days in the first week of Dec-06. It is very clearly noticeable that temperature lags insolation by one and a half hours. The average peak value for insolation was observed at 11:30 am and that for temperature as at 1:00 pm. A similar lag was observed between insolation and water yield. It is theorized that the maximum rate of evaporation occurs at the maximum temperature when the partial pressure of water vapor over the distilland is at its highest. A test of this hypothesis is made in Chapter 4, section 4.5.

The slow decrease in temperature and its effect on the production can be seen from the graph. Even though there was absolutely no insolation after 4:00pm, the still continued to produce for eight more hours on the first two days and almost 14 hours on the next two days. This is because the water mass in the basin, being large (nearly 31 kg), acts as a good energy storage material. It stores solar heat and releases at night. Evaporation of the distilland continues to occur, driven by stored heat. As the cover glass has already cooled due to the drop in the ambient temperature, the evaporated water vapor condenses on the cooled cover. This process continues until all the heat is released by the water. The nighttime evaporation may go on until morning, on days with greater ambient temperature, as more heat will be stored because of higher peak daytime temperatures.

3.4 Total Seasonal Performance

In Figure 3.20a all clear glass data points are plotted for both yield and efficiency. Low-e data has been purposefully deleted. It can be observed how well the yield follows the insolation trend throughout the year. Maximum production of up to 7 $L/m^2/d$ was received in peak summer during July and August. The lowest quantity of nearly 1-1.5 $L/m^2/d$ distillate was being produced during December. Short-term variability in daily productions is about ± 2.0 L/m^2 in summer and ± 1.0 L/m^2 in winter.

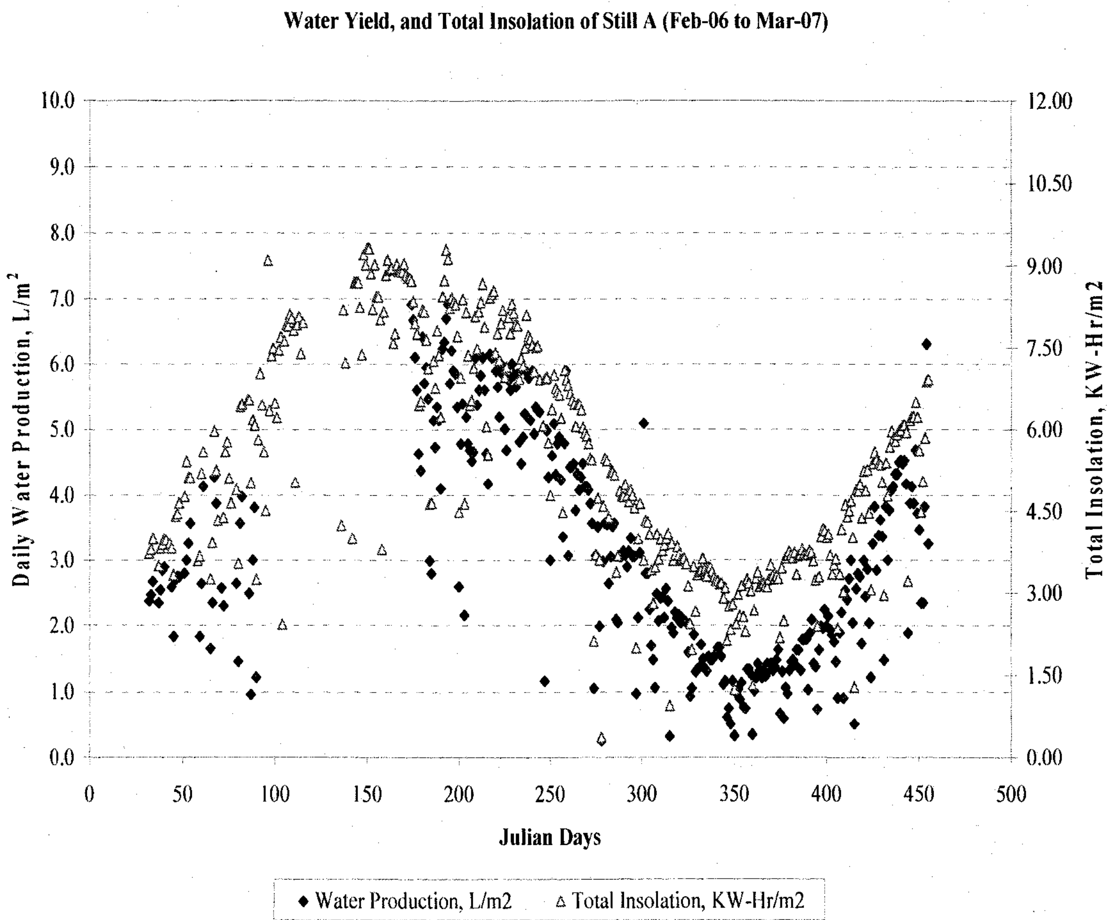

Figure 3.20a: Effect of seasonal variation in global insolation on water yield for still A over the entire test period for clear cover glasses

Figure 3.20b depicts the performance, in terms of efficiency, of still A for the given water productions (Figure 3.20a). It can be observed that the efficiency varies from 31% ± 4.7% in February-2007 to 45% ± 2.2% in August.

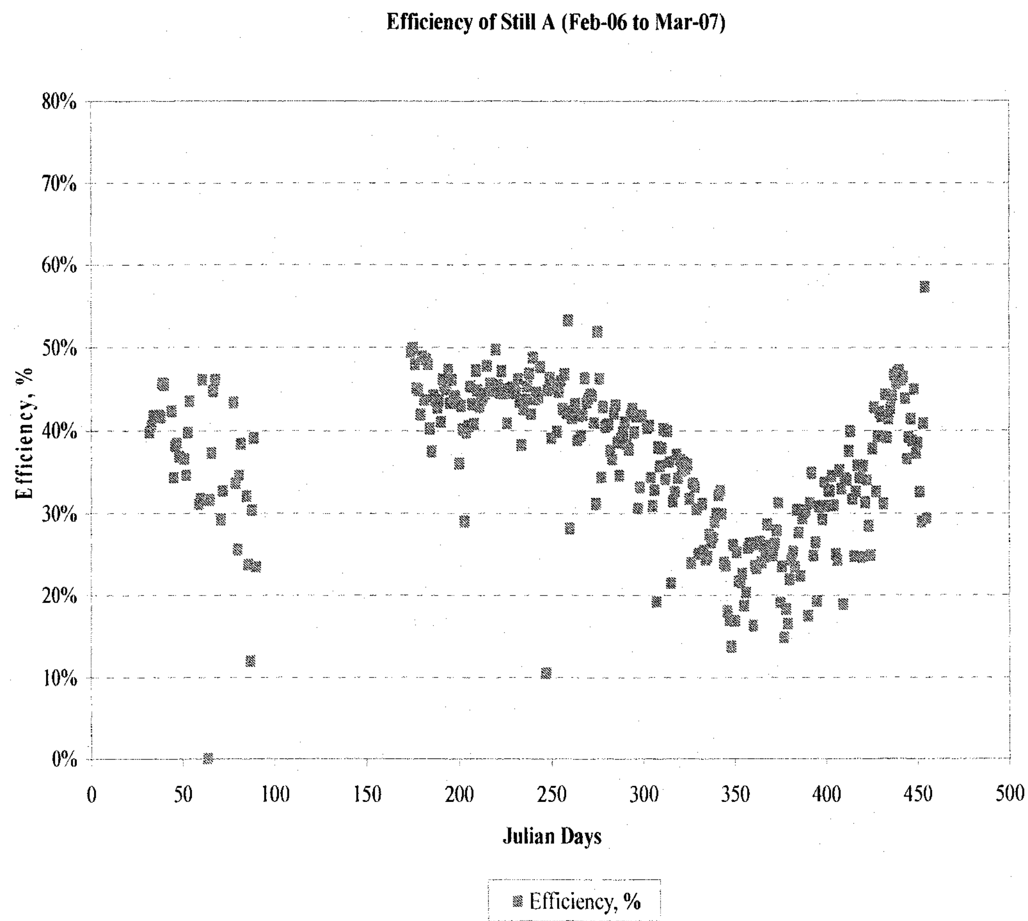

Figure 3.20b: Efficiency over the test cycle for still A with clear cover glasses

Similar plots were made for still S, but this did not have any deleted data as LEG (low-e) was never used on it. Figure 3.21a it can again be noticed how well the yield follows the insolation trend throughout the year. Maximum production of up to 5 L/m^2/d was received in peak summer during July and August. The lowest quantity of about 1 L/m^2/d was being produced during December. Strong seasonality of yield is seen with winter minimum and summer maximum, similar to still A. Short-term variability in daily productions is about ±2.0 L/m^2 in summer and ±0.6 L/m^2 in winter.

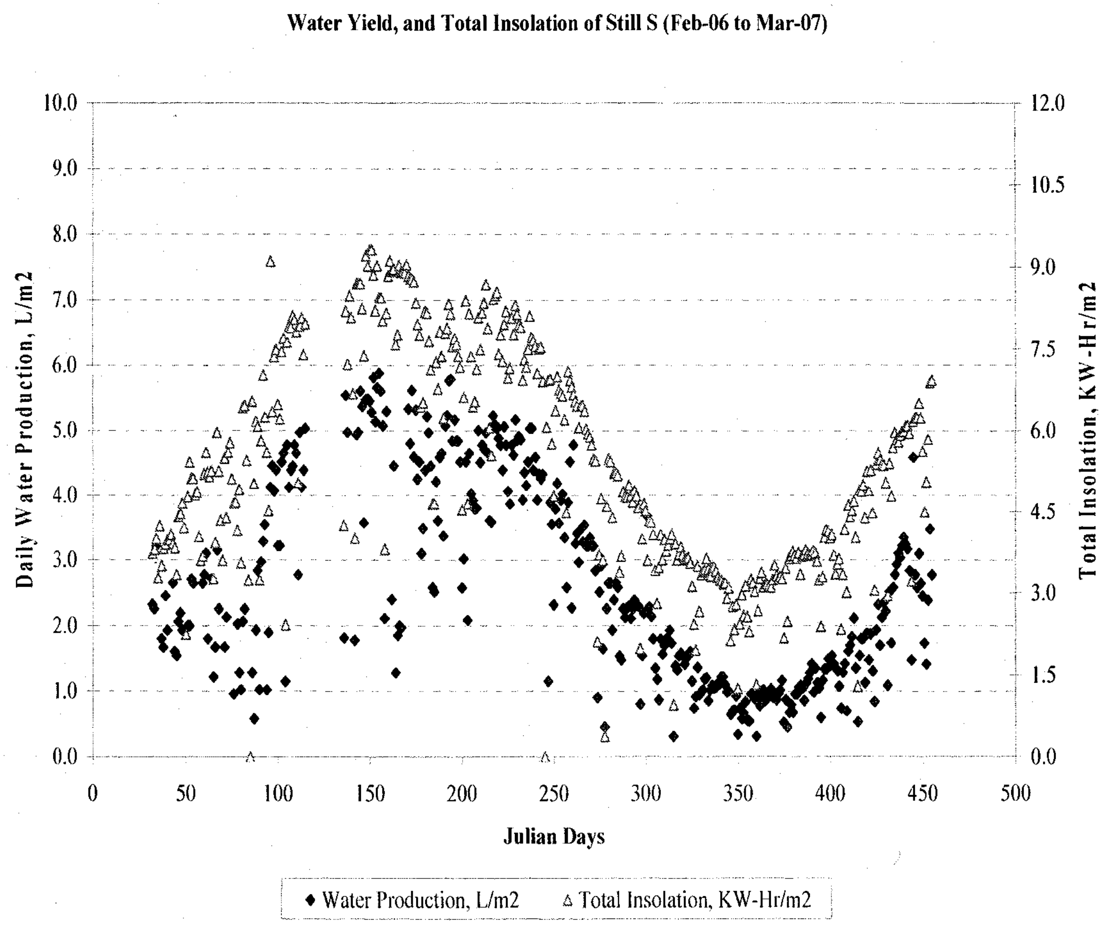

Figure 3.21a: Effect of seasonal variation in global insolation on water yield for still S over the entire test period with clear cover glasses

The efficiency pattern of still S, shown in Figure 3.21b, is quite similar to still A's (Figure 3.20b) though the amplitude is smaller. The efficiency varies from 19% ± 3.5% in December-2006 and January-2007 to 39% ± 1.8% in August.

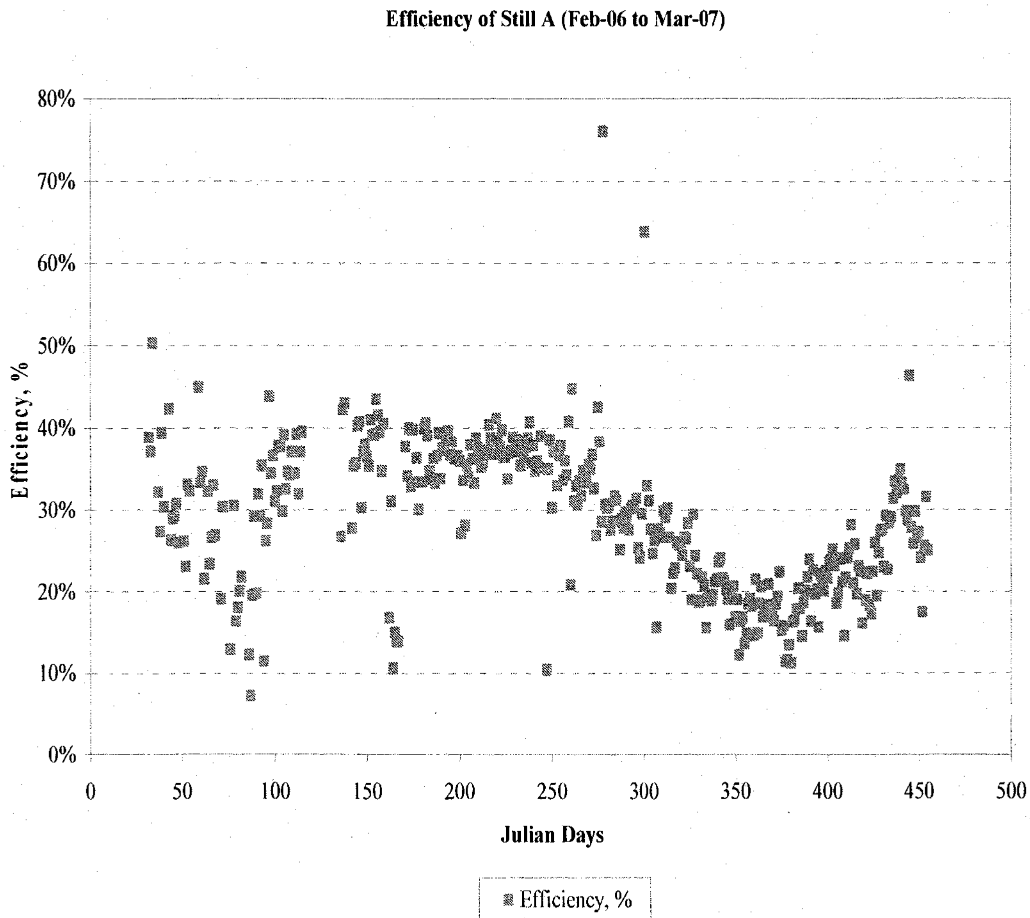

Figure 3.21b: Efficiency over the test cycle for still S with clear cover glasses

3.5 New Double-Basin Still Results

Temperatures at various points such as still headspace, hot vapor slot, condenser headspace, and cold vapor return slot were measured to check if the vapors were following the desired path. From Figure 3.22 it can be seen that still headspace temperature was the highest (greater by approximately 25°C), hot vapor and condenser headspace overlapped closely followed by cold returning vapors. Though all peak temperatures occurred nearly at the same time, between 1-3:00 pm.

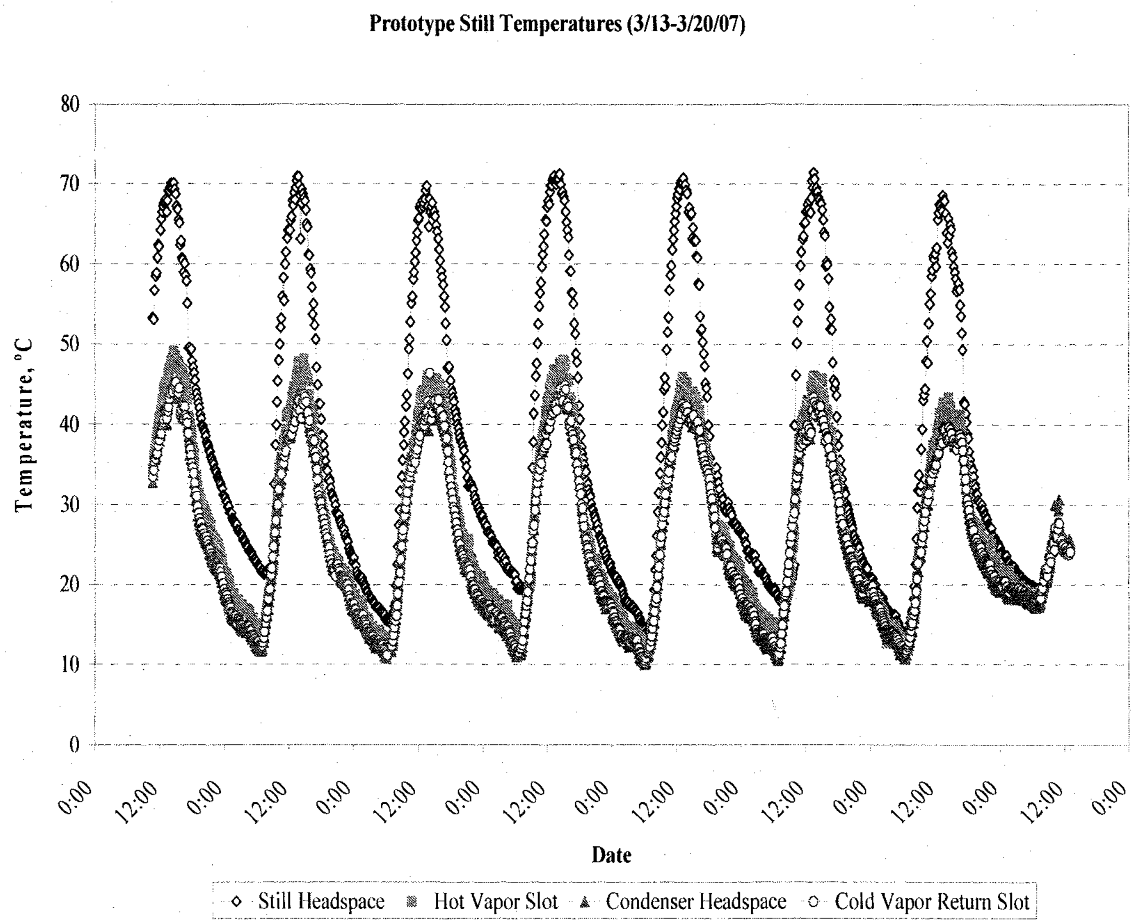

Figure 3.22: Variation of temperature at different points in the prototype still

It can be observed that at night, the condenser headspace becomes even cooler than cold vapor return. This is because the condenser is made of sheet metal, dropping its temperature considerably.

Towards the end of second installation, on 3/20/2007, the condenser had collected nearly 4L of distillate after 11 days of operation, resulting in a daily average of 0.47 L/m^2. During the third installation, after five days of operation, the condenser side had collected 0.200 L. But on the very next day, the highest one-day production of 0.530 L was collected, which turned out to be highest till now. This was followed by 0.100 L and

0.05 L respectively on the following days. But due to failure of liner, the still had to be taken out of service on 4/10/2007.

CHAPTER 4

WATER SUPPLY DESIGN CONSIDERATIONS AND PRELIMINARY EVALUATION OF HOT STILL EFFICIENCY HYPOTHESIS

As solar stills depend on varying solar energy to produce distillate, they cannot be expected to give consistent performance, for a particular location, throughout the year. Large day-to-day variations in insolation can create large daily variations in water yield. How important is this variability in design of a variable water supply system?

This fluctuation in the performance is the sole factor on which the design of a still depends and that is why it is so important. Long-term water production of stills cannot be determined based on a short-term experimental work of a few days or weeks. Hence, based on our experimental work of 14 months, the following design considerations are presented for stills A and S.

4.1 Sunwater® Single-Basin Still-Vegas Trailer (Still A)

Figure 4.1a depicts the monthly averages of daily water yield and total insolation for the year 2006-2007. The averages were calculated by using the daily data. The monthly peaks and lows were found out by adding error bars corresponding to two standard deviations above and below the mean. This gives us an idea of the possible variation in monthly yields due to daily variations in insolation within each month.

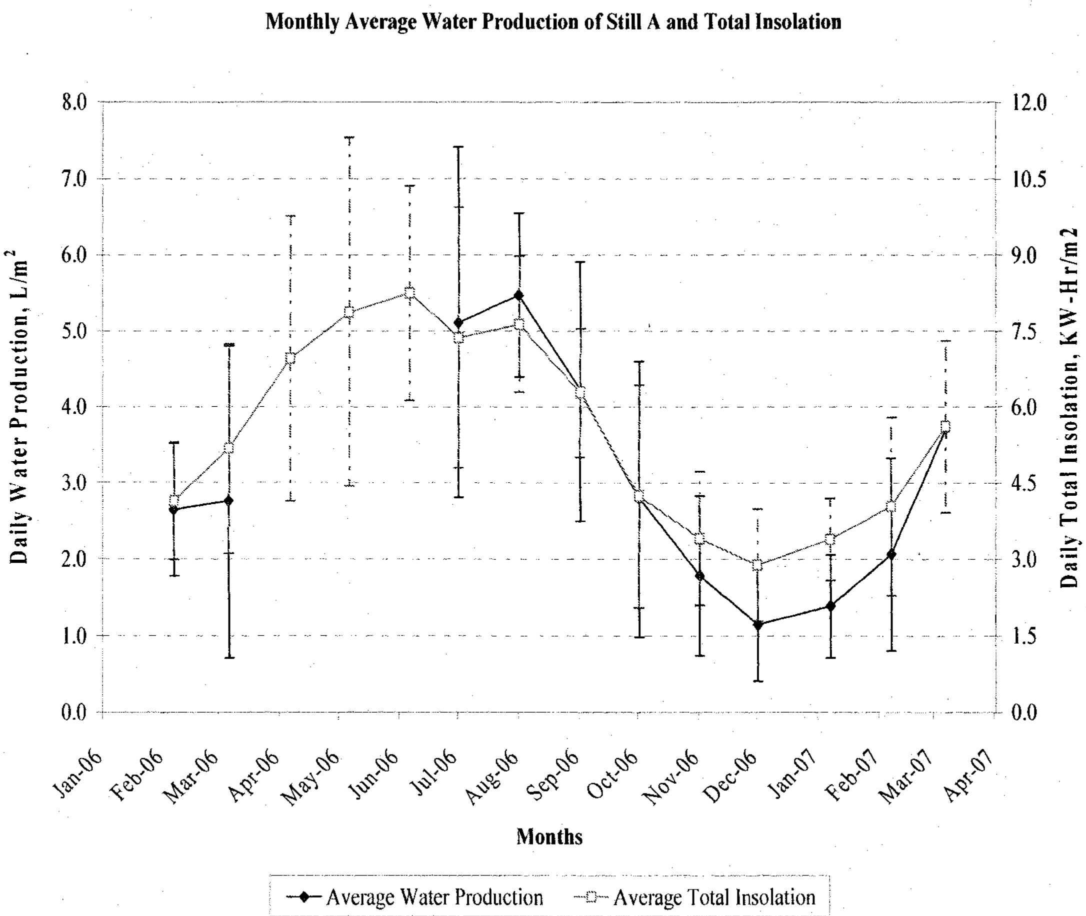

Figure 4.1a: Monthly averages of daily water produced by still A and total insolation, provided with Y-error bars representing 2-standard deviations above and below the mean

The highest average daily yield occurred in July and August at 5.1 and 5.5 L/m^2/d respectively. Minimum daily yields occurred in December and January (2007) at 1.1 and 1.4 L/m^2/d respectively.

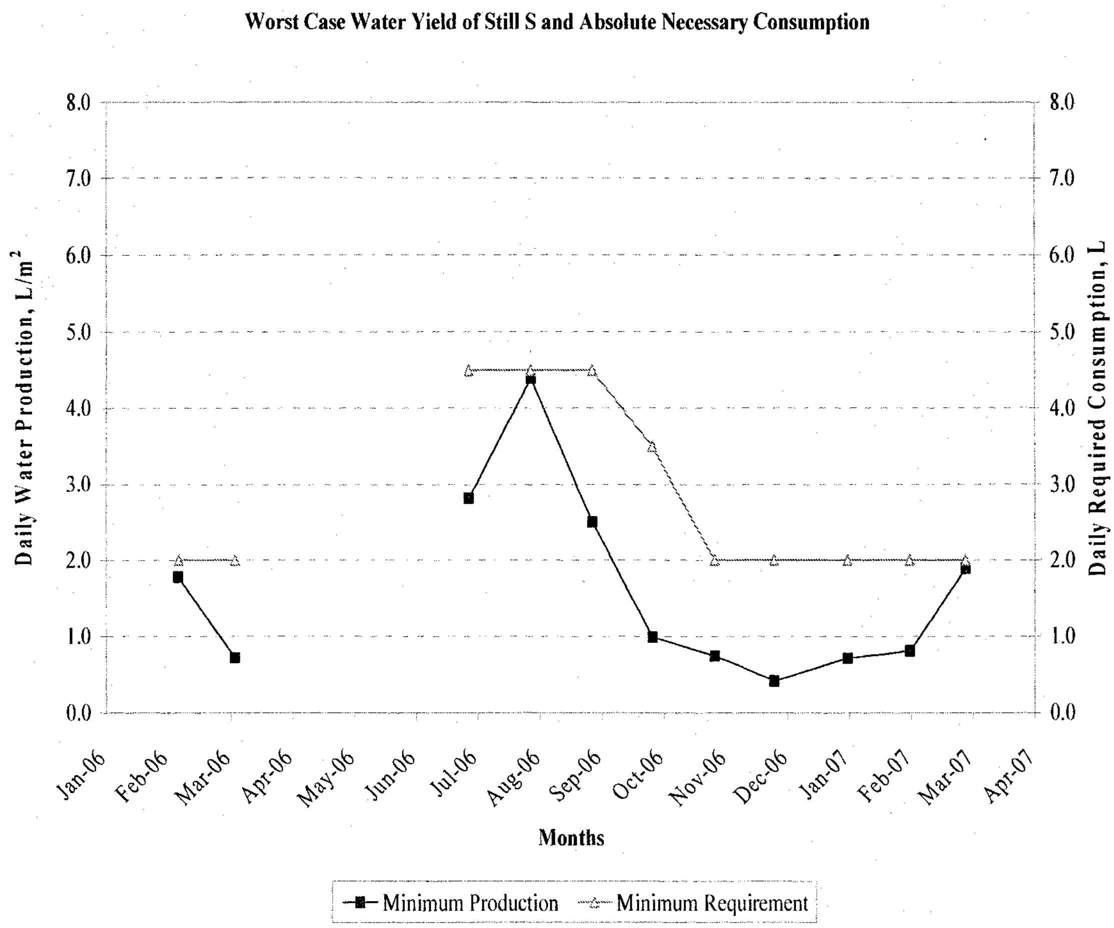

Figure 4.1b: Fifth percentile production by Still A

In Figure 4.1b, the worst case yield or the lowest production can be observed which is obtained by drawing a line through the lower limits of mean minus two standard deviations, which corresponds approximately to the 5^{th} percentile yield. The plot also contains the average potable water quantity which should be consumed by per person on a daily basis [WHO, 2003].

It is noticeable that only during the months of February-2006, August-2006, and March-2007 did the minimum yield from one square meter of still meet the minimum requirement. For the rest of the year, minimum yield from one square meter fell below daily requirements. The 5th percentile yield is very conservative assuming very low insolation and no storage of excess distillate from high insolation days.

4.2 SolAqua Rainmaker™ 550 (Still S)

Monthly average yields for the SolAqua™ are as shown in Figure 4.2a

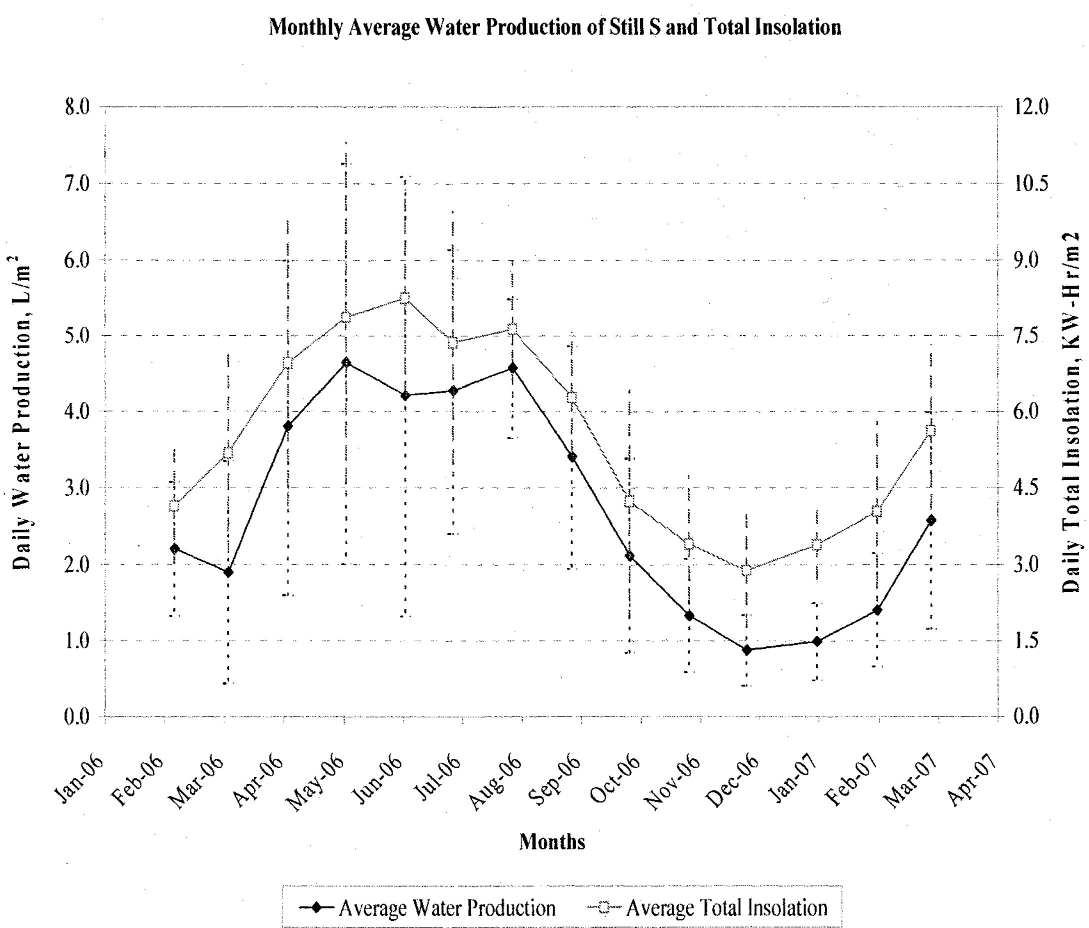

Figure 4.2a: Monthly averages of daily water produced by still S and total insolation, provided with Y-error bars representing 2 standard deviations above and below the mean

Highest average daily yield occurred in July and August at 4.3 and 4.6 $L/m^2/d$ respectively. Minimum daily yields occurred in December and January (2007) at 0.87 and 0.99 $L/m^2/d$ respectively.

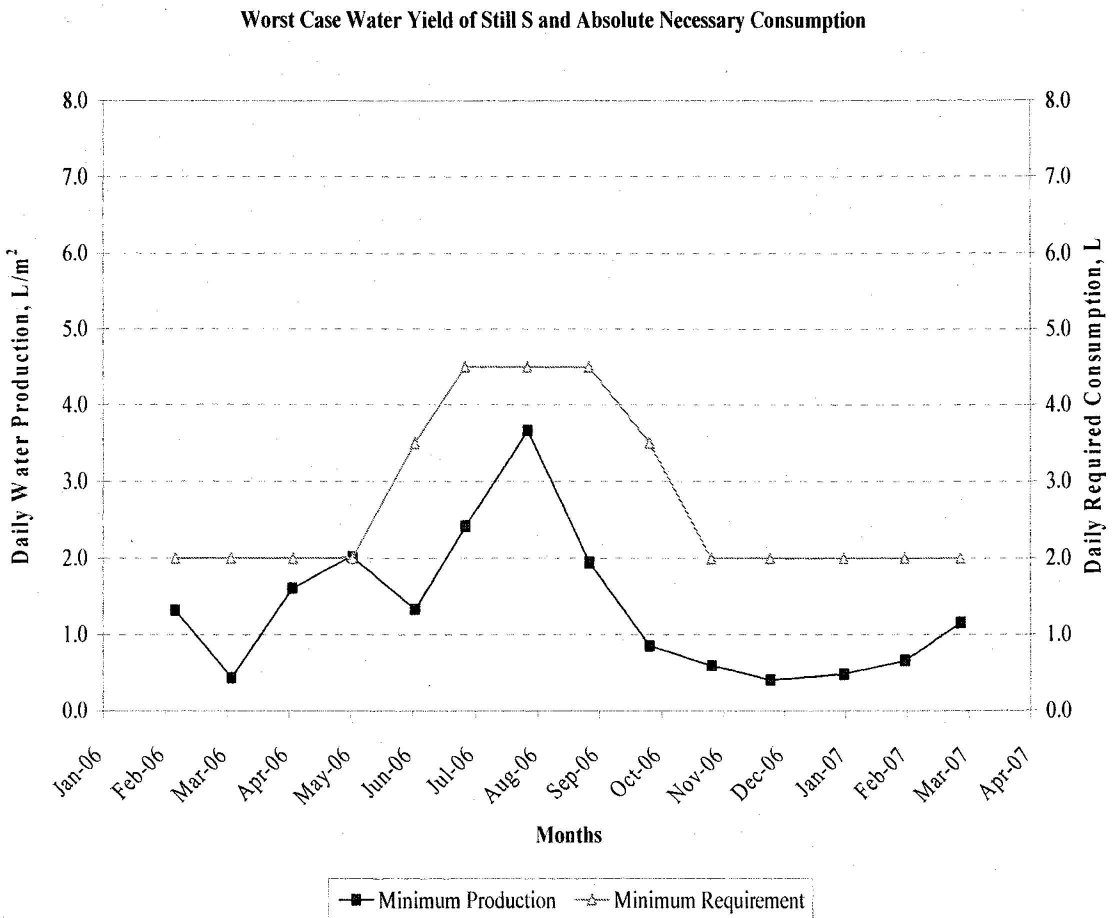

Figure 4.2b: Fifth percentile production by Still S

From Figure 4.2b, it can be observed that only during the month of May-06, did the still seemed to have matched the minimum requirement. But this data cannot be completely relied upon as only partial data is available for the month.

4.3 Minimum Basin Area Requirement

The minimum basin area can be defined as the least area of basin required to produce potable water to meet the daily individual needs. It is obtained by dividing the quantity of minimum water demand for hydration by the minimum distillate yield of a still. This number (in m^2) forms the basis of still design criteria for reliably delivering water to an individual assuming that no surplus water is being stored.

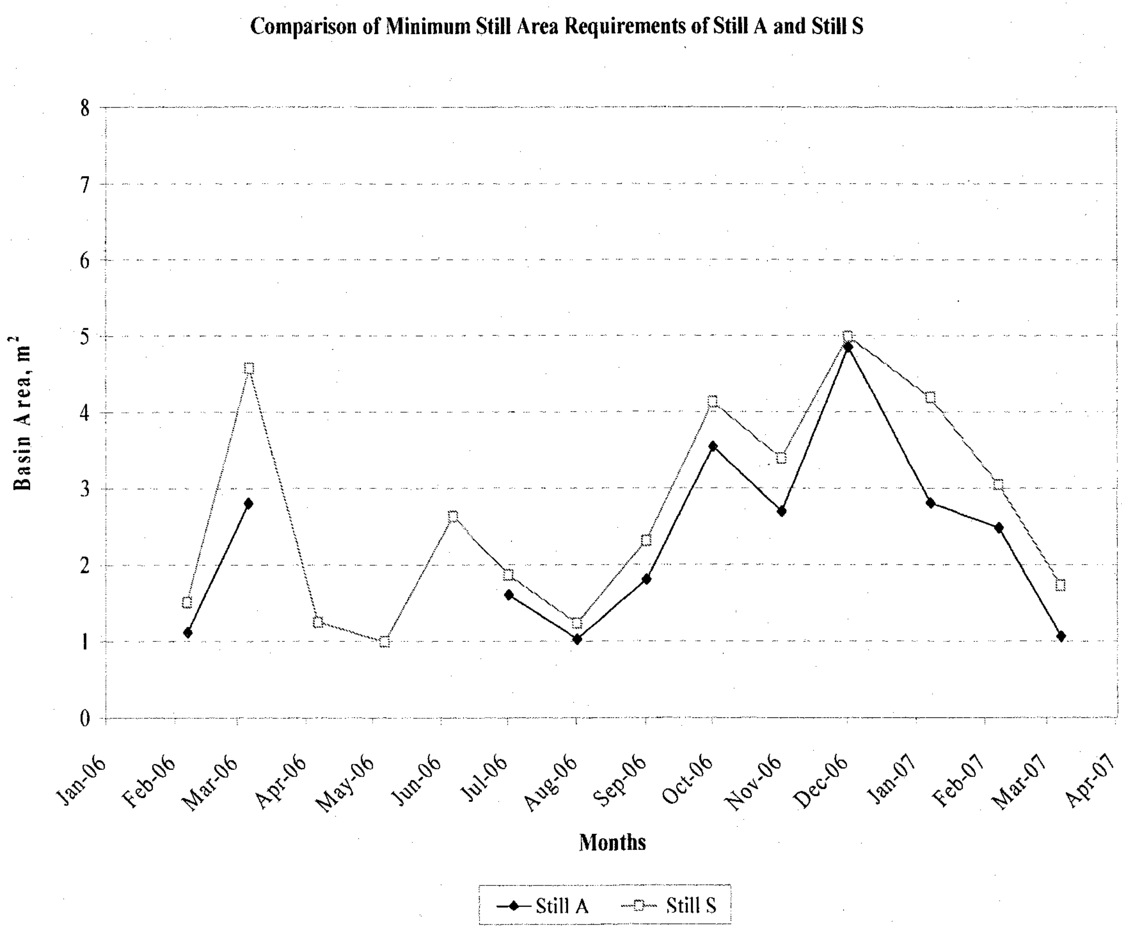

Figure 4.3a: Comparison of minimum basin areas of still A and S necessary to meet absolute required needs

Figure 4.3a compares of required basin areas of stills A and S for the worst case production. Though the basin area requirement, per person, for stills A and S varies between 1–5 m^2, the monthly variation is higher for still S. This is because the overall efficiency of still S is lower than still A (as explained in Chapter 3). Based on these worst case criteria of 5^{th} percentile yield, a conservative still design estimate for a single individual would be 5 square meters for the weather observed in Las Vegas between February-2006 and March-2007. This corresponds to 6 Sunwater® stills or 7 SolAqua™ stills.

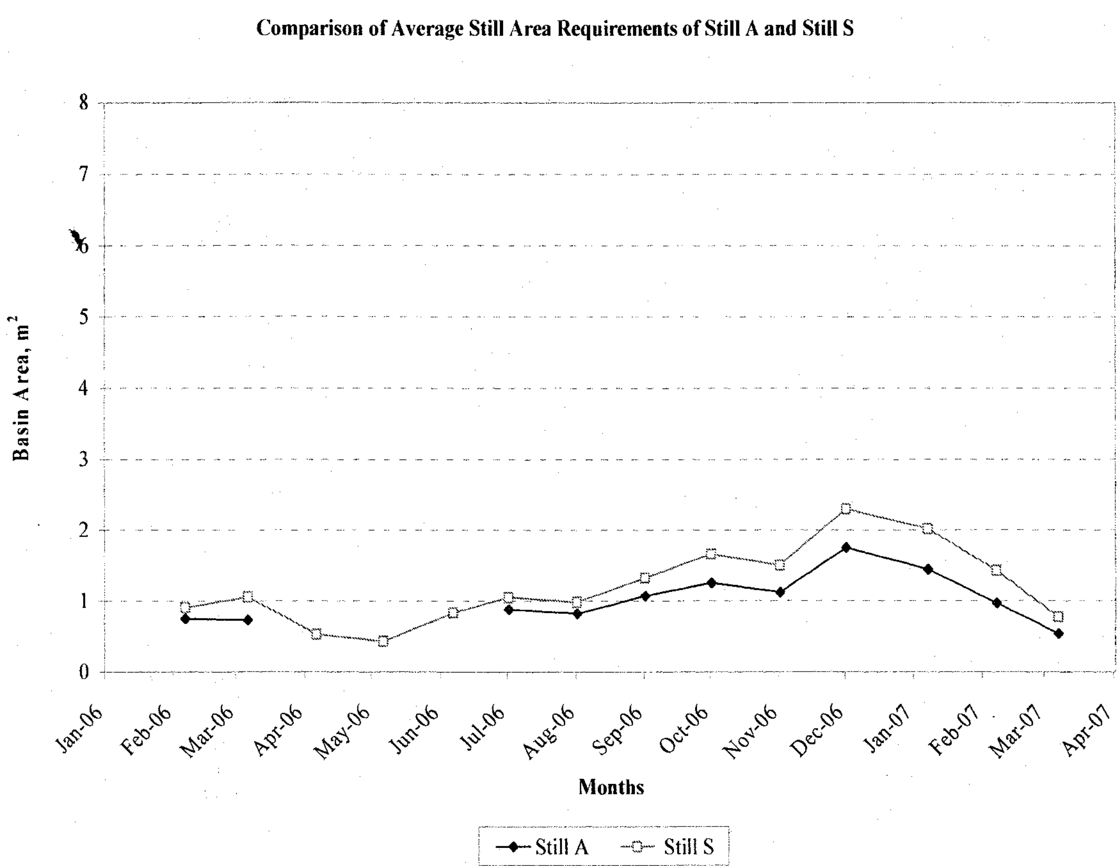

Figure 4.3b: Comparison of average basin areas of still A and S necessary to meet absolute required needs

Figure 4.3b gives a comparison of the basin areas of stills A and S for their average monthly productions. It can be observed that compared to Figure 4.3a, the area requirements for the stills greatly reduced to a range of 0.5-1.7 m^2 (still A) and 0.8-2.3 m^2 (still S). If one was to design a still based on average yields, assuming storage of surplus water, still areas of 1.8 m^2 (in case of Sunwater®) and 2.3 m^2 (in case of SolAqua™) would be selected. This corresponds to 2 Sunwater® or 3 SolAqua™ Rainmaker 550 stills.

4.4 Comparison of Results with Other Papers

There were three published long-term experimental studies that can be compared with the results of this thesis. Numerical comparisons are made in Table 4.1.

Foster et al. [2002] reported the performance of an earlier type of SolAqua® still in Las Cruces, New Mexico. For every KWh/m^2 of insolation, the still produced 1 L/m^2. The minimum area required to meet the demands at the latitude of El Paso (32°N) was calculated to be $0.70 m^2$/person. For Las Vegas, to produce 1 L/m^2, still S (the newer SolAqua™ model) required about 2-2.5 KWh/m^2 of insolation, whereas, still A required nearly 1.75 KWh/m^2. This difference could be because of the geographical location, and also that the SolAqua® model we used was different from the one used in Las Cruces. The Las Cruces still could have been more efficient overall as they report efficiencies in the range of 50% (winter) to 60% (summer), while we observed efficiencies in the range of 15% to 45%. Minimum still area requirements were calculated to be 0.8-2.3 m^2 (still S) and 5-1.7 m^2 (still A) from winter to summer respectively, in Las Vegas,

Table 4.1: Summary of Similar Results for Comparison

<table>
<tr><th>Author</th><th>Location</th><th>Latitude, Longitude</th><th>Their Results</th><th>My Results</th></tr>
<tr><td>Foster et al. [2002]</td><td rowspan="2">Las Cruces, New Mexico</td><td rowspan="2">32°.32' N
106°.77' W</td><td>Daily normalized production against total insolation plot (time of year not mentioned) showed that to produce 2 L/m^2, atleast 3 KWh/m^2 is required.</td><td>The closest match to their plot was that the data from Feb to Oct-06. To produce 2 L/m^2, still S required 4-4.5 KWh/m^2. Whereas at 9 KWh /m^2 it produced nearly 5.5 L/m^2. In case of still A, (data from 6/23-10/30/06), 2 L/m^2 of distillate required about 3.5 KWh/m^2. For a maximum recorded insolation of 8.5 KWh/m^2 it produced nearly 6 L/m^2.</td></tr>
<tr><td>Foster et al. [2005]</td><td>Peak water production lags peak insolation by 2 hours and nearly remains so for another 2 hours. Production after sunset was also observed. The still had a typical efficiency of 60% in summer and 50% in winter, and for every sun hour produced nearly 0.8 L/m^2.</td><td>The highest consistent efficiency observed till now was in the range of 40-45% in summer, and in winter it dropped to a mere 15%. The peak production generally lagged the peak insolation by 2-2:30 hours and continued producing throughout the night.</td></tr>
<tr><td>Minasian et al.
[1994]</td><td>Baghdad, Iraq</td><td>33°14' N
44°22' E</td><td>In the year long experimental work, maximum average monthly production of 5.103 L/m^2 was observed in June, and minimum was in the month of December with 0.552 L/m^2.</td><td><table>
<tr><th>Still</th><th>Max, L/m^2</th><th>Min, L/m^2</th></tr>
<tr><td>A</td><td>5.472 (Aug)</td><td>1.144 (Dec)</td></tr>
<tr><td>B2</td><td>5.542 (Jun)</td><td>1.065 (Dec)</td></tr>
<tr><td>C</td><td>Not available</td><td>1.109 (Dec)</td></tr>
<tr><td>S</td><td>4.572 (Aug)</td><td>0.871 (Dec)</td></tr>
</table></td></tr>
</table>

Author	Location	Latitude, Longitude	Their Results	My Results
Sodha et al. [1979]	New Delhi, India	28°35' N 77°12' E	One winter day's data reported a total production of almost 2.32 L/m^2 for nearly 6.6 KWh/m^2 insolation.	For an insolation of 6.5 KWh/m^2 on 9/24/06, the productions (L/m^2) of stills A, B2, C, and S were 4.7, 4.1, 4.5, and 3.1 respectively.
Onyegegbu et al. [1986]	Nsukka, Nigeria	6°78' N 7°28' E	The peak water surface and ambient air temperature were observed to lag peak insolation by nearly two hours, whereas the peak production lagged by approximately eight hours. Nocturnal production was found to be directly proportional to the distilland volume. Maximum average efficiency of 78% was observed for a water depth of 17.8 cm.	Peak distilland temperature followed ambient in a gap of about half-an-hour to one hour. And ambient temperature lagged the solar noon by atleast an hour. Based on three days data, for water depth of 5 cm, the average nocturnal efficiency was found to be a little over 50%.
Hamdan et al. [1997]	Amman, Jordan	31°57' N 35°56' E	The cover glass and distilland reach their peak temperatures two hours after peak insolation, and their difference was almost 10°C. **For insolation of single day the still** produced 3.693 L/m^2.	Typical cover glass and distilland peak temperatures occurred about 2 hours and 2:30-3 hours after solar noon respectively and had a difference of about 9°C (Jan-07).

Author	**Location**	**Latitude, Longitude**	**Their Results**	**My Results**
Nafey et al. [2001]	Port Said, Egypt	31°17' N 32°14' E	During the test period (in September), highest production of 5 L/m^2 was received for a feed of 20 L/m^2.	For an input of 20 L/m^2, stills A, B2, and S produced monthly averages of 2.76, 2.12, and 2.21 L/m^2 respectively.
Morcos et al. [1993]	Assiut, Egypt	27°3' N 31°1' E	For a feed of 20 L/m^2 (during March and April), maximum distillate quantity of 1.08 L/m^2 was received.	

Minasian et al. [1994] observed maximum and minimum average monthly production in the months of June and December in Baghdad while we noticed our highs and lows during August and December.

Onyegegbu et al. [1986] in Nigeria and Hamdan et al. [1997] in Jordan reported that the distilland temperature reached its peak two hours after the peak time of insolation. We also observed that the lag between distilland and ambient air and distilland and cover glass temperatures were one and a half and two hours respectively.

Nafey et al. [2001] and Morcos et al. [1993] experimented with different water volumes (at different times of the year and different locations in Egypt). Both concluded on 20L /m^2 to be optimum and received an average daily production of 5 L /m^2 and 1.1 L /m^2. For the same feed volume, we obtained an average monthly production of 2.1 L /m^2 - 2.8 L /m^2 for all the stills that were operating at that time.

4.5 Explanation for increase in efficiency of stills at higher temperatures

In Chapter 3, it was hypothesized that on days with high insolation and ambient temperature, stills become more efficient as they get hotter because the partial pressure of water increases rapidly (p 76). To evaluate this hypothesis, tabulated values of equilibrium water vapor partial pressure were plotted against temperature (Figure 4.5a). A least squares 3rd order polynomial fit best matched the data, indicating that partial pressure increases with the cube of the temperature.

Figure 4.5b shows the rising and falling limbs of water production for one day's still A data. This graph shows hysteresis with two distinct regimes for water production versus temperature. The transition occurs at the time of day when the still begins to cool off. For the rising limb of water yield curve, experimental hourly water production data were plotted against hourly average temperature for seven days. An example plot for 2/24/07 is as shown in Figure 4.5c. The data have been provided with a power fit which gave an exponent of 2.9. Table 4.1 summarizes results for seven days. Power fit exponents ranged from 2.7 to 3.9 with an average of 3.3 ± 0.47 indicating that water production (during the heat gain period-daytime) approximately rises as a cubic function of temperature, matching the trend observed for partial pressure.

Similar to Figure 4.5c, for the falling limb of water yield curve, experimental hourly water production data were plotted against hourly average temperature for seven days. An example plot for 2/24/07 is as shown in Figure 4.5d. The data have been provided with a power fit which gave an exponent of 1.6. Table 4.2 summarizes results for seven days. Power fit exponents ranged from 1.5 to 2.6 with an average of 2.1 ± 0.48. This means that during the time when stored heat is being utilized, the rate of water production declines as a squared function of temperature.

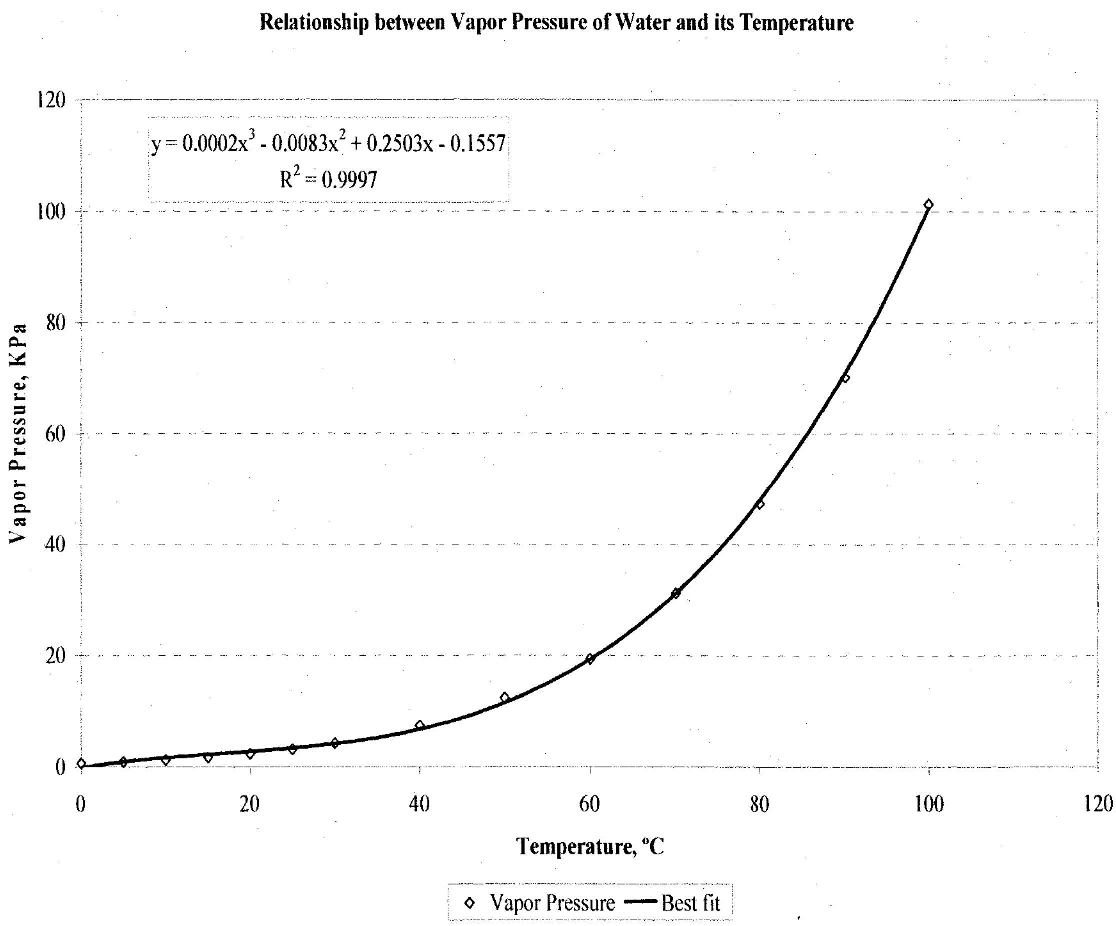

Figure 4.5a: Depiction of variation in partial pressure of water with respect to its temperature

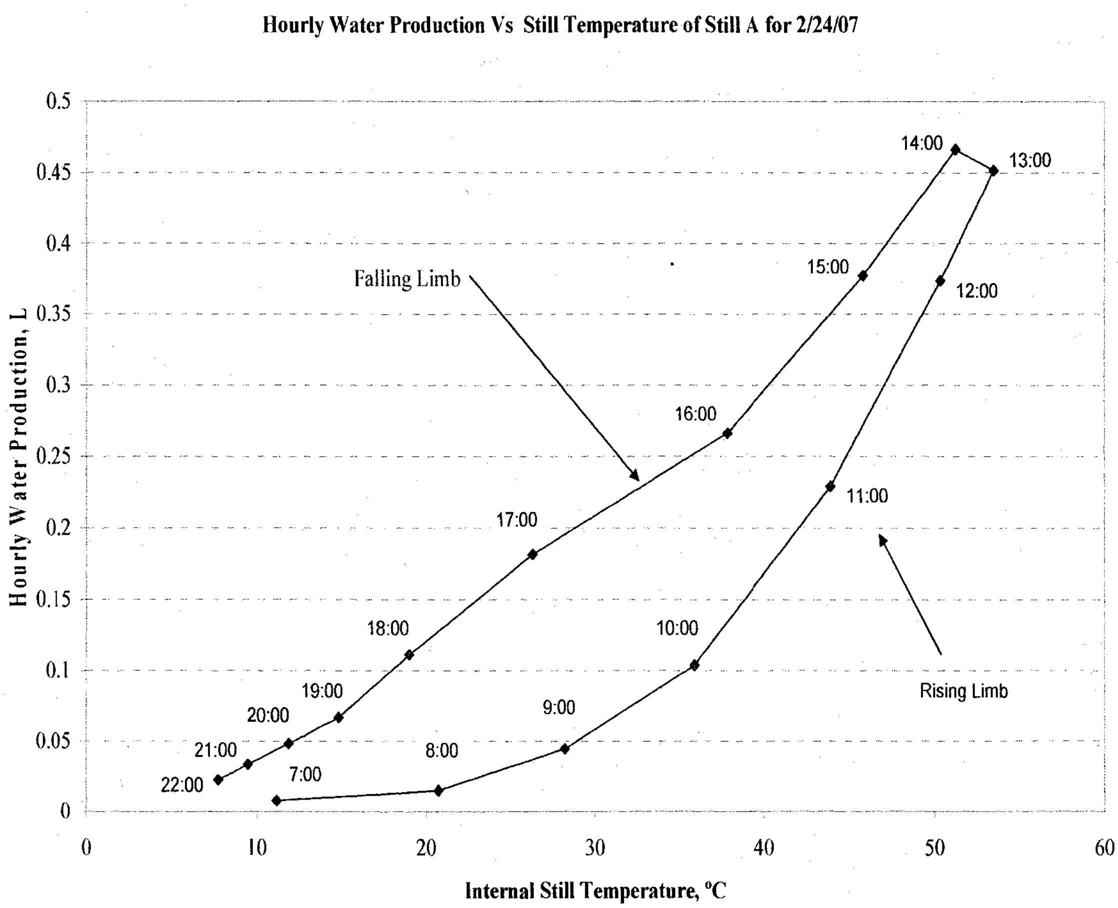

Figure 4.5b: Variation in hourly water production with respect to the internal still temperature

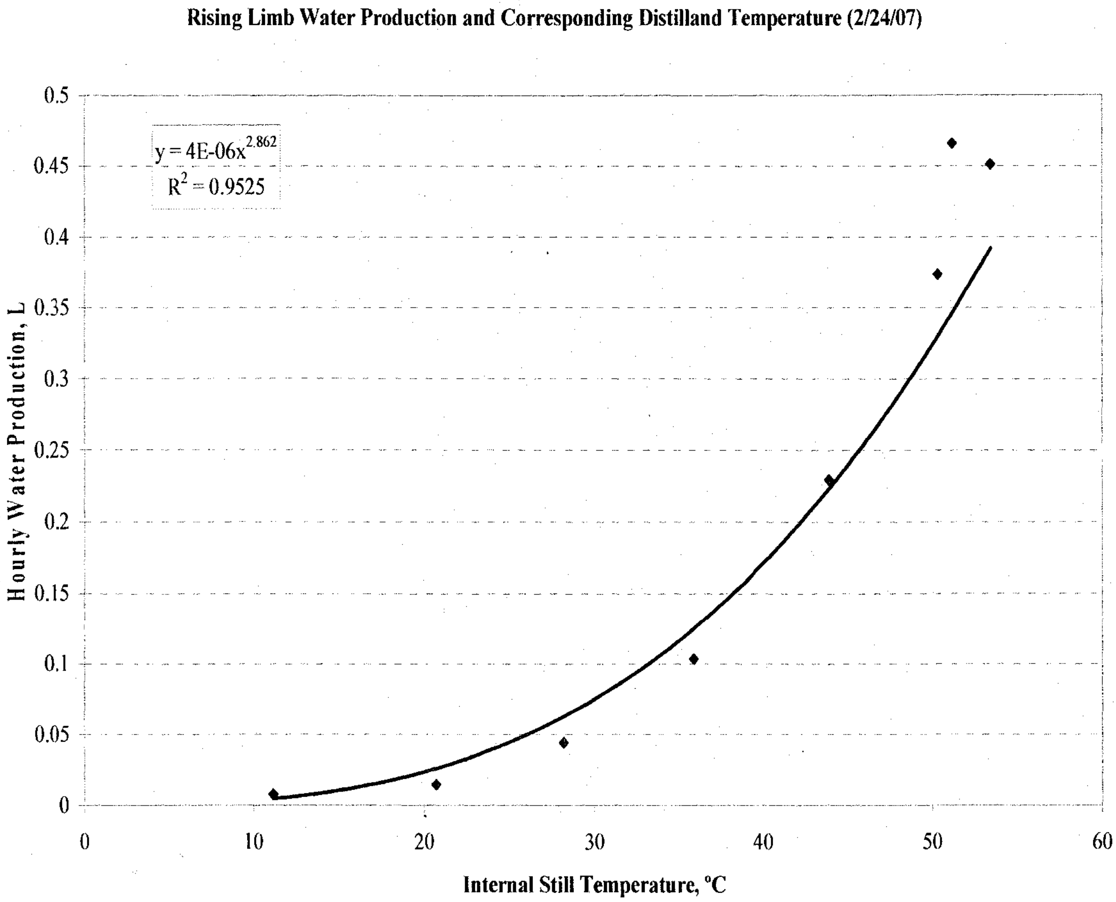

Figure 4.5c: Rising limb depiction for still A

Table 4.2: Rising limb of hourly water production for 2/24/07

Date	Start Hour	End Hour	Exponents
2/20/2007	8:00	14:00	3.6
2/21/2007	7:00	14:00	3.1
2/22/2007	7:00	13:00	3.8
2/23/2007	7:00	13:00	3.1
2/24/2007	7:00	14:00	2.9
2/25/2007	7:00	14:00	2.7
2/26/2007	7:00	14:00	3.9

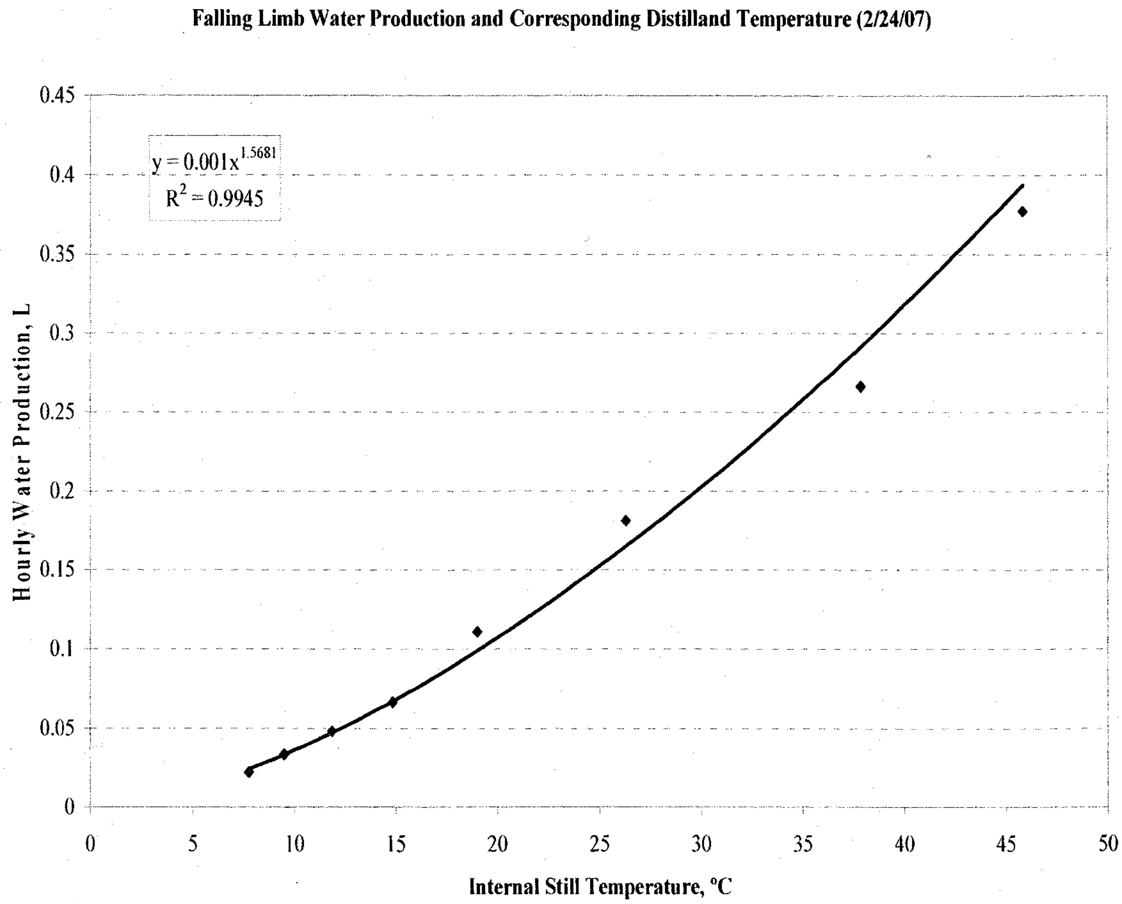

Figure 4.5d: Falling limb depiction for still A

Table 4.3: Falling limb of hourly water production for 2/24/07

Date	Start Hour	End Hour	Exponents
2/20/2007	15:00	22:00	1.8
2/21/2007	15:00	21:00	2.0
2/22/2007	14:00	21:00	2.6
2/23/2007	14:00	21:00	1.5
2/24/2007	15:00	22:00	1.6
2/25/2007	15:00	21:00	2.5
2/26/2007	15:00	21:00	2.6

Figure 4.5e depicts the cover glass and ambient air temperatures whose difference was used to calculate the heat transfer coefficient (h) across the cover glass, in the following way:

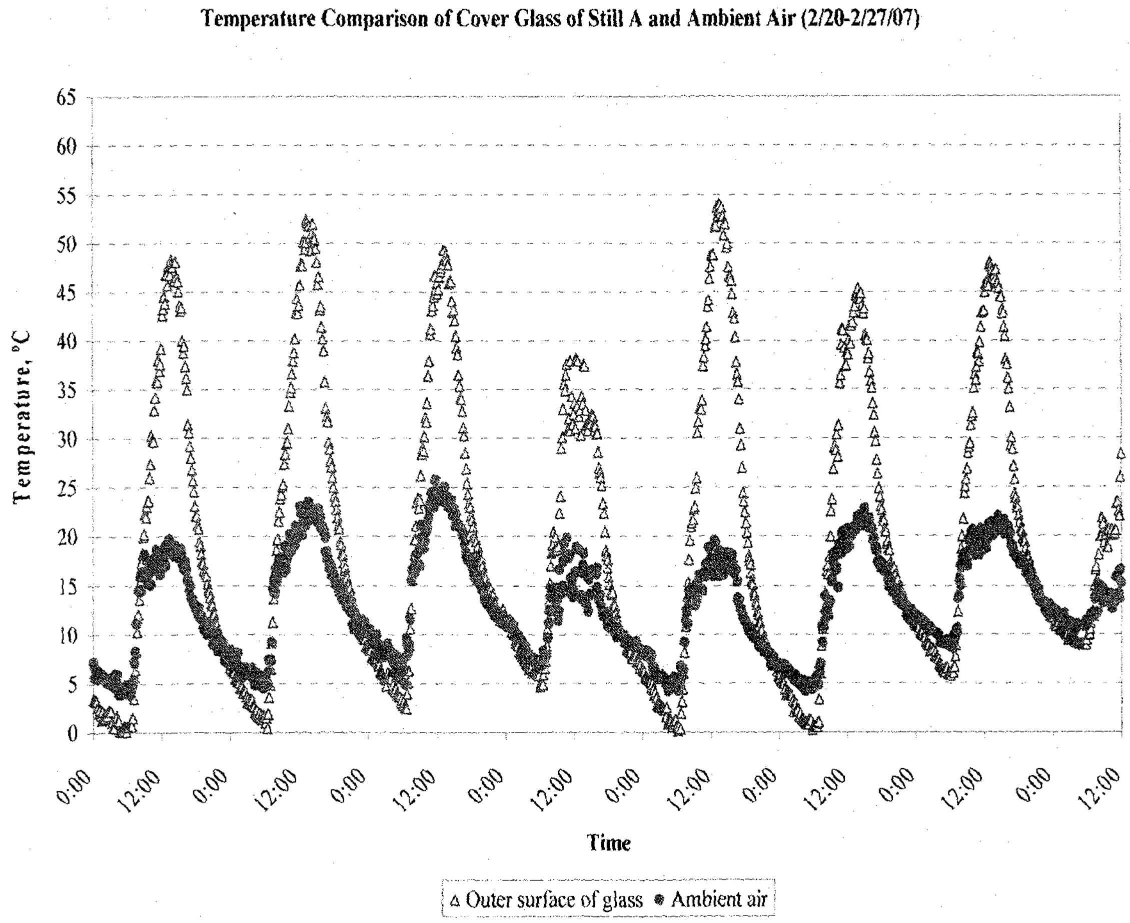

Figure 4.5e : Temperature difference between the cover glass and ambient air

We know that the h is a function of convection heat transfer, area and temperature difference between the cover glass and the ambient air.

$$h = \frac{q\ (\text{water})}{A \Delta T}$$

Where,

$$q = Q\ (L/hr) \times \rho\ (Kg/L) \times Hv\ (J/Kg)$$

$$q = 0.47 \times 0.996 \times 2356000 = 1102891\ J/hr$$

From Figure 4.5e, ΔT has been taken for the hour (14:00) with the highest water yield (0.47 L) rate 33.7 °C for the given days. Taking data of 2/24/07 for further calculation, ΔT was observed to be 17.5°C. Hence,

$$h = \frac{q\ (water)}{A\Delta T} = \frac{1102891}{0.976 \times 33.7}$$

$$h = 33531\ J/hr\text{-}m^2\ {}^{\circ}C$$

$$h = 9.3\ Watt/\ m^2\ {}^{\circ}C$$

In this way, h was calculated throughout the day and graph shown in Figure 4.5f was plotted. It can be observed that the h values do not vary much from noon till late evening. Hence, for this range, h can be averaged, as shown in Table 4.4.

Table 4.4: Average calculated values of heat transfer coefficients, h

Date	**Start Hour**	**End Hour**	**Average h, W/m2°C**	**Two-Standard Deviation**
2/20/2007	12:00	19:00	8.8	0.9
2/21/2007	12:00	19:00	10.2	1.1
2/22/2007	12:00	19:00	12.9	0.8
2/23/2007	12:00	18:00	8.3	1.6
2/24/2007	12:00	19:00	8.6	0.6
2/25/2007	12:00	20:00	12.7	1.3
2/26/2007	12:00	18:00	13.0	1.7

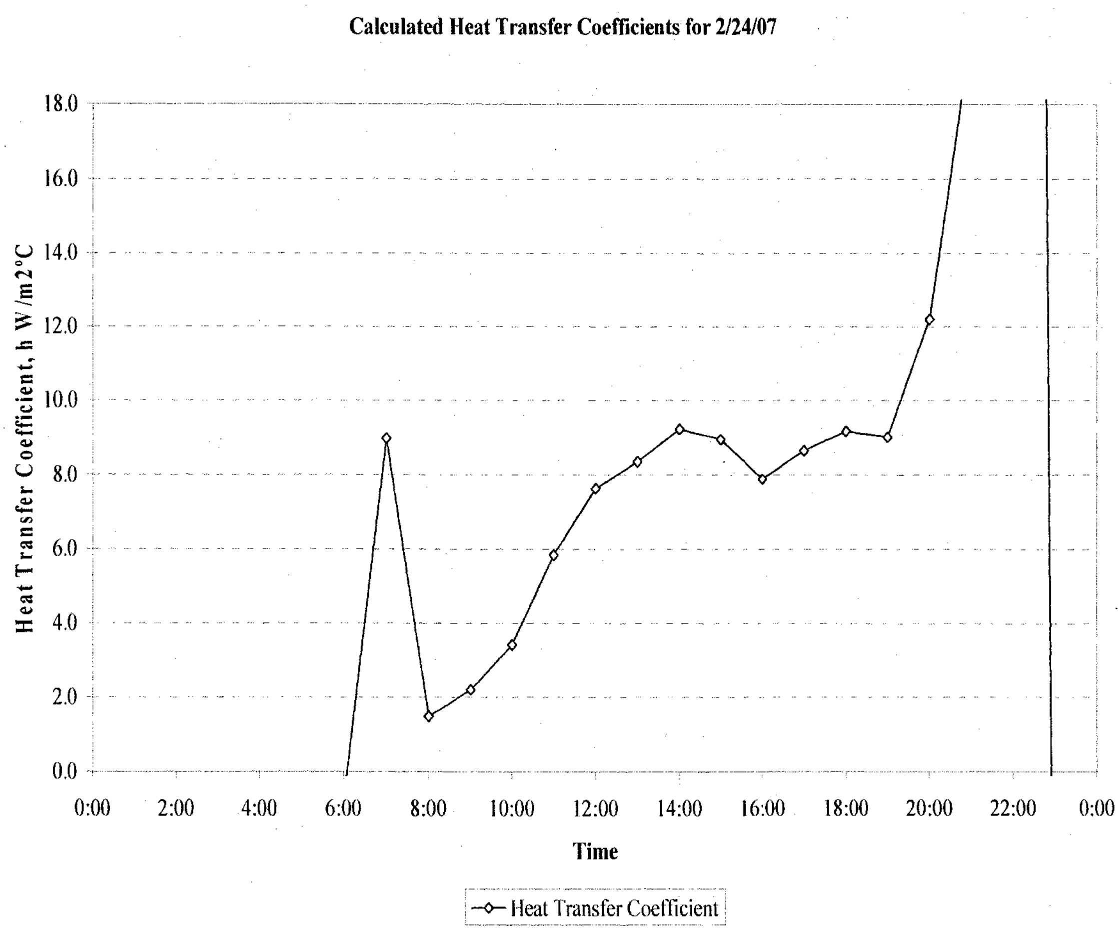

Figure 4.5f: Calculated values of heat transfer coefficients for 2/24/07

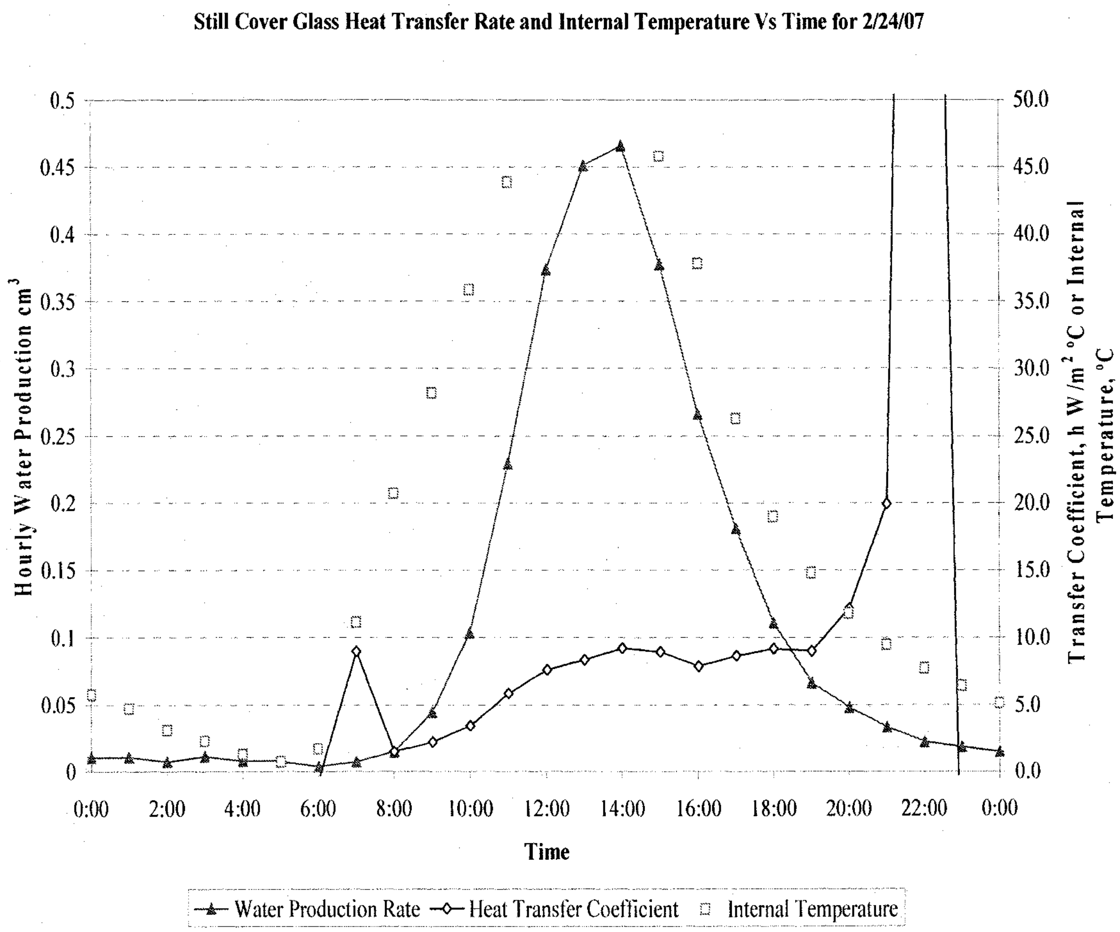

Figure 4.5g: Variation of heat transfer coefficient, still internal temperature, and resulting water production rates as a function of hour of the day

Since,

- Rising limb water production rates rise with the cube of the temperature, and show hysteresis with a more gradual decline in the falling limb, and
- Heat loss rates across all still surfaces are linear functions of the temperature difference, with nearly constant overall heat transfer coefficients from mid-day until early morning, hotter still temperatures will result in higher water production in rates as a larger proportion of absorbed heat is used to evaporate water.

CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

In this research, experiments were carried out to basically study the effects of:

- Different glass covers (1 low-e, and 3 clear samples)
- Water volume/depth
- Additional condenser

No significant differences were observed among different type of clear tempered cover glasses. Standard clear glass was found to be significantly better than low-e glass. Observed efficiencies were lower than generally claimed in the literature.

Strong seasonal variations in water yield and efficiency were observed. Water yield varied in the range of 1 $L/m^2/d$ (in winter) to up to 5 $L/m^2/d$ (in summer) with the short-term daily variability equaling $\pm 1L/m^2$ to $\pm 2L/m^2$ in winter and summer respectively.

To enhance night-time production, the double-basin stills were operated with different deep-shallow basin water depths ratios. Though we did notice night-time production, we could not really prove the hypothesis of deep-basin concept as the basin dimensions restricted us from going over 27.5L and below 10L for the risk of overflowing and drying up the basin.

The two-basin prototype showed operating temperature differences but short-term yields were very low. We could not operate it for a longer time because of constant failure of the plastic liner and insulation within the hot still insert. But over a short period, we did receive an average production of 0.47 L/m^2.

5.2 Recommendations

5.2.1 Future Work:

To further improve the still's winter performance in temperate climate, following suggestions are made:

- Add a mirror reflector to verify if yields go up due to increase in heat gain.
- Install additional insulation to the base of the still, as there is generally considerable loss from the bottom too. Hence if the heat doesn't get a place to escape, the yield should get enhanced.
- Test a still with a deeper basin to better observe the effects of stored heat on nocturnal production.

5.2.2 Operating Recommendations:

Based on the difficulties faced during the test period, the following is suggested:

- Select the location for setting up stills with care so that the stills do not get shaded.
- Operate the stills with enough water, so that they don't go dry.
- Keep the stills secured to protect them from heavy winds or rain.
- Keep the cover glass clean.
- Choose the sealant with care. It should not provide any air gap.
- Choose peripheral items such as collection cans, liner, insulation material such that they withstand temperatures over a wide range.
- Instrument the stills to continuously record temperature.

APPENDIX A

Table A1: Summary of Results Discussed in Chapter 1

Main Feature	Author	Still Type	Results
Treatment of cover glass	Bahadori et al. [1973]	SBSS	Etching of glass, using sodium metasilicate or hydrofluoric acid, makes it more wettable, thus increasing its efficiency
Latent heat utilization	Sodha et al. [1979] Hamdan et al. [1997]	Single-basin and Double-basin Single, double, triple-basin stills	In winter, the Double-basin's performance was 36% better than the Single-basin Triple-basin still was found to be 6.5% and 32% more efficient than double-basin and single-basin stills. Whereas, double-basin was 24% better than single-basin.
Effects of air gap, base and cover slope angles on the still performance	Elkader [1998]	Three SBSS of same front end but different back end heights, having inclined jute	Best results of 5.5 $L/m^2/d$ was obtained for the still with highest back end height with the base inclined at 15° and cover glass sloped at 35°.
Sewage treatment and plant culture	Qasim [1978]	Greenhouse type	Still with ventilation in the greenhouse section had healthy growth of plant with the treated sewage

Main Feature	Author	Still Type	Results
Role of absorbing materials such as black rubber mat, black ink, and black dye in improving the still efficiency	Akash et al. [1998]	SBSS	Black dye, black ink, and rubber mat enhanced the standard stills production by 60%, 45%, and 30% respectively.
Use of black rubber mat and black gravel	Nafey et al. [2001]	Four identical stills	Rubber mats ability to increase the still efficiency was directly proportional to its thickness and water depth (highest efficiency was 20%, better than standard still, with 10 mm thick mat and distilland volume of 60 L/m^2) whereas, gravels worked better for shallow depth of water (20-30 mm gravels improved the efficiency by 19% for distilland volume of 20 L/m^2)
Outside condenser	El-Bahi et al., [1999]	SBSS	Increase in efficiency by 70%
Effect of still modifications such as preheating of brine and vapor condensation	Khalifa et al. [1999]	Simple stills, double sloped stills, and their combinations with parabolic collector, external and internal condensors	The efficiency of single-slope still was increased by 33.8% with the addition of an eight pass internal condenser made of copper pipes.

Main Feature	Author	Still Type	Results
Performance evaluation of different designs of solar stills	Tayeb [1991]	Four SBSS, three had Plexiglas cover and one had glass	Still with glass cover was the most efficient at 22%
Nocturnal operation	Onyegegbu [1986]	SBSS	High night time efficiency in deep-basin compared to shallow-basin due to thermal heat storage
Use of energy storage material (ESM) to improve nocturnal production	Naim et al.	Simple solar still with aluminum tray containing ESM	It was found that Phase Change ESM was most efficient at higher feed flowrate, ambient temperature, duration of operation and lower saline water concentration. For similar conditions, still without ESM had daytime production of 170 ml and no overnight production, whereas, one with the PCM had daytime and overnight production of 330 ml and 240 ml respectively.
Product water quality comparison and economic analysis	Balladin et al. [1999]	Concrete cascade still and electrically heated conventional still	For small scale purpose cascade still was found to be more feasible

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Main Feature	Author	Still Type	Results
Presence of soot for insulation and inverted aluminum cover over glass cover	Madani [1995]	Galvanized still body placed in shallow seabed	Improvement in efficiency was observed during cloudy days due to addition of soot, but there was hardly any noticeable difference on sunny days. On average there was 35% enhancement in efficiency. Whereas absence of insulation decreased the efficiency by 13-17%.
Still with solar collector	Tiris [1995]	SBSS	Still became highly productive with flat plate collector, followed by the presence of charcoal
	Morcos [1973]	SBSS	With thermosyphon circulation and water mass, salinity, black dye concentration and distance between water surface and jute cloth at their optimum values, the still gave the maximum efficiency of 21.3%.
	Boukar et al. [2001]	SBSS and active still	The addition of solar collector resulted in doubling of daily production by the active still (8.02 L/m^2) compared to that of the simple still (4.01 L/m^2)
	Kumar et al. [2002]	Active still	Highest production was observed in May due to maximum number of clear days. The average daily yield for the depth of 6 cm was 3.33 L/m^2. The ideal inclination of the collector was determined to be 20° and that of the still was 15°.

Table A2: Summary of Main Events of Still A in Chronological Order

Date	Water Volume, L	Water Depth, cm	Cover Glass	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
11/4/05	20	2.1	SSG	Yes	No	Fluke 51 K/J Thermometer with Fluke K-type immersion probe	Nalgene 1L graduate cylinder	Bead formation
1/9/06	20	2.1	"	"	"	"	"	Cover glass removed for cleaning, and silicone sealant replaced with rubber foam weatherseal
1/12/06	20	2.1	"	"	"	"	"	Sheet of condensation formed
2/1/06	20	2.1	BJTG	"	"	"	"	Started producing measurable quantity of distillate
3/31/06	23	2.4	LEG	"	"	"	"	Cover glass exchanged with still B1. Onset® Rain Gauge with HOBO® Data Logger disconnected from still S and launched here

Date	Water Volume, L	Water Depth, cm	Cover Glass	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
4/1/06	33	3.4	LEG	No	Yes	Fluke 51 K/J Thermometer with Fluke K-type immersion probe	Nalgene 1L graduate cylinder	Covering of still at nighttime stopped
4/5/06	23	2.4	"	"	"	"	"	Heavy winds knocked down the rain gauge, spilling the distillate
4/26/06	33	3.4	"	"	"	"	"	From 3/31/06-4/26/06, alternate days 23 L & 33 L of distilland was being fed in the still
4/27/06-5/15/06	"	"	"	-	-	"	"	Still operated but with unknown volume of water
6/6/06	"	"	"	"		"	"	Evaporation loses around the seal
6/9/06	40	4.1	"	"	"	"	"	
6/16/06	26.6	2.7	"	"	"	"	"	

Date	Water Volume, L	Water Depth, cm	Cover Glass	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
6/23/06	26.6	2.7	SSG	No	Yes	Fluke 51 K/J Thermometer with Fluke K-type immersion probe	Nalgene 1L graduate cylinder	
6/27/06	27.1	2.8	"	"	"	"	"	
6/30/06	38.5	3.9	"	"	"	"	"	
7/1/06	38.5	3.9	"	"	"	"	"	Rain Gauge shifted to still C, deep-basin
7/19/06	38.5	3.9	"	"	"	"	"	Weatherseal changed, as it had started leaking
7/24/06	38.5	3.2	"	"	"	"	"	Weatherseal had to be changed again
9/30/06	31.2	3.2	"	"	"	"	"	
10/17/06	"	"	"	"	"	"	"	Jerrican leaking, replace with a 8L bucket
10/30/06	31.2	3.2	"	"	"	"	"	YC-747D Temperature Data Logger launched to measure distilland, headspace, outer glass, and ambient air temperatures
10/31/06	31.2	3.2	BTG	"	"	"	"	

Date	Water Volume, L	Water Depth, cm	Cover Glass	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
11/1/06	31.2	3.2	BTG	No	Yes	Fluke 51 K/J Thermometer with Fluke K-type immersion probe	Nalgene 1L graduate cylinder	Sheet formation noticed in the morning
11/2/06	31.2	3.2	"	"	"	"	"	HOBO® Pendant Temperature/Light Data Logger launched
11/6/06	31.2	.2	"	"	"	"	"	New glass sheeting
11/8/06	31.2	3.2		"	"	"	"	Weatherseal leaking again, ambient air temperature measuring probe shifted to collection trough
11/30/06	31.2	3.2	"	"	"	"	"	Distilland found to be frozen in the morning
12/1/06	31.2	3.2	"	"	"	"	"	YCT relaunched, now measuring back wall, inner wall, outer glass , and bottom wall temperatures
12/7/06	31.2	3.2	"	"	"	"	"	Thermometer's K-type thermocouple replaced by YCT K-type thermocouple
1/17/07	31.2	3.2	"	"	"	"	"	YCT K-type thermocouple stopped working, replaced by a similar one

Date	Water Volume, L	Water Depth, cm	Cover Glass	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
1/25/07	31.2	3.2	BTG	No	Yes	Fluke 51 K/J Thermometer with Fluke K-type immersion probe	Nalgene 1L graduate cylinder	YCT thermocouples repositioned to measure distilland, inner glass, outer glass, and bottom wall temperatures
2/3/07	"	"	"	"	"	"	"	YCT thermocouples repositioned to measure inner wall, outer wall inner glass, and bottom wall temperatures
2/5/07	"	"	"	"	"	"	"	YCT thermocouples repositioned to measure inner wall, outer wall outer glass, and bottom wall temperatures
2/8/07	"	"	"	"	"	"	"	YCT thermocouples repositioned to measure inner wall, outer wall outer glass, and ambient air temperatures
2/9/07	"	"	"	"	"	"	"	YCT thermocouples repositioned to measure inner wall, outer wall headspace, and ambient air temperatures
3/8/07	"	"	"	"	"	"	"	YCT disconnected

Table A3: Summary of Main Events of Still S in Chronological Order

Date	**Water Volume, L**	**Water Depth, cm**	**Cover Glass**	**Night Cover**	**Weekend Operation**	**Temperature Measurement**	**Water Measurement**	**Comments**
11/18/05	20	2.6	STG	Yes	No	Fluke 51 K/J Thermometer with Fluke K-type immersion probe	Nalgene 1L graduate cylinder	Little condensation occurring but no collection
11/21/05	"	"	"	"	"	"	"	Sheet of water formed, also seal loosened a bit leading to leakage
11/22/05	"	"	"	"	"	"	"	Leak continues inspite of putting duct tape, also no collection
11/28/05	"	"	"	"	"	"	"	first time measurable quantity of distillate collected-0.650L
1/14/06	"	"	"	"	"	"	"	Onset® Rain Gauge with HOBO® Data Logger launched
1/16/06	"	"	"	"	"	"	"	Tips on the rain gauge noticed every 2 min 30 sec

Date	Water Volume, L	Water Depth, cm	Cover Glass	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
2/3/06-2/15/06	20	2.6	STG	Yes	No	Fluke 51 K/J Thermometer with Fluke K-type immersion probe	Nalgene 1L graduate cylinder	Polystyrene panel used to insulate at nighttime on alternate days
2/10/06	"	"	"	"	"	"	"	Thermocouple stopped working
2/24/06	"	"	"	"	"	"	"	Cover glass cleaned using distillate of still B1 and flipped
3/31/06	23	3	"	"	"	"	"	Rain Gauge with Data Logger disconnected from and launched on still A
4/1/06	"	"	"	No	Yes	"	"	
4/27/06 5/15/06	"	"	"	"	"	"	"	Operated with unknown volume
5/26/06	"	"	"	"	"	"	"	Clamps put on the seal

Date	Water Volume, L	Water Depth, cm	Cover Glass	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
6/9/06-6/29/06	30	3.9	"	No	Yes	Fluke 51 K/J Thermometer with Fluke K-type immersion probe	Nalgene 1L graduate cylinder	Polystyrene panel used to insulate at nighttime on alternate days
6/11/06	"	"	"	"	"	"	"	Not collecting enough to run down the collection trough
6/12/06	"	"	"	"	"	"	"	Again leaking, stopped after Frost King® Rubber Foam Weatherseal put
6/16/06	26.6	3.5	"	"	"	"	"	Leaking again, weatherseal replaced with another one, leaking stopped
6/18/06	"	"	"	"	"	"	"	Neither leak noticed nor distillate collection
6/21/06	"	"	"	"	"	"	"	Collection after three days
6/27/06	21.4	2.8	"	"	"	"	"	New clamps put
6/30/06	30.3	3.9	"	"	"	"	"	Cover glass cleaned

Date	Water Volume, L	Water Depth, cm	Cover Glass	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
7/6/06	"	"	"	"	"	Fluke 51 K/J Thermometer with Fluke K-type immersion probe	Nalgene 1L graduate cylinder	Collection bucket knocked down by wind spilling the distillate
7/21/06	26	3.4	"	"	"	"	"	Table (as-supplied) found to be warped, hence still positioned on a steel table
8/20/06	"	"	"	"	"	"	"	Thermocouple not working
9/30/06	24.5	3.2	"	"	"	"	"	
10/31/06	"	"	BTG	"	"	"	"	
11/30/06	"	"	"	"	"	"	"	Ice formation in distilland noticed in the morning
12/7/06	"	"	"	"	"	"	"	Fluke K-type thermocouple replaced with YCT K-type thermocouple

Table A4: Summary of Main Events of Still B1 in Chronological Order

Date	**Water Volume, L**		**Water Depth, cm**		**Cover**	**Night Cover**	**Weekend Operation**	**Temperature Measurement**	**Water Measurement**	**Comments**
	Deep Basin	**Shallow Basin**	**Deep Basin**	**Shallow Basin**						
11/4/05	10	10	2.1	2.1	As-supplied	Yes	Yes	Fluke 51 K/J Thermometer with Fluke K-type surface probe	Nalgene 1L graduate cylinder	
11/15/05	"	"	"	"	"	"	"	"	"	Still found broken
3/18/06	10	0	2.1	0	LEG	"	"	"	"	Damaged still brought to service after repairs
3/30/06	11.5	0	2.4	0		Alternate days on deep and shallow	"	"	"	
4/1/06	1.5	0	2.4	0	BGTG	"	"	"	"	

Date	Water Volume, L		Water Depth, cm		Cover	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
	Deep Basin	Shallow Basin	Deep Basin	Shallow Basin						
4/27/06-5/16/06							-			Still operated unmonitored
6/9/06					BJTG			Fluke 51 K/J Thermometer with Fluke K-type surface probe	Nalgene 1L graduate cylinder	Started leaking from underneath
6/16/06	13.3	13.3	2.77	2.77	"	"	"	"	"	
6/27/06	"	"	"	"	"	"	"	"	"	Cover rotated by 180°
7/1/06	27.5	9	5.73	1.9	"	"	"	"	"	Onset rain gauge shifted from still A
7/2/06	"	"	"	"	"	"	"	"	"	Rain gauge shifted to deep and shallow-basins on alternate days
8/31/06	"	"	"	"	"	"	"	"	"	Out of service

Table A5: Summary of Main Events of Still B2 in Chronological Order

Date	Water Volume, L		Water Depth, cm		Cover	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
	Deep Basin	Shallow Basin	Deep Basin	Shallow Basin						
11/18/05	10	10	2.1	2.1	Clear agricultural plastic	Yes	No	Fluke 51 K/J Thermometer with Fluke K-type surface probe	Nalgene 1L graduate cylinder	Condensing but no collection
12/29/05	10	10	2.1	2.1	SSG	"		"	"	
1/27/06	11.5	0	2.4	0	LEG	"		"	"	
4/27/06 - 5/16/06						-	-			Still operated but with unknown volume of water
6/9/06	26.7	13.3	5.56	2.77	"	No	Yes	"	"	
6/16/06	13.3	13.3	2.77	2.77	"	"	"	"	"	
6/23/06	"	"	"	"	LEG	"	"	"	"	Cover exchanged with still A

Date	Water Volume, L		Water Depth, cm		Cover	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
	Deep Basin	Shallow Basin	Deep Basin	Shallow Basin						
6/27/06	"	"	"	"	"	"	"	Fluke 51 K/J Thermometer with Fluke K-type surface probe	Nalgene 1L graduate cylinder	Cover rotated by 180°
8/22/06	26	13	5.42	2.71	LEG	"	"	"	"	Rain gauge shifted here from still B1 and launched on shallow-basin
9/17/06	"	"	"	"	"	"	"	"	"	Deep-basin jerrican started leaking
9/30/06	24	12	5	2.5	"	"	"	"	"	
10/31/06	"	"	"	"	BTG	"	"	"	"	New clear glass installed
11/2/06	"	"	"	"	"	"	"	"	"	HOBO® Pendant Temperature/Light Data Logger launched

Date	Water Volume, L		Water Depth, cm		Cover	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
	Deep Basin	Shallow Basin	Deep Basin	Shallow Basin						
11/17/06	"	"	"	"	BTG	No	Yes	Fluke 51 K/J Thermometer with Fluke K-type surface probe	Nalgene 1L graduate cylinder	Rain gauge shifted to still A
11/30/06	"	"	"	"	"	"	"	"	"	Ice formation in the basin
12/7/06	"	"	"	"	"	"	"	"	"	Fluke k-type thermocouple replaced with same kind from YCT
1/17/07	"	"	"	"	"	"	"	"	"	YCT K-type thermocouple stopped working, replaced by another one of its own kind

Table A.6: Summary of Main Events of Still C in Chronological Order

Date	Water Volume, L	Water Depth, cm	Cover Glass	Night Cover	Weekend Operation	Temperature Measurement	Water Measurement	Comments
11/8/06	31.2	3.2	BJTG	No	Yes	Fluke 51 K/J Thermometer with Fluke K-type immersion probe	Nalgene 1L graduate cylinder	HOBO® Pendant Temperature/Light Data Logger launched

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