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CONSTRUCTION AND TESTING OF A HIGH EFFICIENCY SOLAR WATER STILL

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Abstract

The present study tested the feasibility of a new type of solar still which covers an elongated pool of feedstock water with an inflatable transparent plastic film canopy and uses a fan to blow air along the length of the pool allowing it to return through an overlying transparent air duct where it condenses its acquired vapor. A prototype still was built and shown to successfully distill water. The still was tested to determine whether its rate of daily water production would exceed the milestone goal of 2.5 gal/m^2/day and whether its rate of power consumption per gallon of water distilled would be less than 4 Wh/gal. Tests showed that the prototype's performance fell far short of these goals, producing 0.5 gal/m^2/day at the end of September with a power consumption of 47 Wh/gal. The prototype was calculated to have a distillation efficiency of 25%, or 30% if its canopy were fabricated of PFA Teflon film instead of polyethylene. These results demonstrate that the still operates as a single-effect still, rather than as a multi-effect still, with an efficiency comparable to that of a conventional greenhouse solar still. If fabricated with a PFA film canopy, it is projected to produce water at an average cost of $16,400/AF, as compared with $1,000/AF for a reverse osmosis desalinator. We conclude that this solar desalination technology is not feasible in comparison with existing desalination technologies.

Key words: solar, water desalination, still, multi-effect, water re-use

Executive Summary

In certain arid agricultural regions such as the San Joaquin Valley, there is currently a pressing need to desalinate and recycle irrigation drainage water to lower the water table of saline ground water and to do this in a way that is economical and that does not require large amounts of energy. The present study was carried out to test a new type of solar desalination technology to see if it could provide a viable solution to this problem. The still, called the Dune Solar Still, consists of a transparent canopy fabricated of light-weight plastic film that covers an elongated solar heated water basin and which is inflated by a small electric fan. The interior air space is divided by an additional transparent film into a lower evaporation air duct and an upper condensation air duct. A fan located within this enclosure circulates air down the lower air duct where it evaporates water from the pool and allows it to return by passing down the length of the overlying upper air duct where condensation takes place.

One objective of this project was to construct a Dune Solar Still prototype covering an area of approximately 10 m^2 and to show that it would successfully distill water. Another objective was to measure temperatures developed within the still and to discover how these varied according to the time of day and according to the rate at which air was circulated within the still. Furthermore the project intended to discover how much water the still could desalinate per day per unit land area and to determine the thermal efficiency with which it used incident solar radiation to produce distilled water. An additional objective was to discover how many watt hours the still would consume to produce one gallon of water.

The prototype still was built having a canopy fabricated from 6 mil polyethylene film and was found to operate properly to distill water. Temperatures were measured within the still and logged over time to see how temperatures were distributed within the still, how they changed over time in relation to the level of solar radiation, and how they changed in relation to changes in the rate of air flow within the still. The polyethylene prototype was found at its best to produce only 0.5 gallons/m^2/day, which failed the minimum goal of 2.5 gallons/m^2/day. It was found to have an efficiency of 25%. By comparison, a conventional greenhouse solar still has an efficiency of about 30%. The Dune Still is projected to perform somewhat better when fabricated with a canopy made of PFA Teflon film rather than polyethylene, and is expected to achieve a distillation efficiency of about 30%.

Testing demonstrated that the Dune Solar Still also performed poorly from an energy saving standpoint in that it was found to consume electric power at a rate of about 47 watt hours per gallon of produced distillate, which is equivalent to about 15,300 kilowatt hours per acre foot of water produced (kWh/AF). This is about 12 times higher than the milestone of 4 watt hours per gallon (1300 kWh/AF). This is also four times higher than the power consumption rate achieved by large reverse osmosis desalinator plants. Making the still canopy out of Teflon film would have lowered its energy consumption per gallon to about 39 Wh/gal (12,800 kWh/AF).

It is concluded that the Dune Solar Still would be more expensive than existing desalination technologies. A version of the still made with an inflatable PFA Teflon film canopy, producing a year average output of 0.66 gallons/m^2/day in a San Joachin Valley location is projected to produce distillate at a cost of about $16,400/AF. By comparison, a reverse osmosis desalinator is expected to produce water at a cost of about $1,000/AF. The cost of water produced by a conventional greenhouse solar still would be about $12,700/AF.

This project demonstrated that the Dune Solar Still functions to effectively distill water. It also demonstrated that many aspects of the still's mode of operation had been correctly anticipated, such as its ability to generate a thermal gradient along the length of its air ducts and its ability to produce a temperature inversion during daylight hours, with air in the upper condenser air duct being warmer than air directly below it in the lower evaporator air duct. However, testing also showed that the initial belief that the Dune Solar Still would function as a multi-effect solar still was unfounded and that the still instead functions as a single-effect still.

In addition the project examined the performance of the still when heated both by solar energy and by an external source of heat supplied continuously in the form of hot water. When continuously supplied with water heated to a temperature of 177° F (80° C), the still's water production output averaged 2 gallons/m^2/day, or about 80% the 2.5 gallons/m^2/day milestone. But its efficiency averaged 25%, less than that of a conventional greenhouse solar still. The power consumption of this hot feedstock version of the still calculated to be at best about 53 watt hours per gallon (17,300 kWh/AF).

Although the Dune Solar Still would produce considerably more distilled water when fed continuously with externally heated feedstock water, its cost per gallon would still be almost five times higher than for reverse osmosis desalination, $4,500/AF as compared with $1,000/AF. Moreover a conventional greenhouse solar still continuously supplied with externally heated feedstock water should produce water at a lower cost of $3,000/AF.

A version of the still fabricated with a polycarbonate roof did not perform as well as the polyethylene film version and hence it also would not be economically competitive with other desalination technologies. Heated by solar energy alone, its water production output averaged only about 0.35 gallons/m^2/day at the end of August and operated at an efficiency of only about 12%. Its low distillate production was due to its inability to consistently establish a positive thermal gradient along its length. The power consumption of this design was about 26 watts per gallon (8,500 kWh/AF).

Computer simulations performed on the Dune Solar Still design by Professor Yong Tao of Florida International University indicated that there would be no benefit to increasing the length of the still since water production per unit area decreased slightly with longer still designs.

It would be impractical to use the Dune Solar Still as an alternative to solar pond evaporation as a way of desalinating irrigation run-off water since the Dune Solar Still (version made with a PFA Teflon canopy powered by solar heating alone) plus its brine evaporation pond would require about 9% of the agricultural land area. A conventional solar evaporation pond, on the other hand, would require slightly more land area, about 10%, but would have a much lower construction cost.

This study does not recommend that further research be undertaken into this type of solar still design. If the technology had proven effective, the California public would have benefited through implementation of an inexpensive means to lower the salinity of fertile agricultural land. However, since the technology did not prove to be cost effective or energy efficient, there would be no future benefits to its implementation.

Introduction

The purpose of this project has been to determine the feasibility, performance, and operating characteristics of a novel, multi-effect solar water still, here termed the Dune Solar Still, which had been invented in the mid 1970's by the principle investigator Paul LaViolette. When fully inflated, the Dune still has the shape of an arching tube; see Figure 1. The solar distillation bay prototype that was constructed and tested measured about 1.17 meters in width, about 8.8 meters in length, with a height of about 0.5 m when inflated. In an actual installation distillation bays could measure up to 30 meters in length and would be arrayed side by sideto form a solar distillation "farm" (see Appendix A, Figure A-1). The Dune Solar Still uses solar energy to evaporate water into a ducted airstream and subsequently condenses water from this airstream to produce fresh water. Initially, it was theorized that the Dune Solar Still should function as a *multi-effect* still, recycling its released heat of condensation to assist evaporation; see Figure 2. By comparison, a conventional greenhouse solar still is a single effect still, meaning that it uses its acquired solar heat only once to distill a given amount of feedstock water.*

The project focused on the potential use of this still to the application of desalinating high-salinity agricultural drainage water for reuse in crop irrigation. Consequently, this research was appropriate to the Industrial/Agricultural/Water End-Use Efficiency subject area of the EISG Program. As noted in the PIER website (www.energy.ca.gov/pier/indust/index.html), "the availability of low-cost clean water is essential to California's economy and continued prosperity" and that the treatment of large volumes of substandard and saline water relies heavily

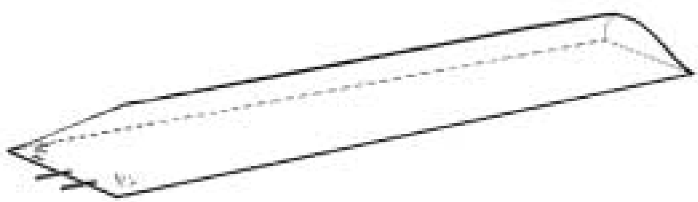

Figure 1. Schematic of a single distillation bay.

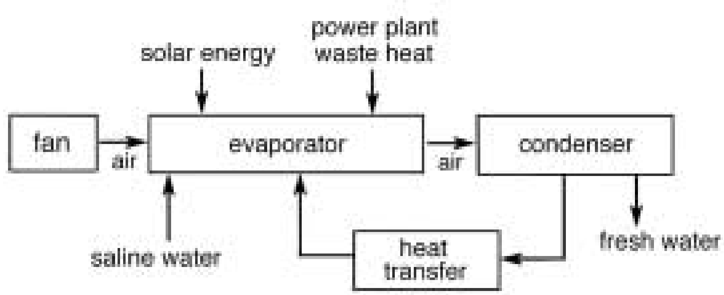

Figure 2 Heat recycling in a multi-effect solar still.

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* In a greenhouse still, solar radiation is absorbed by a light-absorbing floor panel and heats an overlying layer of water (see Appendix A, Figure A-2). The heated water evaporates and its vapor condenses in droplets on an overlying, cool, inclined window pane. The condensed water droplets run down this pane and collect in a trough at the side of the still. Such stills are designed to lose heat through their window pane to the environment so as to encourage vapor condensation. Thus all of the solar energy they absorb to evaporate water is lost to the environment upon condensation.

on electric power. So if this technology were to prove superior to existing desalination technologies it could result in substantial savings to California in terms of reduced kilowatt hour consumption used in the desalination of irrigation drainage water, or in the production of desalinated water for residential or industry use.

In the past, solar distillation technologies have been considered economically impractical because their water cost has been high when compared to that of municipal drinking water at ~$460 per acre-foot (AF). The economics for water desalination is more favorable in the San Joaquin Valley in the application to desalinating irrigation drainage water since drainage water desalination and reuse is a necessity here *independent of the price of irrigation water*. For example, in the San Joaquin Valley soil salinity has become excessive because of failure in the past to recycle agricultural drainage water. The long time practice of importing irrigation water has raised the water table in the area due to the presence of an impermeable clay layer which prevents downward percolation of the water. Fertilizer salts have leached into the ground water and the resulting salty ground water has risen to root level killing crops. About 2.5 million acres of productive farmland there are threatened by saline shallow ground water, of which about 750,000 acres have already been lost due to elevated soil salinity. The California Department of Water Resources (DWR) has implemented a program to address this problem which currently promotes solar evaporation ponds as a way of dispensing of this water. However, these require excessive acreage: ~10% of the arable land area for evaporating once-used irrigation water. Moreover in many regions these ponds pose a threat to bird wildlife due to their high concentration of toxic metals such as selenium. Consequently, California is interested in exploring drainage water desalination and reuse as a way of reducing the needed solar evaporation pond acreage. Furthermore, the California Dept. of Water Resources is interested in exploring alternatives to reverse osmosis desalination since R.O. by itself does not provide a complete brine disposal solution. At 10,000 TDS, R.O. desalinators must discharge 25% of the input stream volume as high-salinity water as compared to only 5% in the case of a solar still such as the Dune still. Also, as noted below, R.O. consumes large amounts of electricity per acre-foot (AF) of processed water. Hence if an alternative technology can be found that consumes less power per AF of water produced, this would be of great benefit to California and the world as a whole.

Project Objectives

Project objectives were as follows:

1) Hire personnel, set up and prepare the office for the project, purchase equipment and supplies, and erect an instrument shed and set up a fence around the test site.
2) Prepare a working sketch of the 10 m^2 still. Fabricate initial prototype of solar water still having a polyethylene film canopy.
3) Test the solar still constructed with a polyethylene canopy and demonstrate that it will produce more than 2.5 gallons per day per square meter of still land area and that it will consume less than 4 watt-hours per gallon (Whr/gal) on the average under winter season testing conditions (cloudless sky, 75° F weather) typical of southern California and process agricultural drainage water of less than 10,000 TDS salinity. Also demonstrate that the polyethylene prototype still will produce more than 3.5 gallons/m^2/day on average and consume less than 2.5 Whr/gal on average under summer conditions typical of southern California (100° + weather), while processing agricultural drainage water of less than 10,000 TDS salinity.

4) Fabricate and install a still canopy made of PFA Teflon film.

5) Test the still fitted with a canopy made of PFA Teflon film. Determine whether the still will produce more than 3.5 gal/m^2/ day on average and consume less than 2.5 Whr/gal on average (< 800 kWh/AF) under winter season testing conditions (cloudless sky, 75° F weather) typical of southern California and processing agricultural drainage water of less than 10,000 TDS salinity. Also demonstrate that under summer conditions typical of southern California (100° + weather) it will produce more than 5 gallons/m^2/day on average and consume less than 1.53 Whr/gal on average, while processing agricultural drainage water of less than 10,000 TDS salinity.

6) Perform a cost analysis. Show from the data generated in this project that the projected cost of \$113/m^2 for building a 173 m^2 still module continues to be supported. Show from the data generated in this project that the projected cost of \$490/AF for desalinating drainage water having a salinity of less than 10,000 TDS continues to be supported.

Project Approach

1. Design and Operation of the Still

The lower part of the still consists of a shallow water filled basin whose floor is covered with black Hypalon membrane overlying an insulating concrete base. An electric pump fills this basin to a depth of a few inches with brackish feedstock such as agricultural drainage water, saline river water, seawater, or high-salinity well water. The still's canopy section is fabricated from several layers of transparent plastic film heat-sealed together at the edges. This may be made of 4 year polyethylene film or long life, UV resistant Teflon film such as PFA or FEP which have lifetimes (> 30 years). One of the canopy's transparent film layers divides the still's interior air space into a lower evaporating air duct and an upper condensing air duct; see Figure 3. Also two additional transparent films form the roof of the upper air duct, the double layer helping to prevent heat loss much as would the thermopane window of a flat plate solar collector. The insulating air space between these two outer transparent films is inflated with dry air. The edges of the plastic film canopy are secured to the basin floor of the still by means of film gripping strips. The canopy may be detached from the basin, allowing the still to be opened for periodic cleaning.

During daylight hours the brackish water pool is heated by solar radiation which passes through the still's transparent roof and which is absorbed by the still's light-absorbing floor. An electric fan, similar to a desktop computer cooling fan, is mounted in a partition that rests upright on the floor of the still at one end of its enclosed air space and beneath the heat exchanger film. When operating, the fan circulates air in a closed loop within the still. As air is blown down the length of the lower tubular air duct, it passes over the surface of the heated feedstock water and becomes humidified. Under steady state conditions a temperature gradient will become established along the length of the still, the temperature of both the air and water increasing with increasing distance along the length of the lower air duct. As the air travels forward, its temperature rises and it accumulates an increasing amount of water vapor.

At the far end of the still, the hot moist air enters the cooler upper tubular air duct through a hole in the transparent heat transfer film. Here it reverses its direction of flow to travel toward the fan end of the still. As the air passes down the length of this air duct, it gradually cools due to heat being lost both upward through the roof of the still and downward through the lower transparent heat transfer film. Condensation takes place on the wall surfaces of this upper air duct and especially at the lower edges of the air duct where the heat transfer film directly

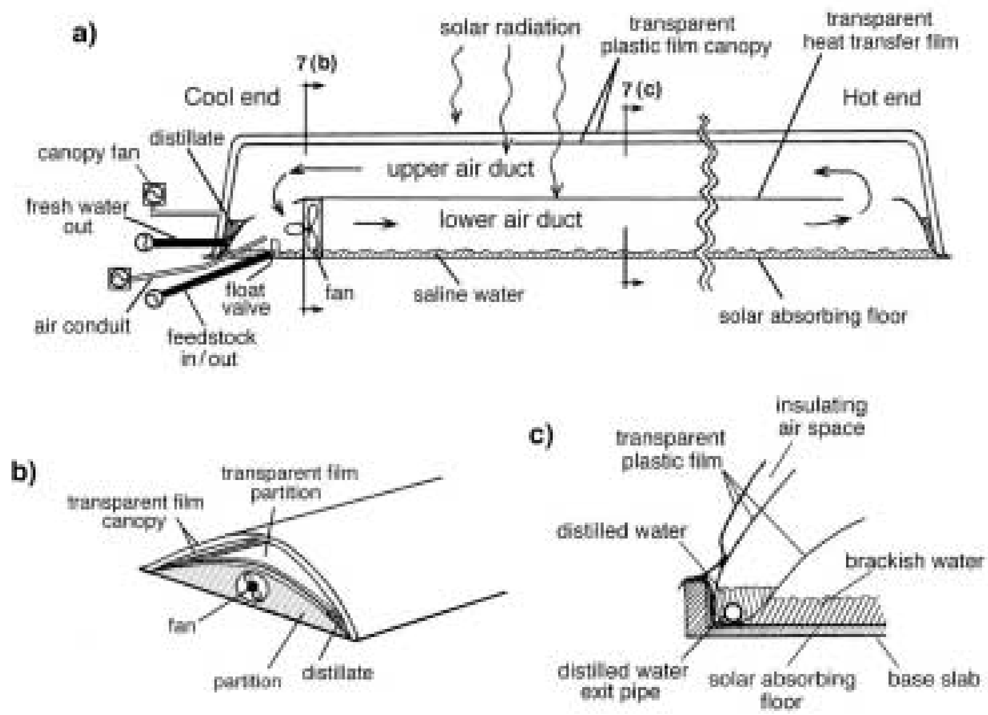

Figure 3. The Dune Solar Still: a) side view, b) end section view, and c) edge detail.

contacts the pool of feedstock water allowing efficient transfer of the heat of condensation. At the fan end of the still the air reenters the lower air duct through a second hole in the transparent film at a point behind the fan intake. The still is kept pressurized by an outside air vent tube that terminates in the low pressure region behind the fan.

Throughout a portion of the length of the still, the air in the upper condenser air duct is expected to be warmer than the air in the lower evaporator air duct. This is due to the time lag involved in heating the air in the lower air duct and the complementary time lag involved in cooling air in the upper air duct, as illustrated in the hypothetical diagram shown in Figure 4. Consequently, heat will conduct and radiate through the plastic film partition from the upper to the lower air duct. The condensate that collects at the edges of the plastic tube will also be warmer than the adjacent pool of brackish feedstock water and will transfer heat to this pool through the heat transfer film.

The Dune still insulates its evaporator chamber better than a greenhouse still by making its canopy from two transparent films separated by an insulating air space. Rather than encourage condensation through roof heat loss, as in the conventional greenhouse solar still, the Dune still seeks to develop its condensation thermal gradient along the length of its enclosure while minimizing its upward heat loss. It was expected that this would allow the Dune still to achieve higher interior temperatures than those within a greenhouse solar still. Since a given volume of air is able to hold far more water vapor at higher temperatures; see Appendix A, Figure A-3. This would act to favor the operation of the still.

The Dune still could incorporate control circuits to automate its operation. Generally speaking, higher levels of insolation will require higher fan speeds and greater air flow rates to maintain optimal distillation rates. Consequently, one control circuit design might utilize a

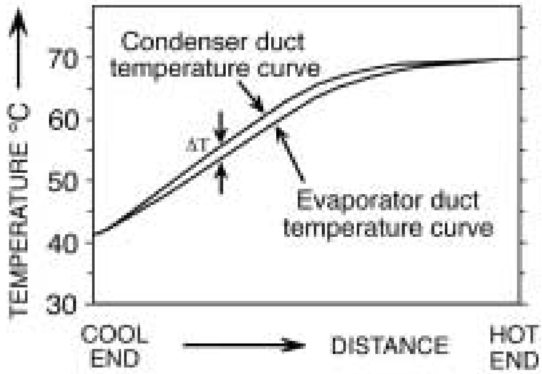

Figure 4. Hypothetical graph of temperature gradients developed along the length of the evaporator and condenser air ducts. Actual test data indicates that the temperature differential between the hot and cold ends of the still actually is about one fourth as much as shown here.

photovoltaic cell to sense the level of insolation and control the fan speed accordingly. Another control circuit might use a sensing thermistor to turn on the still's fan when its evaporator chamber has warmed to a sufficiently high temperature. Control for the feedstock water pumps could be manual or automatic via a timer. The pump would begin its cycle in the morning before the still had warmed up. First, the concentrated brine would be pumped out from the basin and then a new batch of feedstock water would be admitted to the basin. Distillate pumping would be done at periodic intervals.

2. Construction Phase

a. Construction of the Still Base and Test Site

The project to test the Dune Solar Still prototype was carried out by the Starburst Foundation on facilities leased from the California Water Institute (CWI) of Fresno, California. The test site was located at the northwest corner of the California State University Fresno campus.

The first phase of the project was to bring water and electric utilities out to the test site which was located on a plot of land in an open field adjacent to the CWI building. Trenches were dug and pipe and conduit was laid down to supply water and 20 amps of line current to the site. The site was then tractor graded and leveled with the aid of a laser level. A load of sand was added prior to final leveling. The area was then wetted and compacted with a vibra compactor.

Two-by-four beams were laid out, nailed together, and secured to the ground with cement stakes to form frames for the bases of two adjacent solar still bays. One bay measured about 28 feet long and the other bay measured about 56 feet long. Each bay was about 46 inches wide. Trenches were dug at the end of each bay and four PVC pipes were laid to each bay to supply, feedstock water to the basin, drain brine from the basin, remove freshwater distillate from the still, and supply air and electrical power to the still interior; see Appendix A, Figures A-4 and A-5. The frames were aligned and leveled with the aid of strings and a laser level. Next, the frame was filled with a 3.25" layer of insulating concrete (mixture of Perlite, cement, and aerating agent); see Appendix A, Figures A-6. The surface was trawled and leveled with a screed. Next, after the cement had cured, the basin sideboards were nailed on and the cement surface was sanded level; see Appendix A, Figure A-7. Then, a 36 mil thick Hypalon® membrane was glued to the basin bottom and side walls; see Appendix A, Figure A-8. The sides of the basin were insulated with foam insulation. Bowl like drains were formed at the ends of each basin and were plumbed to underground drain pipes leading to water storage tanks. The basins were filled with water and found to be to level within 1 centimeter along their lengths. At a later time this basin was to be covered with a polyethylene film canopy.

Two polyethylene tanks, holding 325 and 510 gallons respectively were installed and plumbed to the still; see Appendix A, Figure A-9. Four pumps operating on 12 volts DC were installed on a vertical board near the tanks, two hooked up to each basin. But it was discovered that the pumps were not self priming, so they were later were moved underground to valve boxes located at each end of the still bays. For each basin, one pump pumped brine from through the basin drain and into the top of one of the polyethylene tanks. It was actuated by a float level switch when water in the basin fell below a certain lower limit; see Appendix A, Figure A-10. After a set time period during which the bay would be drained of water, a timer relay mounted in the circuit breaker control box (Appendix A, Figure A-11) would shut off the pump and open a solenoid valve allowing feedstock water to flow from the bottom of the tank to the bay. The pump would shut off when the water level in the bay had risen above a set upper limit. In order to conserve water, the test set up was designed as a closed water circulation system: from the still to the tank and from the tank back to the still. Another timer relay at set intervals would cause a second diaphragm pump to turn on and pump distillate from the still into a 15 gallon distillate holding tank located on top of each of the main storage tanks; see Appendix A, Figure A-12. The amount of distillate was measured either by siting the tank's level from gradations marked on its side or by actuating a solenoid valve to empty the tank while measuring the water flow rate through a data logged water flow meter.

b. <u>Construction of the Polyethylene Canopy Version of the Dune Solar Still</u>

While the test facilities were under construction, a plastic fabricating company was fabricating the tubular polyethylene canopy. The fabrication involved heat sealing three layers of clear, 6 mil thick polyethylene film along their edges to form an inflatable tubular enclosure according to the design shown in Figure 3. The film had an anticondensate coating. The fabricators were supplied with drawings and with a 1/4 scale model mock up of one end of the canopy; see Figures A-13 and A-14 (Appendix A). The first canopy they manufactured unfortunately was flawed. After testing was begun it was discovered that the heat seal along its long dimension was open in four places. Hence the canopy had to be remanufactured at a considerable delay to the project.

Meanwhile we experimented with several methods of anchoring the edges of the polyethylene film canopy to the bottom of the still basin. Various types of film grips were installed along the edges of the basin and tested for their effectiveness. First, a rubber U channel was installed to grip both the edge of the canopy and the distillate tube running along the perimeter of its interior, but the air pressure inflating the canopy pulled the canopy free. Then, cupped flexible polyethylene strips (Figure A-15) were fastened to the basin perimeter in various orientations, but these also failed to retain the canopy upon inflation. PVC pipe tees were also tried. Finally, it was concluded that the canopy would need to be redesigned to include a three inch flap along its perimeter. This flap was to be secured by aluminum poly-grip fasteners used in securing greenhouse canopies. A new polyethylene canopy was manufactured and the poly fasteners were installed (see Figure A-16 of Appendix A). This method was found to successfully hold down the canopy under inflation.

Figure 5 shows the solar still canopy inflated and in operation. In this picture a 12 volt hair dryer fan was being used to inflate the canopy by applying a positive pressure to the vertical air pipe leading to the interior of the still. By redesigning the air pipe to provide less flow resistance a low wattage 18 cfm 12 volt (0.14 amp) axial fan was later used to keep the canopy inflated; see Figure A-17, Appendix A. The metered control panel leaning against the edge of the still was used to operate the still's fans. The voltage to the fans was controlled by a rheostat. The meters read out voltage and current flowing to the fans to assess power consumption. A partition divided the 56 foot long water basin approximately in half to accommodate the still canopy which measured about 29 feet long.

The lower air duct had a cross sectional area of approximately 1800 cm^2 and the upper air duct had a cross sectional area about 30% larger. When operating the fan blew air down the length of the bay, evaporating water from the pool of feedstock water. At the other end of the bay the air would pass through a 12 inch diameter hole into the upper air duct formed within the canopy and would flow back to the fan end of the still, condensing a portion of its water vapor as it cooled. Then, the air would pass through another 12 inch diameter hole into the airspace below the canopy and downstream of the fan inlet to be recirculated once again. Air blown through one of the vertical PVC pipes helped to keep the canopy inflated. A 3/8" black Norprene tube which ran along the perimeter of the interior of the canopy can be seen in the photograph. It would make a complete loop of the perimeter with both of its ends attaching via the T connector to the distillate suction hose, This hose led to a 12 volt diaphragm pump located in an underground valve box.

Figure 5. The Dune Solar Still with its canopy installed and inflated.

c) <u>Construction of a System to Externally Heat the Feedstock Water</u>

In November the still design was modified so that hot feedstock water would continuously circulate through it. One reason this was done was to study the still's performance at a higher temperature range. Since construction of the Dune Solar Still was delayed, testing did not begin until after the equinox, and as a result, maximum temperatures achieved in the still were much lower than they would have been if tested close to the solstice. By artificially heating the feedstock water with an external heat source, the performance of the still could be examined in this higher temperature range. A second reason for testing the still with an external heat source was to simulate the still's performance if it were designed to distill saline geothermal water passed continuously through the distillation bay from the hot to the cool end of the still. Such water could be supplied from geothermal water exiting a geothermal power plant and diverted to the still prior to subterranean reinjection. It could also come from saline produced water, the by-product geothermal water discharged from petroleum wells. Often this water comes out of the ground at moderately high temperatures, 140° F or more, and is costly to dispose of. The advantage of using geothermally heated water as feedstock water is that the still may be made to operate continuously, rather than just during daylight hours.

To test the Dune Solar Still modified for receiving a continuous flow of hot water, the output from the still's drain pump was connected to an insulated rubber hose (Appendix A, Figure A-20). Feedstock water pumped from the cool end of the still through this hose was conducted through a water filter and into a Takagi TK-Jr. tankless water heater located at the hot end of the still; see Figure A-21 (Appendix A).* From there the heated water was discharged through another insulated hose which emptied into the hot end of the still. The water heater was fueled with propane tanks which were recharged daily. The ends of the still were covered with pieces of foam insulation to reduce heat loss from the heated water pool which at these end locations would otherwise be exposed to the atmosphere (Appendix A, as shown in Figure A-22).

d) <u>Construction of a Version of the Dune Solar Still Made with a Polycarbonate Roof</u>

Another variation of the Dune solar still that was built was one that used clear, polycarbonate sheet (6 mm thick twin-wall Lexan® containing an insulating air space) to form the roof and end pieces of the still; see Appendix A, Figure A-23. This replaced the upper two film layers of the inflatable polyethylene canopy version. The roof was self supporting being a stiff sheet that was spring loaded against the walls of the basin to form an arch. Cut panels were sealed to the ends with putty. As in the polyethylene canopy version, a 6 mil polyethylene sheet was used to divide the upper and lower air ducts. The film was wrapped around the edge of the polycarbonate sheet and taped to its outside (Figure A-24, Appendix A). The air flow along the lower air duct would keep this dividing film inflated allowing distillate to collect at the edges of its upper surface. A fan partition was placed below one end of this film in the same manner as was done with the polyethylene canopy version of the still. Although the polycarbonate sheet had an anticondensate coating on its lower side, there was still considerable beading of water droplets on its surface.

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* Earlier in October several other types of water heaters had been tried, both tank type and tankless, but were found to be inadequate. It was found that they were not able to take heated water as an input since as the input temperature approached a certain threshold an internal thermostatic safety switch would be tripped, preventing the heater from achieving a high enough exit water temperature. Only the Takagi water heater was found to be suitable. This was able to take heated water as an input and achieve exit water temperatures as high as 182° F (83° C) regulated to within ±2° C.

3. Instrumentation

Thermocouples were installed in the still and their leads connected to a 16 channel Consort T851 temperature data logger kept within the instrument cabinet seen on the right hand side of Figure 6. Temperatures were measured at four points along the length of the still as shown in Figure 7. Measuring from the cool end of the still where the fan was located, the probes were positioned at: 0.9 meters, 3.4 meters, 5.8 meters, and 8.3 meters. They were encapsulated within heat shrink tubing to prevent electrical contact with the water and were wrapped in aluminum foil to minimize direct solar heating of the thermocouples. Wire mesh arches helped to position the probes vertically (Appendix A, Figure A-25). One set of probes were attached to the bottom of the basin to measure water temperature (Channels 1, 4, 9, and 14). A second set were suspended in the lower air duct air stream to measure air temperature in the lower air duct (Channels 2, 5/6, 10/11, and 15). A third set were passed into the upper air duct to measure air temperature in the upper air duct (Channels 3, 7/8, 12/13, and 16). In the case of the middle two temperature locations (3.4 m and 5.8 m), two probes were used to sample the lower air duct temperature and

Figure 6. A view showing the canopy wired up with thermocouple leads to measure temperature at four points along its length.

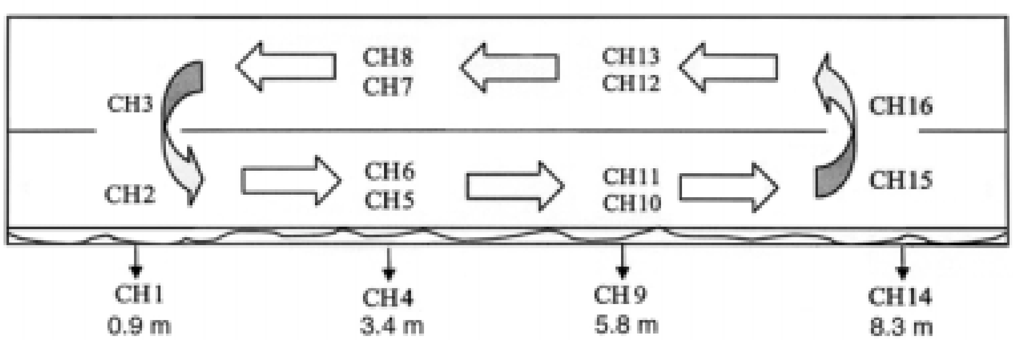

Figure 7. Depiction of air flow along the length of the still and the approximate locations of thermocouples measuring water and air temperature.

two to sample the upper air duct temperature. The readings of the two probes were later averaged together.

The temperature readings were estimated to have an absolute error of about ±1.5° C. When comparing one temperature probe to another, their relative error was somewhat lower at about ±0.4° C (see Appendix A, Figure A-26). The vertical scale marks the amount by which the temperature reading for each of the 16 thermocouple probes deviated from the average bath temperature measured by three mercury thermometers and plotted against bath temperature on the horizontal axis.

Air speed in the lower air duct was measured with a rotating vane Extech anemometer placed upstream of the fan intake (Appendix A, Figure A-27). Initially, air speed was measured at the hot end of the still at the entrance to the hole between the upper and lower air ducts. But it was determined that measuring at the fan intake gave a more accurate reading.

Solar insolation levels, ambient air temperature, and wind speed were logged hourly at the CIMIS (California Irrigation Management Information System) weather station located on the Fresno State University Campus. This data was accessible from the CIMIS website at http://wwwcimis.water.ca.gov/cimis/welcome.jsp .

4. Solar Still Performance Data

a) Dune Solar Still with an Inflatable Polyethylene Film Canopy

Experimentation and testing of the Dune Solar Still with a polyethylene canopy were carried out from September 16th to October 7th and on October 14th. Figures 8 through 12 plot data that was logged over a 24 hour period on September 27th. Figure 8 shows the temperatures measured at four locations along the length of the still by the 16 thermocouples (colored data points) compared with the level of solar insolation (solid black line). Ambient air temperature on September 27th ranged from a low of 11° C at 9 AM to a maximum of 33° C at 3 PM. Wind speed averaged about 2 meters per second. As seen here, temperature in the still reached a maximum around 3:30 PM, three and a half hours after solar insolation maximum. The dip in temperatures around 4 PM was due to the shadow from the tops of two tall pine trees near the southwest corner of the site which shaded about 30% of the still's area until sundown. When the site was first staked out in mid April, it had been thought that the site had been located sufficiently northward to avoid these tree shadows. But these measurements were made on a date that was one month further from solstice when the trees cast longer shadows to the north.

Figures 9, 10, and 11 show the diurnal temperature variations at four locations along the length of the still in the feedstock water pool, lower air duct, and upper air duct respectively. Figure 12 plots the temperature gradients measured along the length of the still at 3:02 PM in the feedstock water pool (blue), lower air duct (red), and upper air duct (yellow). The still's fans were circulating air through the air ducts at a rate of 140 cfm (cubic feet per minute). Hygrometer measurements showed that air in the lower air duct at the hot end of the still had a relative humidity of 96%.

Data on daily distillate production per unit area, fan air flow within the still, and energy efficiency are presented in Table I. The gained output rate (GOR) energy efficiency is calculated by taking the volume of distillate produced per square meter, multiplying it by the heat of evaporation (539 calories per gram), and dividing it by the daily incident solar energy flux per square meter as measured by the CIMIS weather monitoring station.

At the time when the still achieved its maximum temperature, around 3:02 PM, the feedstock

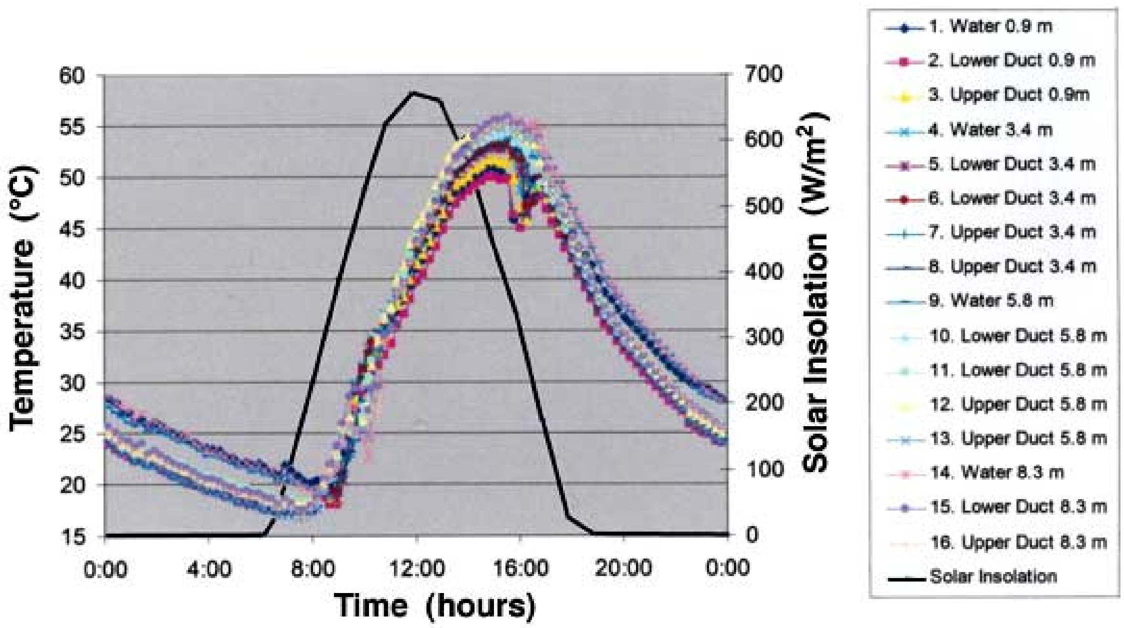

Figure 8. Temperatures measured in the still at various times of the day (colored data points) compared with the level of solar insolation (solid black line) for September 27th, 2004.

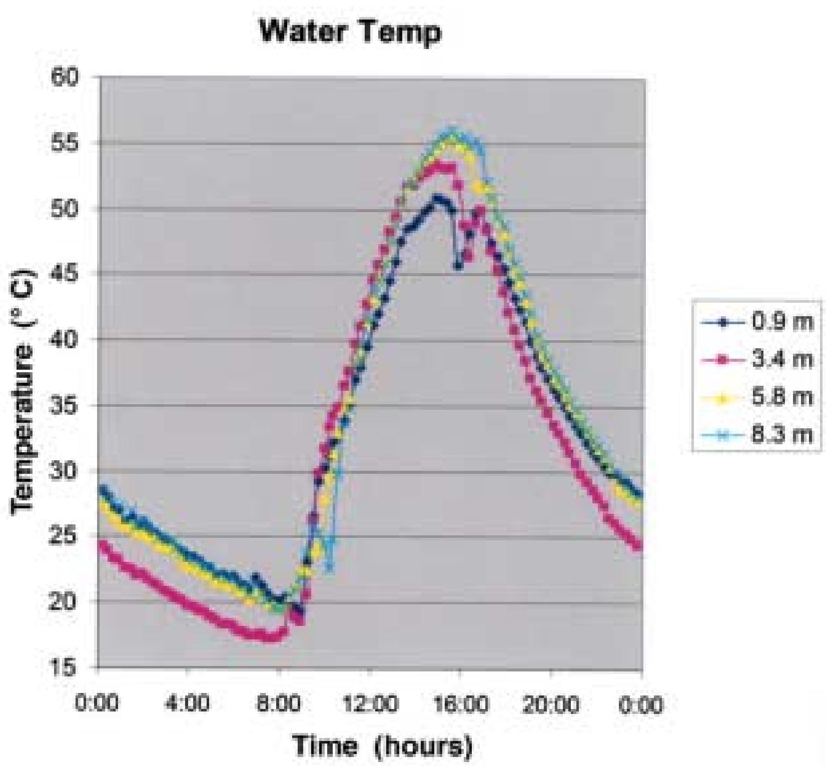

Figure 9. Diurnal variation of feedstock water temperature measured at certain distances along the length of the still on September 27th, 2004.

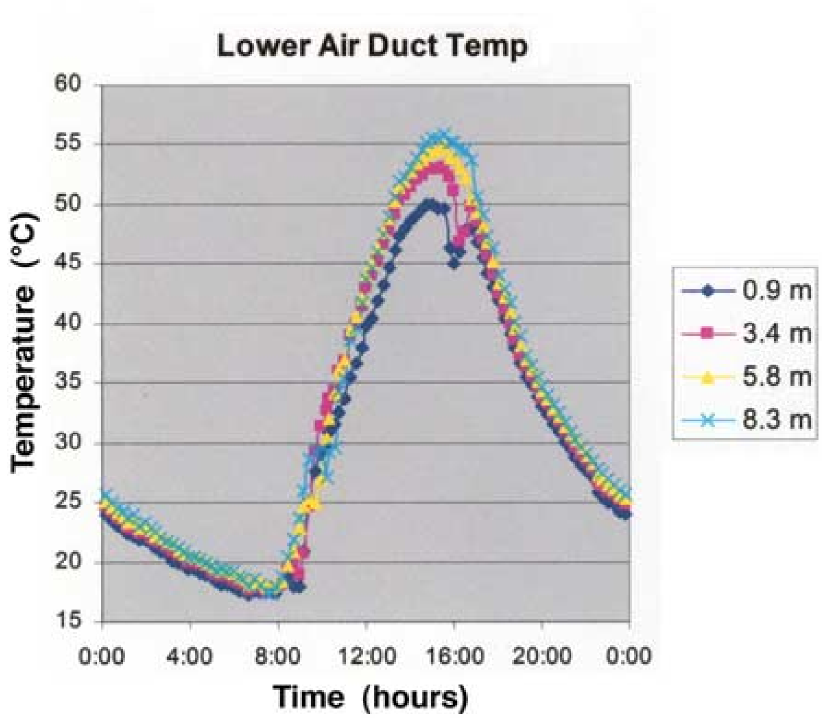

Figure 10. Diurnal variation of air temperature in the lower air duct measured at certain distances along the length of the still on September 27th, 2004.

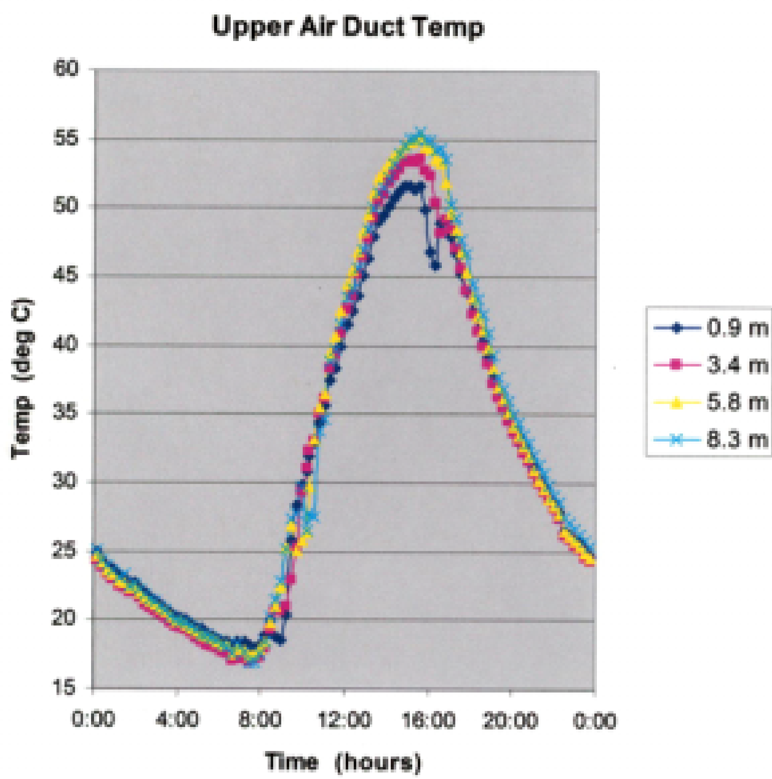

Figure 11. Diurnal variation of air temperature in the upper air duct measured at certain distances along the length of the still on September 27th, 2004.

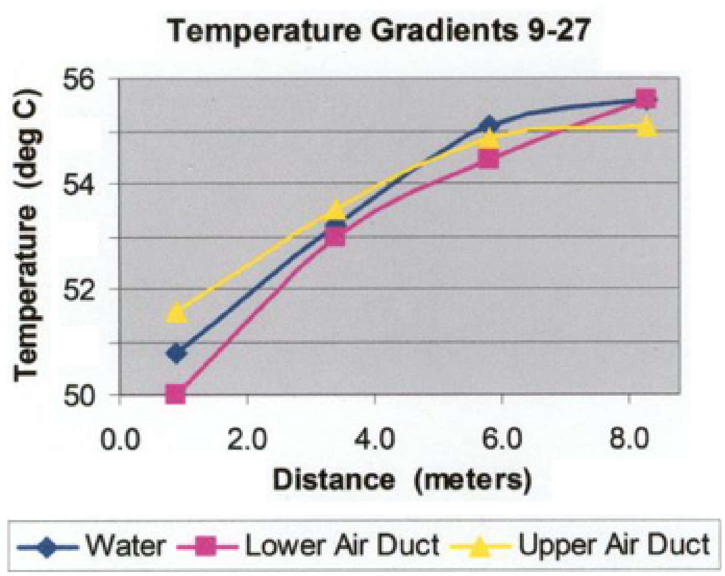

Figure 12. Temperature gradients developed along the length of the still in the feedstock water, lower air duct, and upper air duct.

Table I
Distillate Production by the Dune Solar Still Made with a Polyethylene Film Canopy

Date	Water Produced (gal/m^2/day)	Energy Effic. (%)	Air Flow (cfm)	Water ΔT (°C)	Comments
9/16	0.3		110	9	Still down from 9:30 - 10:30 for adjustment
9/17	0.3				Canopy deflated from 12 AM to 4:50 PM
9/18	0.27				
9/19	0.27		65	11	
9/20	0.48		280	7	Repair/canopy open 1 - 3:15 PM fan end
9/21	0.48		135		
9/22	0.48		115	4	
9/23	0.38		85		Repair/ hot end open 1:15 PM
9/24					Still not operating
9/25					Still not operating
9/26 - 27					Still began operation 12:50 PM
9/27 - 28	0.5*	24.8*	180		As of 10:40 AM, 9/27
9/28 - 29	"	"	160		
9/29 - 30	"	"	100 - 200	8.3	Until 5:30 PM. Still under repair for 3/4 hr
9/30	0.25	13.3**	70	5.7	
10/1	0.3	"	80	6.8	
10/2	0.3	"	80		
10/3	0.3	"			Still under repair
10/4	0.25	"	525	3.7	
10/5	0.31	"	200-500		
10/6	0.32	"	240	4.7	
10/7					Still is operated until 12 noon
10/14	0.35	23.7	225	3	

* Average of 9/27 through 9/29 ** Average of 9/30 through 10/6

water achieved a temperature difference of 4.8° C along the length of the still (blue line in Figure 12). The air temperature in the lower evaporator air duct achieved a greater temperature differentials of 5.6° C while the air temperature in the upper condenser air duct achieved a lower temperature differential of 3.5° C (red and yellow lines in Figure 12). These gradients were substantially less or nonexistent during night time and early morning hours.

In general, when the still was at its maximum temperature, the air in the lower air duct averaged about half a degree cooler than the temperature of the solar heated water that it was in contact with. Over three fourths of the still's length, the air in the upper air duct was from 0.5 to 1.6° C warmer than the air directly below it in the lower air duct. This indicates that heat of condensation could be transferred from the upper to the lower air duct indicating that the still was possibly recuperating some of this heat. Over half of the length of the still the air temperature in the upper air duct was warmer than the temperature of the water in the feedstock water pool directly below it. So it is even possible that some of the heat of condensation was helping to heat this water pool.

It had been initially theorized that due to the fact that air was being advected through the lower air duct from the cooler to the warmer end of the still and through the upper air duct from the warmer to the cooler end of the still and because there would be a time lag for this air to change its temperature, that such a temperature inversion would develop. The observed temperature gradients confirmed these initial expectations that the air temperature in the upper air duct would be greater than that in the lower air duct.

As expected, the thermal gradient along the length of the still tended to decline as air flow rate circulating through the still increased. For example, using the data in Table I, Figure 13 plots the water pool temperature difference between the hot and cold end of the still as a function of air flow rate through the upper and lower air ducts. Although there is considerable scatter in the data, a trend is definitely seen. Figure 14 plots how distillate production was affected by air duct air flow rate. The production rate appears to be low at both low fan speed and high fan speed, with a maximum at around 180 cfm.

The distillate production rate of the still at its best averaged 0.5 gallons/m^2/day during the period September 27th to 30th. This fell far below the milestone goal which was set at 2.5 gallons per day per square meter of still area for suboptimal season conditions. The thermal energy efficiency of the still was also calculated to be very low. The highest efficiency listed in Table I, about 25%, is low compared to that of a greenhouse solar still which typically has an efficiency of 30%. The efficiency would have been higher if the canopy had instead been made of PFA Teflon film, which has a solar transmission of 96% as compared to polyethylene film which has a transmission of 88%. Transmission through three layers of PFA film would have been 30% greater than through three layers of polyethylene film, although the PFA film may have produced more back scattering since it would have had no anticondensate coating. If there had been a proportional increase in distillate production, the efficiency of the Dune still would have been boosted to about 32.5%. Although computer simulations performed on the Dune still by Prof. Yong Tao of Florida International University suggest that distillate production would have increased only about 18% with use of a PFA film canopy, in which case the Dune still would have had an overall efficiency of around 30%, essentially the same as a conventional greenhouse solar still.

The electric power consumption for operating the still was calculated as follows. Power was needed for the following: a) operating the fan inside the still and the external blower inflating the canopy, b) operating the diaphragm pump to extract distillate from the canopy, c) operating the

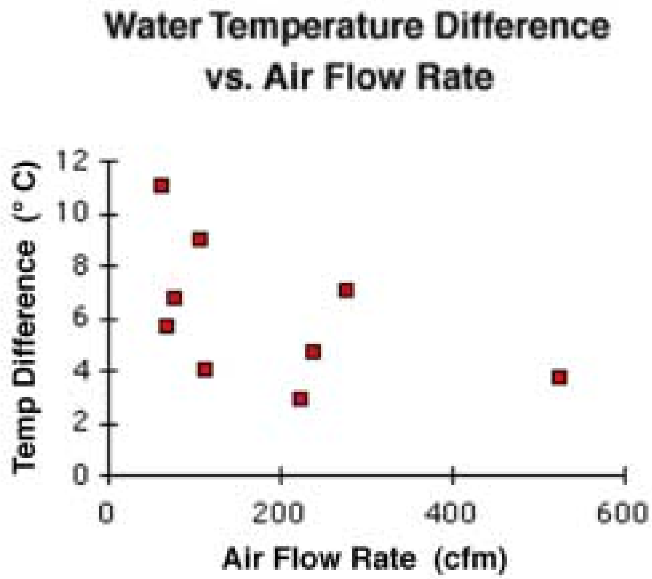

Figure 13. Water temperature difference between the hot and cold end of the still as a function of air flow circulation rate through the still.

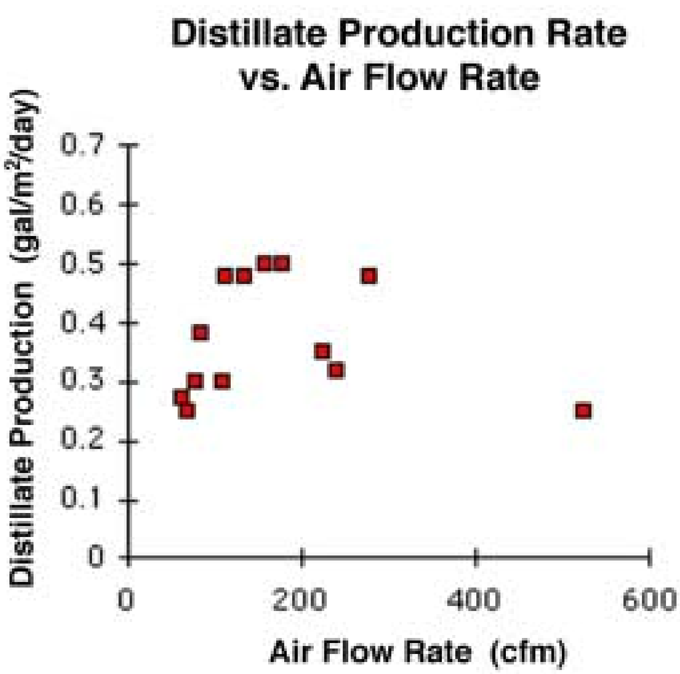

Figure 14. Distillate production rate as a function of air flow circulation rate through the still.

diaphragm pump to empty brine from the still's basin.

fan (180 cfm):	1.5 amps X 12.6 volts = 18.9 watts	X 24 hours =	455 watt-hours
blower:	0.14 amps X 12.6 volts = 1.7 watts	X 24 hours =	40 watt-hours
distillate pump: 4 watt-hours per gallon X 5.9 gallons/day =			24 watt-hours
feedstock water pumping: 6 watt-hours per gallon X 1 gallon/day =			6 watt-hours
		Total:	525 watt-hours/day

525 watt-hours/day ÷ 5.5 gallons/day = 95 watt-hours/gallon

The circulation fan could be run for 10 hours instead of 24 hours (e.g., 10 AM to 8 PM) without any decrease in distillate production, in which case the total daily power consumption would drop to 260 watt-hours for a power consumption of 47 watt-hours per gallon. This exceeds by over an order of magnitude the desired milestone energy consumption goal of 4 watt-hours per gallon.

Using the observed distillate production rate per unit area and the power consumption per gallon, it is possible to estimate a cost per gallon for the water for comparison to other technologies. The derivation of this cost is presented in Table A-I of Appendix A. Let us assume that the still produces water with an efficiency of 30% similar to a conventional greenhouse solar still. This assumes a somewhat higher production rate than would be achieved with the polyethylene version of the still, but which would be possible if the canopy was fabricated of PFA Teflon film. Given that the San Joaquin Valley of California has an average daily insolation of 5.2 kWh/m^2, A still operating at 30% efficiency would produce 0.66 gallons per m^2. Hence for a plant producing 143,000 gallons per day (160 acre-feet per year) the Dune Solar Still farm would need to have a total area of 216,700 m^2, or 52.6 acres. Given an estimated construction cost of \$112.5/m^2, the total plant cost would be \$32,175,000. This would entail an annual financing cost of \$2,224,000. Assuming a power consumption of 39 watt-hours per gallon, a Dune still producing 143,000 gallons/day would require 2,036,000 kWhr/yr at a cost of \$254,000/yr. Adding in the annual operating cost of \$150,000 would bring the total annual cost to \$2,628,000, giving a water cost per acre-foot of \$16,400.

By comparison, a conventional greenhouse solar still, which would produce water at approximately the same rate, would be less expensive to construct and would have essentially no electrical power cost. So its water cost would be somewhat less at \$12,700/AF. A reverse osmosis desalinator, however, would be far less expensive than either of these alternatives, its water cost being estimated to be only about \$1000/AF.

b) Dune Solar Still with Polyethylene Film Canopy and Continuous Hot Feedstock Water Input

The Dune Solar Still with a polyethylene canopy was modified so that it would be continuously supplied with externally heated feedstock water, drawn from the cold end of the still, heated in a tankless water heater, and then discharged at a controlled temperature at the hot end of the still. Experimentation with and testing of this arrangement was carried out from November 4th through November 11th. Figures 15 and 16 plot temperature gradients developed along the length of the still on November 7th at 12 noon and at 7 PM. Water temperature typically had a temperature differential of 8 to 9° C from the hot to the cold end of the still. Temperature differentials in the air ducts were lower, by about 5 to 7° C in the lower air duct and

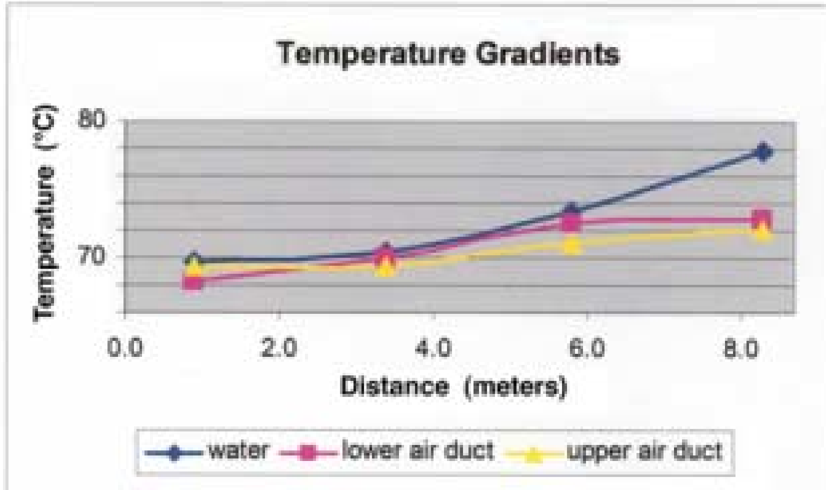

Figure 15. Temperature gradients developed along the length of the still at 12 noon on November 7th with externally heated feedstock water being continuously circulated through the still. Gradients plotted are for the feedstock water, lower air duct, and upper air duct.

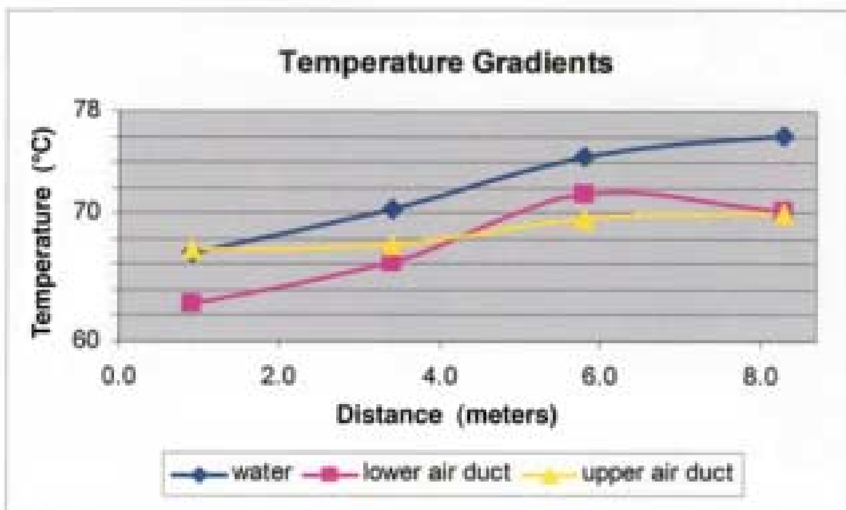

Figure 16. Temperature gradients developed along the length of the still at 7 PM on November 7th with externally heated feedstock water being continuously circulated through the still. Gradients plotted are for the feedstock water, lower air duct, and upper air duct.

by 3° C in the upper air duct. Unlike the version heated by solar energy alone, air temperature in the upper air duct was generally less than that in the lower air duct. So a temperature inversion did not develop and as a result heat would not have been recycled back to the feedstock reservoir.

Solar energy made up a small fraction of the total heat input to the still, with about 90% coming from the externally heated feedstock water being circulated through the still; see Table II (last column). In tests where the Dune still was heated exclusively by solar energy, solar energy

Table II
Distillate Production for the Dune Solar Still with Polyethylene Film Canopy and Hot Feedstock Input

Date	Water Produced ($gal/m^2/day$)	Energy Effic. (%)	Air Flow (cfm)	Hot Inlet Water T (° C)	Outlet Water T (° C)	Water ΔT (° C)	Water Flowrate (lt/min)	Ratio of solar to auxiliary
11/4 - 5	1.6	18	230	72.8	60	12.8	7.8	16.5%
11/5- 6	3.2	38.7	220	73.3 / 80.6	60.9/66.7	12.4/13.9	7.7/7.8	11.5%
11/6-7	1.5	20	256	80.5	67.7	12.8	7.8	8.8%
11/ 7-8	2.0	26	140	80.5	67.1	13.4	7.4	4.6%
11/8-9	2.4	26	122	80.7	65.1	15.6	7.3	8.7%
11/9-11	1.4	23	100	80.5	64.2	16.3	4.45	13.2%
Average:	2.0	25.3						

absorbed by the polyethylene film canopy could have contributed heat to the upper air passage and could explain why the upper air duct temperature in those tests had a higher temperature than the air in the lower air duct. In the present tests, this solar heating contribution would have been much less significant which could explain why the temperature inversion was not seen here. Nevertheless solar heating did produce a rise in the still's temperature. Comparing Figures 15 and 16, we see that at noon the still's s water temperature was about 2° C warmer.

By maintaining the water continually hot with a continuous flow through of heated feedstock, the still was able to distill water both day and night rather than just during midday as would be the case where the still was operated on solar energy alone. As a result, the still's water production rate increased considerably, averaging about 2 $gal/m^2/day$; see second column in Table II. But this was less than the 2.5 $gal/m^2/day$ milestone goal set for the Dune Solar Still operating on solar energy alone. These results dispel earlier hopes that the Dune Solar Still might function as a multi-effect solar still and that if operated continuously to desalinate geothermal water it might have been able to produce 20 gallons or more per square meter per day. These tests show that it in fact produces about an order of magnitude less water than had been hoped.

The third column in Table II lists the still's distillation efficiency. This averaged about 25%, about the same result as when the still was powered by solar energy alone. Again this may be compared with the efficiency of a passive greenhouse solar still which is about 30% efficient. This test determined that even when operating at higher temperatures the still's efficiency did not improve, and that it continued to function as a single-effect still, rather than as a multi-effect still, without any sign of recuperating and reusing its heat of condensation.

The efficiency of the still was calculated by taking the heat of vaporization of the distilled water that was produced in a given day and dividing it by the total thermal energy that entered the still during that time. In this case the total thermal energy input would include both the solar radiation incident on the still and the heat entering the still through recirculation and heating of its feedstock water. Solar radiation falling on the still was estimated from the CIMIS weather station data with the radiation values from noon until sunset being reduced by 50% to take into account the effect of shading on the still by two pine trees at the southwest corner of the test site. Shading was substantially more than for the tests carried out a month earlier. Heat entering the still from the heated feedstock water was calculated by measuring the rate at which feedstock water was circulated through the external heater, multiplying by the water's heat capacity and by its temperature difference, the temperature entering the still minus temperature exiting the still.

This version of the Dune Solar Still is estimated to consume 53 whrs per gallon, which is over ten times higher than the milestone goal of 4 whrs per gallon. The blower for inflating the canopy consumed 1.8 watts, the fan circulating air in the still consumed 9.2 watts, and the feedstock pump circulating water through the water heater consumed 31 watts, giving a total consumption of 42 watts or 1008 watt hours per day. Dividing this by the average distillate production of about 19 gallons per day gives 53 whrs/gal. Energy for heating the feedstock water is not included since it is assumed that this is a free resource (e.g., geothermally heated water). In the event that the still could be designed to use gravity flow for its feedstock water throughput, the total energy consumption would drop to 14 whrs/gal, which is still several times higher than the milestone goal.

Table A-II of Appendix A derives the water cost for the case in which the Dune Solar Still is designed to desalinate geothermal water on a continuous 24 hour operation. Feedstock water is assumed to flow through the still without the need for pumps. In this case the water cost calculates to be $4,500/AF which is still more expensive than the reverse osmosis alternative of $1,000/AF and slightly more expensive than the passive solar still alternative of $3,000/AF.

c) Dune Solar Still with a Polycarbonate Roof

Experimentation and testing of the Dune Solar Still with a polycarbonate roof were carried out from August 19th to 30th. Figures A-28 through A-30 of Appendix A show the diurnal temperature variations at four locations along the length of the still measured on August 25th, measured in the feedstock water pool (Figure A-28), lower air duct (Figure A-29), and upper air duct (Figure A-30). These curves may be compared with the level of solar insolation marked by the x's. Ambient air temperature on August 25th ranged from a low of 16° C at 6 AM to a maximum of 31° C at 4 PM. Wind speed averaged about 1 meter per second. The still's fans were circulating air through the air ducts at a rate of 60 cfm.

Figures 17 and 18 plot the temperature gradients measured along the length of the still at 12:07 PM and 5:37 PM. Gradients are marked as follows: the feedstock water pool temperature (blue), lower air duct temperature (red), and upper air duct temperature (yellow). Note that at 12:07 PM there is no gradient in the feedstock pool and the gradient in the lower and upper air ducts are negative, that is air moving down the lower air duct would cool rather than warm and

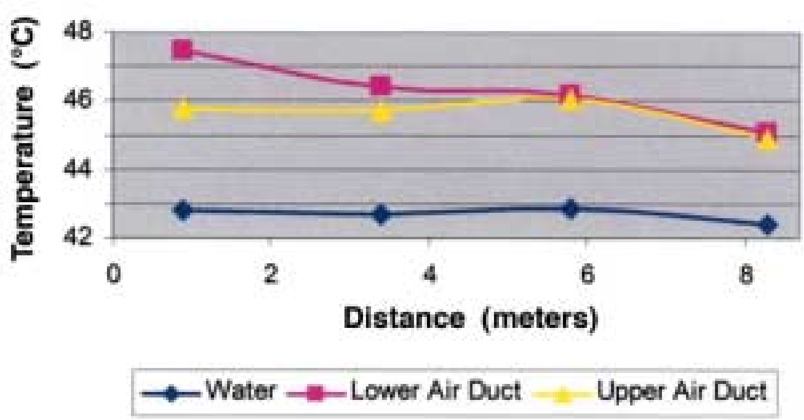

Figure 17. Temperature gradients along the length of the still at 12:07 PM.

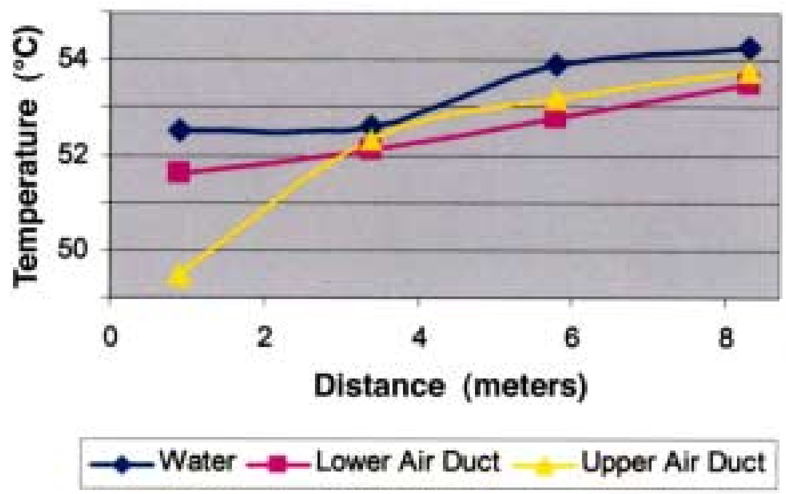

Figure 18. Temperature gradients along the length of the still at 5:37 PM.

hence would not evaporate water. Later in the day, as the still warms up further, these gradients become positive. But still they are rather modest. At 5:37 PM the feedstock water achieved a temperature difference of only about 1.7° C along the length of the still. The air temperature in the lower and upper air ducts showed a similar temperature differential with the exception of a strong drop in the upper air duct temperature at the cool end of the still. Without being able to generate a substantial positive temperature gradient along its length, this version of the still understandably performed poorer than the version with the inflatable polyethylene canopy. Between August 21st and 25th, the polycarbonate version produced an average of 0.35 gal/m^2/day.

The power consumption per gallon of water produced by this version of the Dune still is estimated to be 26 watt-hours per gallon:

fan (62 cfm): 0.5 amps X 6.4 volts = 3.2 watts	X 24 hours =	77 watt-hours
distillate pump: 4 watt-hours per gallon X 3.6 gallons/day =		14.4 watt-hours
feedstock water pumping: 6 watt-hours per gallon X 0.6 gallon/day =		3.6 watt-hours
	Total:	95 watt-hours/day

95 watt-hours/day ÷ 3.6 gallons/day = 26 watt-hours/gallon

A study of the temperature variation of this polycarbonate version of the Dune Solar Still showed that its air ducts developed negative temperature gradients during a relatively large percentage of its diurnal cycle, as compared to what was observed for the polyethylene canopy version of the still. For example, taking the degree Centegrade temperature difference for the two ends of the upper air duct and summing up these temperature differences *for the minutes when the gradient was positive*, gives a total of 1440 °C-minutes. Summing up the total when the gradient was negative gives a total of -840 °C-minutes, hence a positive-to-negative ratio of 1.7:1. If we do the same for the Dune Solar Still operating with a polyethylene canopy, we get 3600 °C-minutes for the sum of the positive gradients and -90 °C-minutes for the sum of the negative gradients, giving a positive-to-negative ratio of 40:1. So the polyethylene version of the still established favorable conditions for desalination over a much longer period of its diurnal cycle and this would explain the difference in performance of the two still constructions.

Increasing the fan speed made matters worse. For example, on October 30th, the fan speed was increased from 62 to 115 cfm. At 11 AM the upper air duct was observed to have a negative thermal gradient of a few tenths of a degree, 48.6° C at the fan end and 48.2° C at the opposite end. At 3 PM the thermal gradient was still negative with 57.3° C at the fan end and 57.0° C at the opposite end. At 10:20 AM on September 1st the gradient was again relatively flat with 38.0° C at the fan end and 38.1° C at the opposite end.

It is not clear why the polycarbonate version had negative temperature gradients so much of the time. Perhaps it is because its roof reflected more sunlight due to droplet formation on the inner polycarbonate surface, or perhaps it is because the polycarbonate absorbed more energy than the polyethylene film and added this energy to the upper air duct. For example note that when the gradient is negative, the temperature in the water pool is substantially cooler than in the air ducts, whereas when the gradient is positive, the water pool is instead warmer than the air duct temperature. Comparing to Figure 12 which shows strong positive temperature gradients for the polyethylene version of the still, we see that the feedstock water temperature is slightly warmer than the air duct temperature, although at the cooler end of the still the upper air duct temperature slightly exceeds its temperature, which is good.

The distillation efficiency of the polycarbonate version of the Dune Solar Still was calculated to be only 11.7%, or almost one third of that of a greenhouse solar still. Solar insolation during this period averaged about 7,000 watt hours/m^2/day, and since the still had a footprint area of 10.3 m^2, the total daily solar energy input calculates to 6.3 X 10^7 calories. Comparing this with an average distillate production of 3.6 gallons per day, or a heat of vaporization of 7.4 X 10^6 calories, gives an efficiency of 11.7%. So, we find no advantage to pursuing this polycarbonate roof design over the polyethylene film design.

Project Outcomes

Project outcomes were as follows:

1) Initially, the Starburst Foundation was based in upstate New York. But to carry out this research project an adequate test site in an arid southwestern U.S. location had to be found. Efforts were begun in January to locate an adequate site for the project. Sites in New Mexico, Arizona, and California were investigated. Finally, in early February, discussions were begun with representatives of the California Water Institute in Fresno, California subcontract their facilities for the research project and to provide needed personnel. It was not until June that a contract was signed specifying the relationship between the Starburst Foundation and CWI/California State University Fresno Foundation.

   The Starburst Foundation hired only one person for the project, the project's principle investigator. All other personnel working on the project at the CWI test site were employees of CWI. They were scheduled to work on the project at times when their help was needed, particularly during the first five or six weeks during which time the test site and still were being constructed. California Water Institute provided office space in the office building adjacent to the test site. This was occupied in mid June. Supplies for the project were being purchased as early as April and continued throughout the course of the project.

   The entire site was enclosed within a rented chain link fence. Instead of erecting a shed at the test site, the Foundation instead purchased a used RV trailer for a comparable price. This had the advantage of being easily moved at the end of the project. It also provided excellent facilities to store the instruments and tools as well as space to work in out of the sun for doing shop work. Its stove and sink facilities were also useful for carrying out thermistor calibration operations. Moreover its battery provided an excellent source of 12 volt DC power for running the solar still.

2) Working sketches of the Dune Solar Still were prepared. A scale model was prepared of one end of the still's polyethylene film canopy and a plastic film fabricating company was subcontracted to fabricate a prototype canopy. The canopy consisted of three layers of polyethylene film about 5' X 29' heat sealed together to form an elongated bag. When tests were begun on the still at the end of July, it was discovered that the canopy's heat seals had come apart in four places. So the subcontractor had to fabricate a new canopy. This was redesigned to include edge flaps for fastening the canopy to the bottom of the still's basin.

   While the canopy was being fabricated, the base of the solar still was constructed along with its solar absorbing lining. Adjoining pump and tank equipment needed to operate the still was also constructed. Due to delays in securing a contract agreement with California Water Institute for use of their test facilities, construction on the project did not begin until mid June and the still was not assembled with its canopy and ready for testing until late July, which was a month and a half past the targeted completion date of mid June. At that point problems emerged with an effective method to anchor the canopy and with separation of the canopy's heat seals. Then there were further delays in getting a new canopy fabricated by the subcontractor. So actual testing of the polyethylene canopy version of the still was not able to begin until the middle of September, three months past the targeted date.

3) As a result of the project delays mentioned above, testing began almost three months after the solstice. So we were not able to evaluate the still's performance under summer season conditions when it would have yielded its best performance. Even so, the still did not perform nearly as well as had been expected. Its daily distillate production was not found to meet the suboptimal season milestone. Production measured in late September (9/27 - 9/30) with the still heated solely by solar energy was found to average about 0.5 gallons/m^2/day, or five times lower than the suboptimal season milestone goal. By using solar insolation data for Fresno, California, it was possible to translate the water production rate into a gained output rate (GOR) efficiency for the still. This was calculated to average around 25%. This may be compared to a conventional single effect solar still which has an efficiency typically of 30%.

   The still also failed to meet the energy consumption milestone for power consumed per gallon of distillate produced. Daily power consumption of the still was measured, as was the daily amount of distillate that was produced. In cases where the still was heated solely by solar energy, in one example this ratio was found to be approximately 47 watt-hours per gallon of produced distillate, which is equivalent to about 15,300 kilowatt hours per acre-foot of water produced (kWh/AF). This is about 12 times higher than the milestone of 4 watt hours per gallon (1300 kWh/AF). By comparison, a 50,000 AF/yr reverse osmosis plant would consume about 3,600 kWh/AF and a 5 AF/yr R.O. would plant consume about 13,000 kWh/AF. If fabricated with a PFA film canopy, this power consumption per gallon is projected to drop about 20% to 39 watt-hours per gallon.

   Replacing the fresh feedstock water with saline feedstock water would not have changed the still's performance efficiency. So, since the still had failed its milestone goals, it was decided not to carry out additional tests using saline feedstock water.

4) Since the polyethylene version of the Dune still failed to meet the water production and energy consumption goals, it was determined that it would be pointless to proceed further on the

project to fabricate a PFA Teflon film canopy for the still. Pyroheliometer tests were carried out on solar transmission through 3 layers of 6 mil polyethylene film for comparison to solar transmission through 3 layers of 2 mil PFA Teflon film. It was determined that the latter transmitted about 30% more solar energy. But even if the still were to produce 30% more water as a result of receiving more solar energy, its daily water production rate and energy consumption per gallon would nevertheless again have fallen well below the suboptimal season milestones set for the polyethylene version.

5) A PFA film version of the canopy was not fabricated for the reason stated in 4) above, so tests that had been planned for this version of the still were canceled.

6) We determined that our initial solar still design was functional and that a still built according to this design would function properly to distill water. Hence we do not see any reason to change our initial estimate of the square meter construction cost of $\$113/m^2$. However, since the water production per square meter fell far below our previous expectations, our projected cost of $490 per acre-foot of produced distillate is no longer supported. The projected output of 0.66 gallons per square meter per day for the Dune Solar Still outfitted with a PFA Teflon film canopy and its high power consumption of 39 watt-hours per gallon, implies a very high cost per gallon of distillate of about $16,400/AF, far in excess of our original cost goal.

7) Tests were also carried out in which a version of the Dune Solar Still was built with a twin-wall polycarbonate sheet roof instead of a polyethylene film roof. However, this did not prove to be an effective design. Its performance was distinctly poorer than the polyethylene film canopy design. The still was unable to generate a temperature difference along the length of its evaporator and condenser air ducts, the temperature difference being either nonexistent or in some cases the reverse of what it should have been. Although this solar still design did have a vertical temperature gradient such that its upper condenser air duct was cooler than its lower evaporator air duct. As a result of its nonexistent lengthwise thermal gradient, the still had a relatively low water production output, averaging about 0.35 gallons/m^2/day at the end of August. This was over 7 times lower than the suboptimal season milestone. Power consumption was 26 watts per gallon (8,500 kWh/AF) which was almost 7 times higher than the set milestone goal. The distillation efficiency of the polycarbonate version was calculated to be very low, about 12%.

8) Tests were also carried out in which the Dune Solar Still prototype with a polyethylene canopy was continually supplied with feedstock water from an external heat source. This allowed the performance of the still to be checked in the instance where it would receive its saline feedstock water from a geothermal water source and also allowed the performance of the still to be checked at higher water temperatures such as those that might be achieved during mid summer months. When continuously supplied with water at a temperature of 177° F (80° C), the still's water production output increased dramatically, averaging a daily production rate of 2 gallons/m^2/day, or about 80% of the 2.5 gallons/m^2/day milestone. But its efficiency averaged about 25%, indicating that its thermal efficiency was somewhat less than that of a conventional greenhouse solar still. The average distillation efficiency of the Dune still boosted with externally heated feedstock water was about the same as that of the Dune still operating on solar energy alone.

The power consumption of this hot feedstock version of the still calculated to be about 53 watt hours per gallon (17,300 kWh/AF). This value is higher than in the version heated by solar energy alone because feedstock must be continuously circulated through the still from the external heat source. If this pumping requirement could be eliminated by use of gravity flow through the still the power requirement would drop to about 14 watt hours per gallon (4600 kWh/AF) which still would exceed the set milestone target by over three fold.

9) Additional information about the Dune Solar Still design were discovered through computer simulations of the Dune Solar Still design performed by Professor Yong Tao of Florida International University. These indicated that there would be no benefit to increasing the length of the still. For example, simulations showed that, compared with an 8.77 meter long still, a 20 meter long still had a 1.3% lower condensation rate per meter area. Also simulations showed that increasing the upper air duct cross section to produce a 50% reduction in air flow velocity resulted in about a 1% increase in condensation rate per unit still area. Simulations also confirmed that at times of low insolation a lower fan speed will result in slightly higher distillation rates. For example an increase from 150 to 350 cfm at 5 PM resulted in a 2% decline in distillation rate.

Conclusions

1) The project successfully located a test site, set up an office space, and erected an instrument trailer and surrounding fencing. It also successfully found adequate personnel for construction and testing of the still, and purchased the needed equipment and supplies to carry out the project.

2) The project successfully prepared working sketches of the still and fabricated an operational prototype solar water still having a polyethylene film canopy.

3) The project successfully tested the Dune Solar Still constructed with a polyethylene film canopy. However, it is concluded from these tests that the still performed poorly in comparison with existing desalination technologies in that both its water production rate per unit area and energy consumption per gallon of distillate were much lower than the milestone goals.

4) Fabrication of a version of the Dune Solar Still using a PFA Teflon film canopy was not justified since its rate of water distillation would have been only about 20% greater than that of the tested prototype which used a polyethylene canopy. So, a PFA version of the still would have failed to meet the milestone goals for water production and energy consumption.

5) It was decided that it was not worth testing the Dune Solar Still fabricated with a PFA Teflon film canopy for the reasons stated in 4) above.

6) The Dune Solar Still is not cost competitive in comparison with other desalination technologies. The cost per gallon of distillate produced by a Dune Solar Still made with a PFA film would be about $16,800/AF, which is high compared with the cost of water produced by a reverse osmosis desalinator ($1,000/AF) or by a conventional greenhouse solar still ($12,700/AF).

7) A version of the Dune Solar Still built with a twin-wall polycarbonate sheet roof did not perform as well as the version of the Dune Solar Still built with a polyethylene film canopy. Hence this version also is not cost competitive in comparison with other desalination technologies.

8) When continually supplied with feedstock water from an external heat source, the Dune Solar Still prototype with a polyethylene canopy was found to increase its water production output per unit area by about four fold in comparison to the case where the still's feedstock water was heated by solar energy alone. However, the cost per gallon of water would be almost five

times higher than for reverse osmosis desalination, $4,500/AF as compared with $1,000/AF. Moreover a conventional greenhouse solar still continuously supplied with externally heated feedstock water could have about an 80% higher water production output as the Dune Solar Still, and without the fan and blower power expense. So it would produce water at a somewhat lower cost of $3,000/AF.

9) In overview, the initial belief that the Dune Solar Still would function as a multi-effect solar still was unfounded. If constructed with a high transparency film, such as PFA, it would have functioned no more efficiently than a conventional single-effect greenhouse solar still.

10) It would also be impractical to use the Dune Solar Still as an alternative to solar pond evaporation as a way of desalinating irrigation run-off water since the Dune Solar Still (version made with a PFA Teflon canopy powered by solar heating alone) plus its brine evaporation pond would consume about 9% of the agricultural land area. A conventional solar evaporation pond, on the other hand, would require slightly more land area, about 10%, but would have a much lower construction cost.

Recommendations

This study does not recommend that further research be undertaken into this type of solar still design.

Public Benefits to California

No public benefits to California are seen for further development of the Dune Solar Still design.

California Energy Commission Energy Innovations Small Grant (EISG) Program **PROJECT DEVELOPMENT STATUS**	[redacted]

Answer each question below and provide brief comments where appropriate to clarify status. If you are filling out this form in MS Word the comment block will expand to accommodate inserted text.

Please Identify yourself, and your project: **PI Name** ___________________**Grant #** ___________	
[redacted]	
Overall Status	
Questions	**Comments:**
1) Do you consider that this research project proved the feasibility of your concept?	*Briefly state why.* No. The research shows that the still's daily water output per unit area was only a fraction of the desired milestone goal. Also its electric power consumption per gallon of water produced was over 10 times higher than the desired milestone goal.
2) Do you intend to continue this development effort towards commercialization?	*If NO, indicate why and answer only those questions below that are still relevant.* No, due to the inefficiency of the still, its low daily water output per unit area and high power consumption, the cost per gallon of its distilled water would be considerably higher than that of other desalination technologies. So there would be no market for this type of still.
Engineering/Technical	
3) What are the key remaining technical or engineering obstacles that prevent product demonstration?	
4) Have you defined a development path from where you are to product demonstration?	
5) How many years are required to complete product development and demonstration?	
6) How much money is required to complete engineering development and demonstration?	*Do not include commercialization costs such as tooling.*
7) Do you have an engineering requirements specification for your potential product?	*This specification details engineering and manufacturing needs such as tolerances, materials, cost, stress etc. If NO indicate when you expect to have it completed.*
Marketing	
8) What market does your concept serve?	*Residential, commercial, industrial, other.*
9) Is there a proven market need?	*If YES, what sources did you use to determine market need?*

10) Have you surveyed potential end users for interest in your product?	*If YES, the results of the survey should be discussed in the Final Report.*
11) Have you performed a market analysis that takes external factors into consideration?	*External factors include potential actions by competitors, other new technologies, or changes in regulations or laws that can impact market acceptance of your product?*
12) Have you compared your product with the competition in terms of cost, function, maintenance etc.?	Yes, based on this research, this desalination approach would be more costly than competing desalination technologies.
13) Have you identified any regulatory, institutional or legal barriers to product acceptance?	*If YES, how do you plan to overcome these barriers?*
14) What is the size of the potential market in California?	*Identify the sources used to assess market size.*
15) Have you clearly identified the technology that can be patented?	*If NO, how do you propose to protect your intellectual property?*
16) Have you performed a patent search?	*If YES, was it a self-search or professional search and did you determine if your product infringes or appears to infringe on any other active or expired patent?*
17) Have you applied for patents?	*If YES, provide the number of applications.* Yes, but the applications were abandoned after it became clear that this solar still design fell short of initial expectations.
18) Have you secured any patents?	*If YES, provide the patent numbers assigned and indicate if they are generic or application patents.*
19) Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	*If YES, is it your intent to put the intellectual property into the public domain?*
Commercialization Path	
20) Can your organization develop and produce your product without partnering with another organization?	*If YES, indicate how you would accomplish that.* *If NO, indicate who would be the logical partners for development and manufacture of the product.*
21) Has an industrial or commercial company expressed interest in helping you take your technology to the market?	*If YES, are they a major player in the marketplace for your product?*
22) Have you developed a commercialization plan?	*If yes, has it been updated since completing your grant work?*
23) What are the commercialization risks?	*Risks are those factors particular to your concept that may delay or block commercialization.*
Financial Plan	
24) If you plan to continue development of your concept, do you have a plan for the required funding?	

25) Have you identified funding requirements for each of the development and commercialization phases?	
26) Have you received any follow-on funding or commitments to fund the follow-on work to this grant?	*If YES, indicate the sources and the amount.* *If NO, indicate any potential sources of follow-on funding.*
27) Have you identified milestones or key go/no go decision points in your financial plan?	
28) What are the financial risks?	
29) Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire?	*If YES, can you attach a non-proprietary version of that plan to your final report?*
Public Benefits	
30) What sectors will receive the greatest benefits as a result of your concept?	*Residential, commercial, industrial, the environment, other.*
31) Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	*Show all assumptions used in calculations.*
32) Does the proposed technology impact emissions from power generation?	*If YES, calculate the quantity in total tons per year or tons per year per relevant unit. Show all assumptions used in calculations.*
33) Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	*If YES, please specify.*
Competitive Analysis	
34) Identify the primary strengths of your technology with regard to the marketplace.	*Identify top 3.*
35) Identify the primary weaknesses of your technology with regard to the marketplace.	*Identify top 3.*
36) What characteristics (function, performance, cost etc.) distinguishes your product from that of your competitors?	
Development Assistance	
The EISG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.	
37) If selected, would you be interested in receiving development assistance?	*If YES, indicate the type of assistance that you believe would be most useful in attracting follow-on funding.*

Appendix A. Additional Diagrams, Photos, and Tables

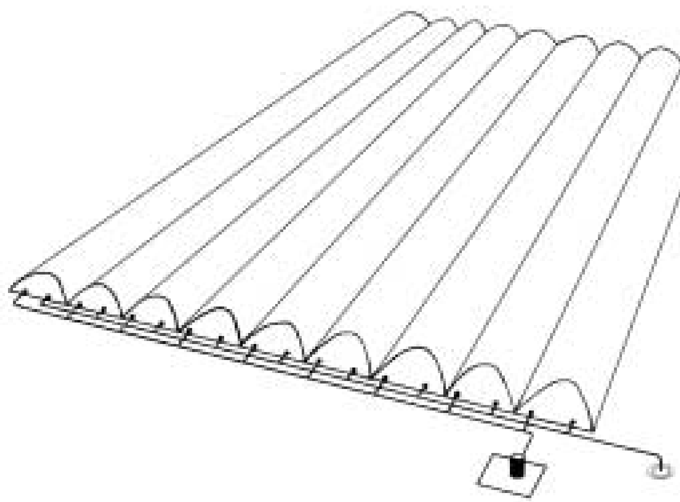

Figure A-1. Solar still farm for distilled water production.

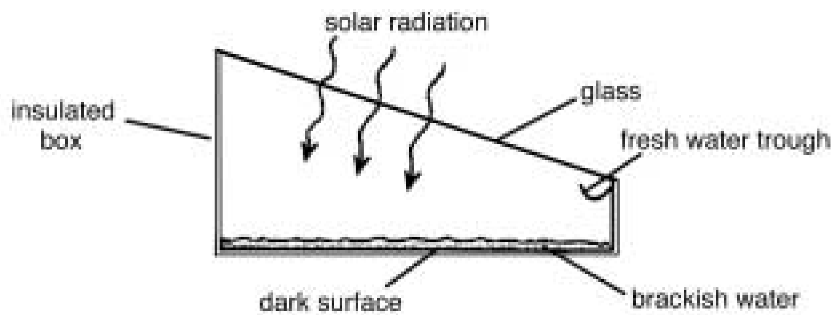

Figure A-2. A conventional greenhouse solar still.

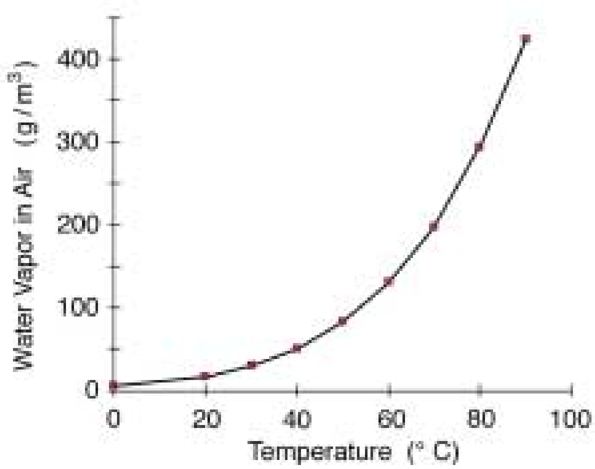

Figure A-3. Concentration of water vapor in saturated air showing a nonlinear increase with air temperature.

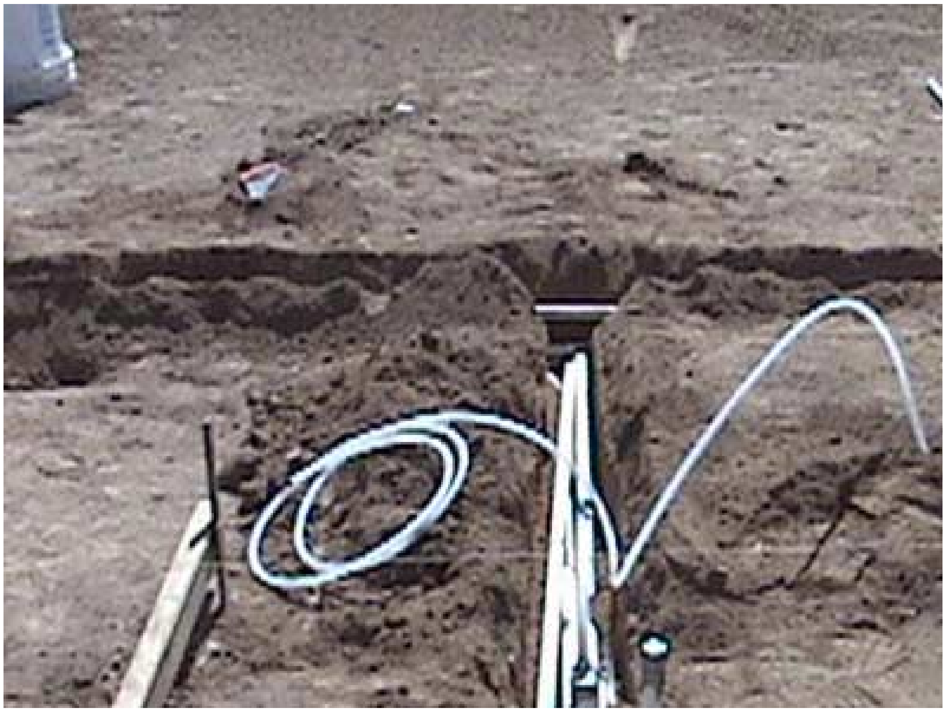
Figure A-4. Trenches are dug and pipe is laid to communicate with the bays of the still.


Figure A-5. Wooden frame aligned, secured and ready for concrete.

Figure A-6. Insulating concrete being trawled into the forms.

Figure A-7. Floor of still being sanded level after basin walls were installed.

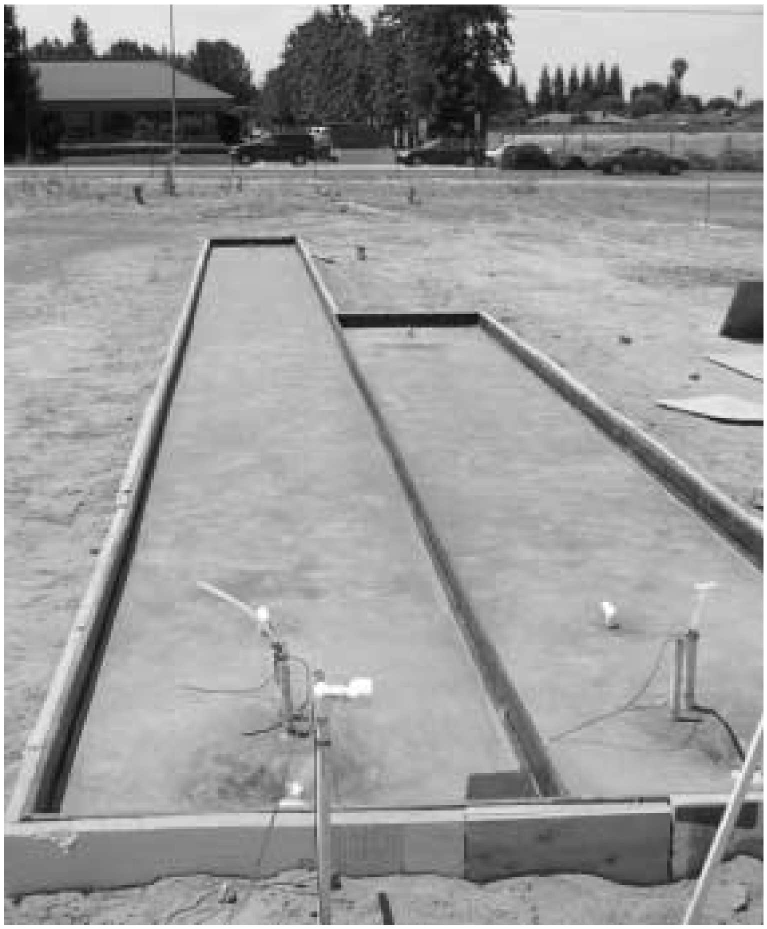

Figure A-8. The still basins completed and lined with 36 mil Hypalon® membrane. Dish depressions at one end of each basin contain drains plumbed to drain pipes. Vertical pipe seen in the foreground is one of two used to blow air into the still enclosure for inflating the still's transparent canopy. The 1/2 inch polyethylene tubes protruding from the PVC pipes will connect to Norprene tubes for evacuating distillate from the still's canopy.

Figure A-9. Water storage tanks and pump panel.

Figure A-10. Float switch positioned near drain well. Its (SPST) contacts close when the water level falls below its lower set point and open when the level rises above its upper set point 3 inches higher.

Figure A-11. Circuit breaker control box with its pump control relays. Lower left is the distillate water flow data logger and to the right are meters that measure the voltage and current to the pumps.

Figure A-12. The 15 gallon distillate measuring tank shown perched on top of the main water holding tank.

Figure A-13. Top view of a quarter scale model mock up of the polyethylene canopy. The foam arch inside the canopy simulates the partition for holding the still's air circulation fan.

Figure A-14. Side view of the canopy mock up mounted in a cardboard enclosure simulating the still's basin enclosure.

Figure A-15. Polyethylene film grip strips being attached to the edge of the basin.

Figure A-16. Aluminum snap-on strips along the basin sidewall are used to secure the canopy by gripping a polyethylene film flap running along the canopy's perimeter.

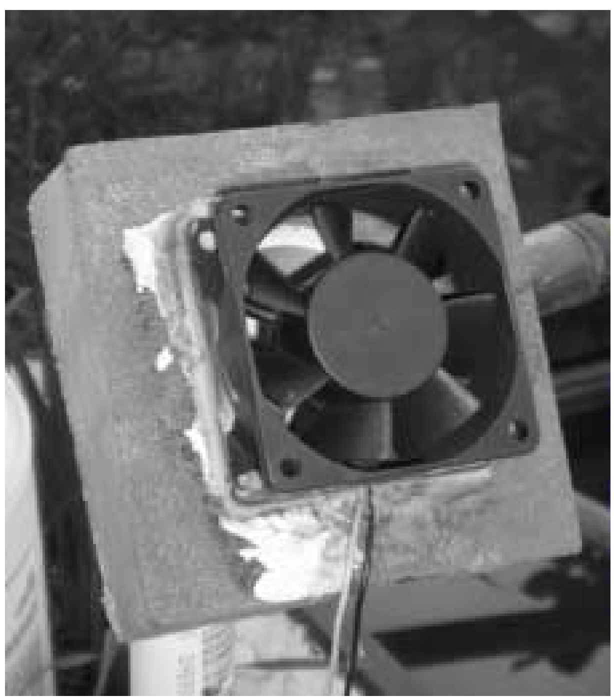

Figure A-17. Fan used to keep canopy inflated.

Figure A-18. Fan end of still with canopy in place and inflated.

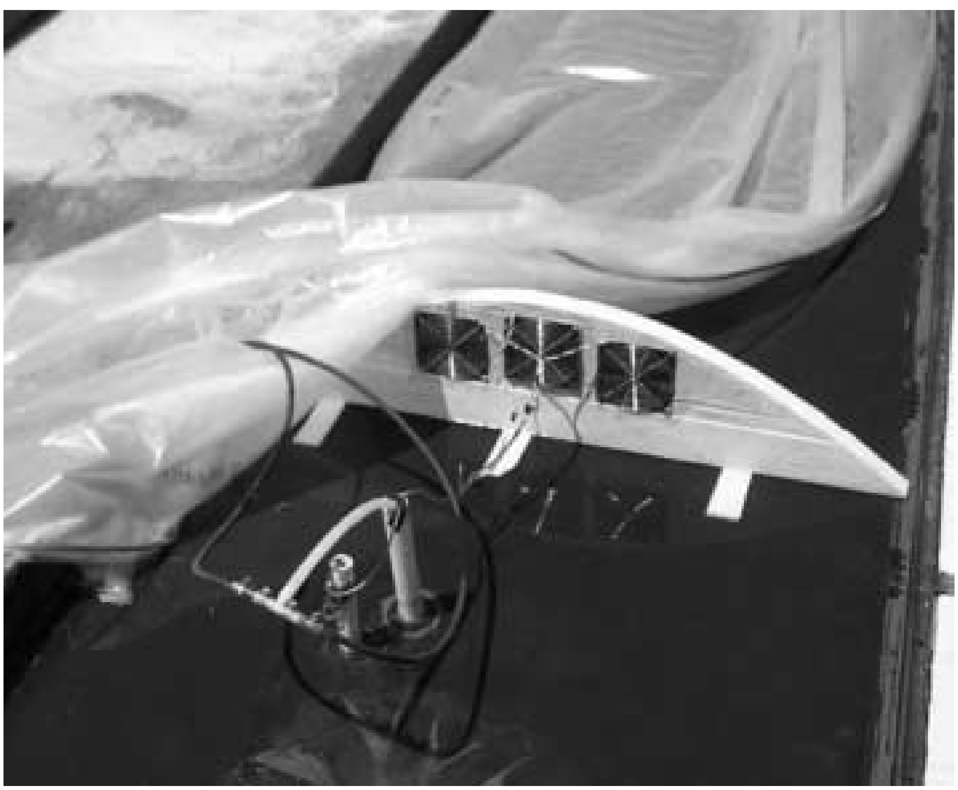

Figure A-19. The poly canopy pulled back to show the fan partition secured beneath the canopy at the still's cooler end.

Figure A-20. Feedstock water from the cool end of the still is pumped through the insulated rubber hose shown exiting the underground pump box.

Figure A-21. Feedstock water is heated in the Takagi tankless water heater (left) and is discharged into the hot end of the still.

Figure A-22. Edges of the still bay where feedstock water is exposed to the open air are insulated by pieces of foam insulation.

Figure A-23. The Dune Solar Still made with a twin wall polycarbonate sheet roof.

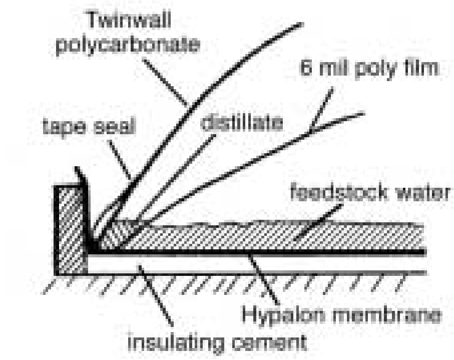

Figure A-24. Cross sectional view of one edge of the still.

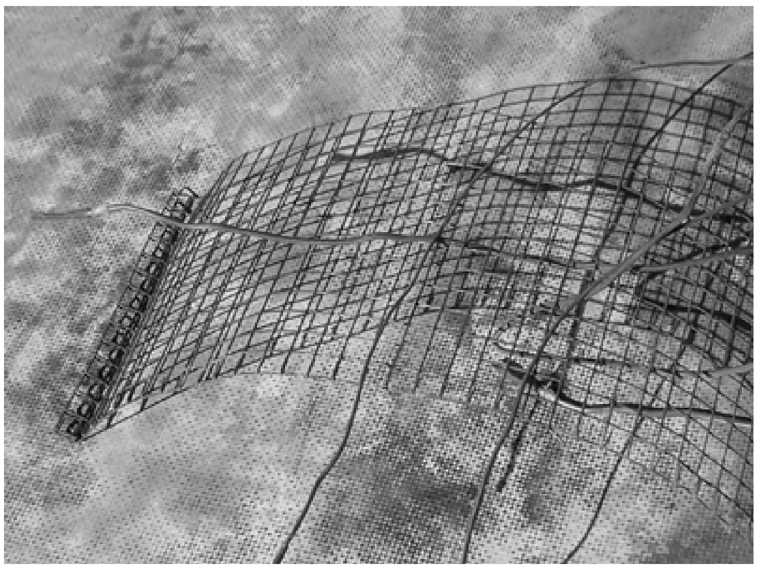

Figure A-25. Thermocouple leads and their wire mesh positioning support.

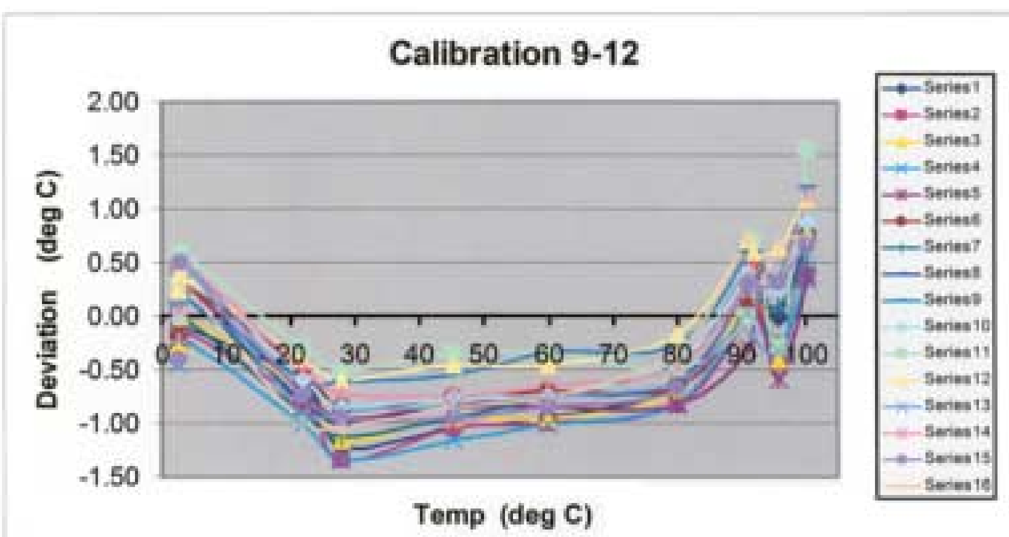

Figure A-26. Thermocouple calibration run done on September 12th on a temperature bath held at various temperatures between 0° C and 100° C.

Figure A-27. Anemometer probe placed near the fan intake to measure air speed.

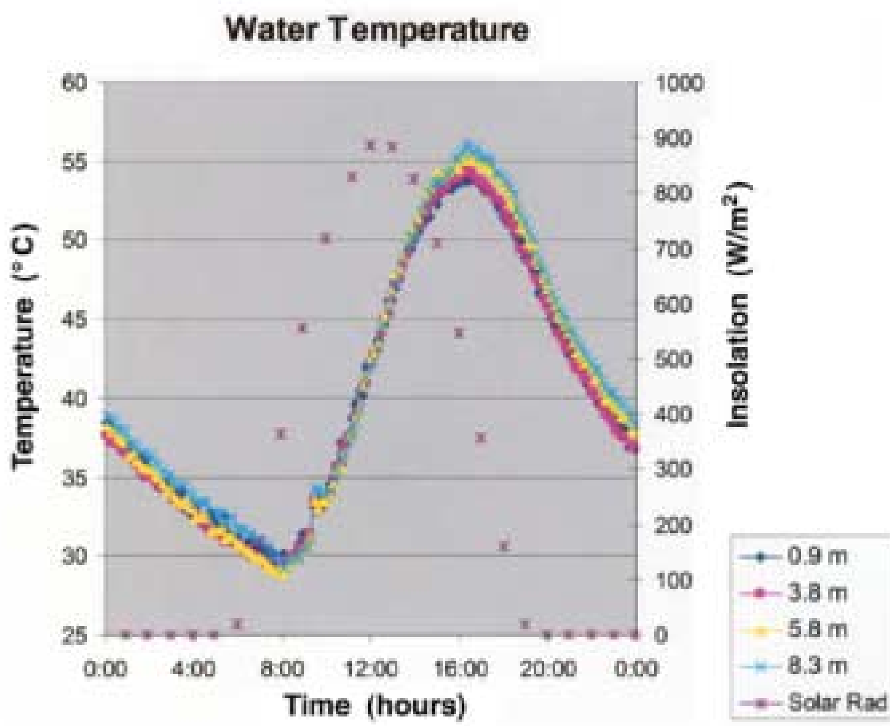

Figure A-28. Diurnal variation of feedstock water temperature along the length of the still made with a polycarbonate roof.

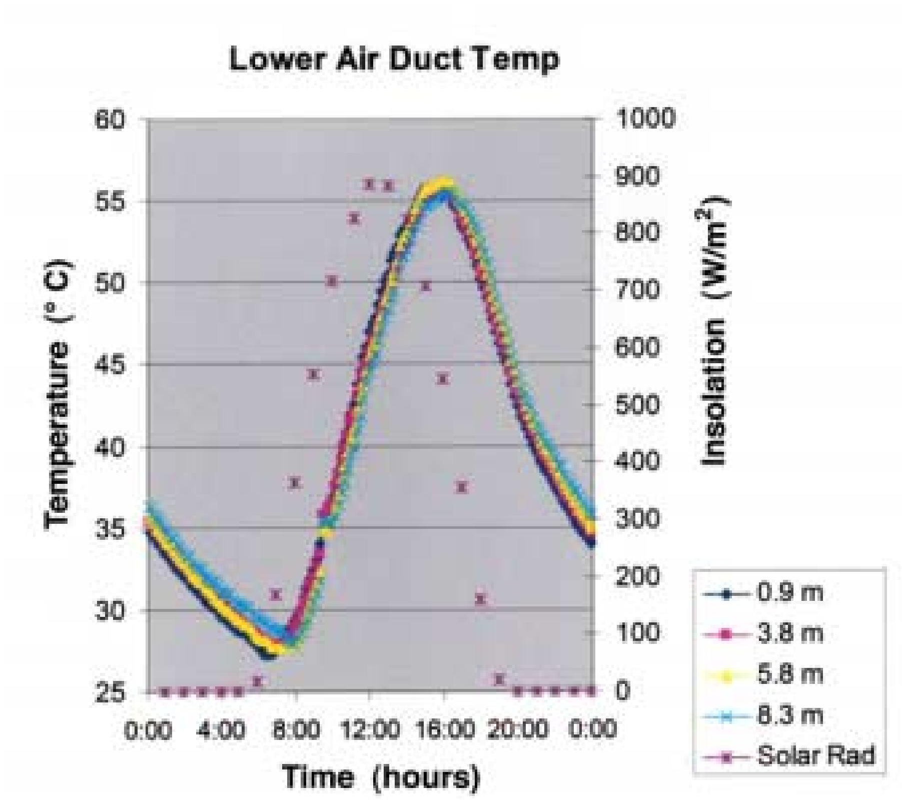

Figure A-29. Diurnal variation of lower air duct temperature along the length of the still made with a polycarbonate roof.

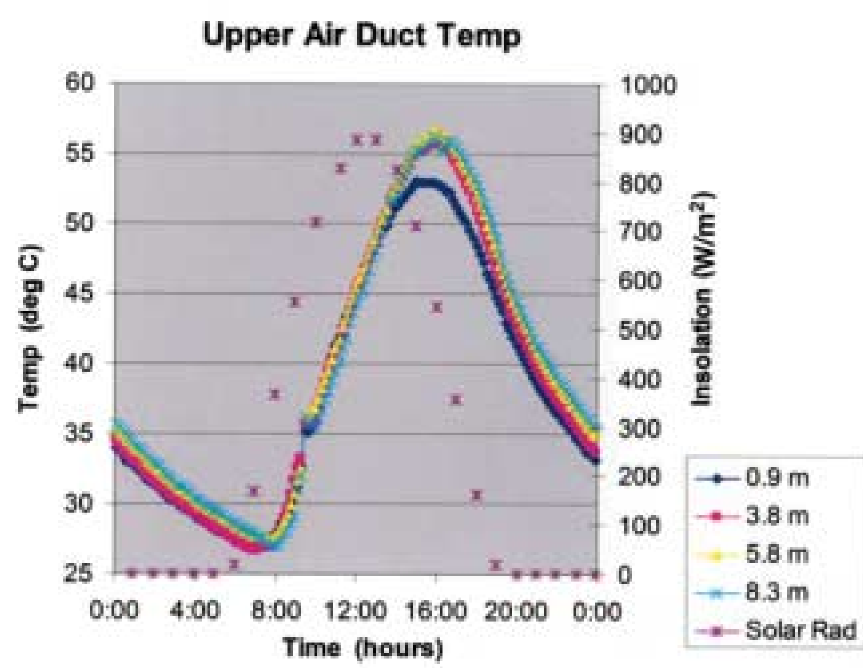

Figure A-30. Diurnal variation of upper air duct temperature along the length of the still made with a polycarbonate roof.

Table A-I
Water Cost for a 160 AF/yr Agricultural Drainage Water Desalting Plant (143,000 gallons/day)
(Size sufficient to reclaim irrigation run off from 640 acres of farm land; 30,000 TDS salinity is assumed)

	Reverse Osmosis Process	Dune Solar Still (entirely solar heated)	Conventional Solar Still (greenhouse type)
1) Capital cost of plant	$715,000	$32,175,000[b]	$27,170,000[b]
2) Amortization 30 year @ 5.6%/yr	$49,300 /yr[a]	$2,224,000/yr.	$1,878,000/yr.
3) Still land requirement Pond land requirement Total land requirement[d]	Still: (400 m^2) Pond: 22 acres (90,600 m^2) Total: 22 acres (91,000 m^2)	Still: 52.6 acres (286,000 m^2) Pond: 5.7 acres (23,500 m^2) Total: 58.3 acres (309.500 m^2)	Still: 52.6 acres (286,000 m^2) Pond: 5.7 acres (23,500 m^2) Total: 58.3 acres (309,500 m^2)
4) Power requirement	70 kw peak 570,000 kWhr/yr[e]	400 kw peak 2,036,000 kWhr/yr	None
5) Power cost[f]	$71,300/yr @ 12.5 ¢/kwhr	$254,000/yr @ 12.5 ¢/kwhr	None
6) Other operating costs	$35,200/yr[g]	$150,000 (includes $110,000 for replacement of 10% of still over 30 years)	$150,000 (includes $100,000 for replacement of 10% of still over 30 years)
7) Distillate production cost lines (2)+(5)+(6)	$156,000/yr	$2,628,000/yr.	$2,028,000/yr.
8) Total annual cost per acre foot of distillate	**$625/AF** not including pretreatment costs **$1000/AF** including pretreatment[h]	**$16,400/AF** @ 0.66 gpd/$m^2$	**$12,700/AF** @ 0.66 gpd/$m^2$
9) Solid waste disposal[i]	Yes, Pretreatment sludge waste disposal problem, plus: 16 metric tons/day of salt	16 metric tons/day of salt	16 metric tons/day of salt

Notes to Table A-I:

a) We assume an R. O. plant construction cost of $5/gal/day or $4465/AF/yr, similar to that stated for a 56,000 AF/yr seawater reverse osmosis plant proposed for Carlsbad, CA which uses power plant waste heat to boost productivity (source: J. Faria, California Dept. Water Resources, San Joaquin District). This is a very conservative estimate since we consider here a plant 350 times smaller, and R.O. plant costs are known to increase with decreasing plant size. But, since we consider water that is here three times less salty, the R.O. plant in the agricultural application should operate at a higher efficiency and not consume as much electrical power. So this cost figure should be fair for this comparison. F. Lopez (San Diego County Water Authority) says that amortization over 30 years at 5.6% is common. Using this rate, the finance charge would be $308/AF/yr. If instead amortized over 25 years at 6%, this would incur a higher finance charge of $345/AF/yr.

b) This assumes a solar still construction cost of $112.5/m^2 (see Table III) and a still productivity of 0.66 gallons per day per m^2 (30% GOR efficiency for a San Joaquin Valley location).

c) This assumes a solar still construction cost of $95/m^2 and a productivity of 0.66 gallons per day per m^2 of still area (30% GOR efficiency for a San Joaquin Valley location)..

d) The cost of land was not included in this estimate since the cost of land is low compared to the cost of constructing the desalinators. For example, land in the Red Rock Ranch area of California presently sells for about $2,800/acre.

e) This assumes a power consumption for R.O. desalination of 2.9 kWhr/m^3 (3600 kwhr/AF) (source: J. Faria, California Department of Water Resources San Joaquin District).

f) While a $0.08/kw-hr may be available to industry, when comparing to alternative green technologies which help to alleviate California's energy crisis it is better to compare to the power cost that a consumer would typically pay which is $0.125/kw-hr.

g) This includes the cost for R.O. element replacement ($80/AF) and the cost for chemicals, labor, and services ($140/AF) (source: J. Faria, California Dept. Water Resources, San Joaquin District).

h) Here we add $375/AF for R.O. water pretreatment costs to prevent membrane scaling and bio fowling. Some have quoted higher pretreatment costs. For example, based on an evaluation of the performance of an R.O. desalinator located in the San Joaquin Valley at Los Banos, CA, Hanna, et al. concluded that pretreatment costs added more than $1000/AF to the cost of water treatment in the case where the brine waste could be disposed of in Class II (nontoxic) evaporation ponds. Quinn, et al. estimate a cost of $560/AF for disposal of the waste brine coming from the Los Banos R.O. desalinator. Summarizing some of the above problems, the Evaporation Ponds report quotes Hanna, et al. who conclude: "the high cost of pretreatment, equipment, maintenance, power, and waste disposal makes [reverse osmosis] desalinization an unlikely option."

i) Regardless of which technology alternative is chosen, 16 metric tons per day of salt sludge will need to be disposed of. The cost of removing the salt from the evaporation pond, transporting it, and disposing of it is not included in the cost comparison. Just the transportation cost alone, trucking the salt 100 miles, would probably cost about $300 per day or $110,000/yr. However, it is possible that this waste could generate a revenue if used as fertilizer. Being rich in boron and selenium, some have suggested that it could be used to fertilize crops requiring these elements in areas where the soil is deficient in boron or selenium. It has also been suggested that, being rich in sodium sulfate, this waste could be used as a raw material for glass making.

Table A-II
Water Cost for 160 AF/yr Solar/Geothermal Desalination Plant Version (143,000 gallons/day)

	Reverse Osmosis Process	Dune Solar Still (multi-effect, advective)	Conventional Solar Still (greenhouse type)
1) Capital cost of plant	$715,000	$8,040,000	$5,548,000
2) Amortization 30 year @ 5.6%/yr	$49,300/yr [(a)]	$553,000/yr.	$381,700/yr.
3) Still land requirement Pond land requirement Total land requirement[(d)]	Still: (400 m^2) Pond: 22 acres (90,600 m^2) Total: 22 acres (91,000 m^2)	Still: 17.3 acres (71,500 m^2) Pond: 9.6 acres (40,000 m^2) Total: 23.7 acres (98,000 m^2)	Still: 14.1 acres (58,400 m^2) Pond: 9.6 acres (40,000 m^2) Total: 23.7 acres (98,000 m^2)
4) Power requirement	70 kw peak 570,000 kWhr/yr [(e)]	150 kw peak 730,000 kWhr/yr	
5) Power cost[(f)]	$71,300/yr @ 12.5 ¢/kwhr	$91,000/yr @ 12.5 ¢/kwhr	
6) Other operating costs	$35,200/yr [(g)]	$80,000 (includes $30,000 for replacement of 10% of still over 30 years)	$100,000 (includes $70,000 for replacement of 10% of still over 30 years)
7) Distillate production cost lines (2)+(5)+(6)	$156,000/yr	$724,000/yr.	$481,700/yr.
8) Total annual cost per acre foot of distillate	**$625/AF** not including pretreatment costs **$1000/AF** including pretreatment[(j)]	**$4,500/AF** @ 2 gpd/$m^2$	**$3,000/AF** @ 2.45 gpd/$m^2$
9) Solid waste disposal[(k)]	Yes, Pretreatment sludge waste disposal problem, plus: 16 metric tons/day of salt	16 metric tons/day of salt	16 metric tons/day of salt