A SIMPLIFIED TEST FOR

SOLAR WATER PURIFICATION

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ABSTRACT

Pure water is one of the most important resources the country has; however, as the demand for water increases, its availability is decreasing. Recent court actions to force states to export ground water graphically illustrate the competition for this diminishing resource. The depleting of the Ogallala aquifer and the accompanying loss of valuable irrigated farmland is another example of the serious pure water problems facing New Mexico and the country.

Vast quantities of brackish and salt water are available; however, the normal purifying techniques such as reverse osmosis, electrodialysis, and, to a minor extent, evaporating salt ponds are not sufficiently economical except where the demand outweighs price considerations.

In this project, "A Simplified Test for Solar Water Purification," conducted by the New Mexico Solar Energy Institute, on-hand equipment was used to determine if a solar-driven, low-pressure system would be technically and economically practical. This technique used a low-cost unglazed FAFCO solar panel as a heater during periods of insolation and as a vapor condenser during cooler periods of no insolation. It used a 30-gallon insulated hot water tank for water storage. The test sequence used domestic water in the tank to simulate brackish, gray, or salt water. Plumbing was added to allow solar heating of the water via thermosiphon and nocturnal low-pressure evaporation by means of a hydrostatic column of water.

Keywords: desalination processes, solar stills, *water purification, distillation, *wastewater treatment, radiation, energy, evaporation, *solar distillation

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JUSTIFICATION OF PROJECT

This project was to utilize an on-hand solar panel and an insulated water tank to check the theory of low-pressure, low-temperature, solar-driven water purification. Initial calculations had indicated that more raw water could be processed to fresh water per square foot of collector and at a lower cost per square foot of solar collector by this method than by solar evaporating ponds. The project was also to demonstrate a technique of water purification that did not require expensive energy such as electricity.

The project was justified on the basis of the very low cost it required to check a technique that could offer less initial cost, less operational cost, and less energy cost than present techniques of purifying brackish and salt water.

REVIEW OF METHODOLOGY

There are numerous techniques for purifying water, including:

Reverse Osmosis
Ultra Filtration
Ion Exchange
Activated Carbon
Filtration
Reverse Osmosis
Electrodialysis
Evaporation
Freezing

These systems in general are too costly and or too difficult to maintain for general use or for inexpensive purification of water. In most cases they also require expensive electrical energy. This simplified test for solar water purification used on-hand equipment to test a simple solar form of water purification.

Large-scale systems typically use reverse osmosis or electrodialysis to purify salt or brackish water. These systems require expensive electrical power to drive the processes. Solar energy has been used to fuel the electrical generation; however, these systems are very inefficient.

1. High-temperature thermal energy is required to drive thermal-electrical systems. High-temperature solar-thermal conversion is inefficient and very costly.
2. The thermal engines are relatively inefficient.

3. Mechanical to electrical conversion is relatively efficient but is a source of loss.
4. Direct conversion of solar to electrical by photovoltaics has been used, but equipment is expensive and very inefficient.
5. Thermoelectric conversion can be a two-stage solar-to-electrical process, but it is highly inefficient and costly.

Items 1, 2, and 3 are stages of the conversion of insolation into electrical energy for driving reverse osmosis or electrodialysis. The two techniques are comparable in costs over a 20-year period.

Solar-Powered Reverse Osmosis Cost Calculations

As extracted from a Boeing Engineering and Construction Company proposal to the American Gypsum Company in 1982, the efficiency of the conversion of insolation energy to heated fluid energy is about 58 percent (see item 1 in preceding section) and the Rankin engine is 10 percent to 20 percent efficient when working with solar-heated fluids (see item 2). The Boeing proposal cited 10.2 percent Rankin engine efficiency. The electric generator and pumps are a combined 65 percent efficient (see item 3). Overall efficiency then is 3.77 to 7.54 percent.

Reverse osmosis requires pressures of 500 pounds per square inch gram (psig), which convert to 1,153.8 feet of water head. The electrically driven reverse osmosis desalting plant being constructed near Yuma, Arizona, will process about 67,000 acre feet of water in a year, using 126 million kilowatt hours of electricity. One acre foot of water weighs 2.7 million pounds. The processed water then weighs 182 billion pounds. Raising this water to 1,153.8 feet of water head requires 210 x 10^{12} foot pounds of work. This converts to 79,090 megawatt hours of pumping per year. At 7.54 percent efficiency, the insolation energy required is 10.49 x 10^5 megawatt hours. Solar energy required to power the desalination of 67,000 acre feet (21,832 million gallons) of salt water is then 10.49 x 10^5 megawatt hours. Dividing megawatt hours by millions of gallons gives 48 watt-hours of insolation per gallon of pure water. This converts to 164 Btu of insolation per gallon of pure water at 20 percent Rankin engine efficiency and 328 Btu at 10 percent efficiency.

Desalination at the Yuma facility is projected to cost $470 million for processing about 21.8 billon gallons of water per year. Over a 20-year period, about 436 billion gallons will be processed at a cost of $1.078 per 1,000 gallons. The cost is expected to be very low because the water does not have to be potable.

Data from the Boeing proposal showed a capital cost of $8,601,700 to produce 2,757 megawatt hours of electricity per year (2,757,000 kilowatt hours). The Yuma desalination system requires 126 megawatt hours of electricity per year. Ratioing the two and equating gives the following: cost of Yuma solarization/126,000 megawatt hours = $8,601,700/2,757 megawatt hours. Cost of Yuma solarization would be $393 million. This would increase the capital cost of the Yuma facility by 393/470, or 83.6 percent. Capital costs of a solarized system would be $1.98 per 1,000 gallons of water over a 20-year period. Operational expenses, based on Yuma data are projected to be $0.916 per 1,000 gallons of water. The total is then $2.90 per 1,000 gallons of water.

Solar-Zeolite Water Purification

Another technique for desalination has been under investigation by the New Mexico Solar Energy Institute. This technique is based on adsorption pumping, freezing, and solar-derived heat. The Solar Energy Institute is presently working on a contract with the Battelle Pacific Northwest Laboratories on a solar-zeolite seasonal cooling storage system. The system now under construction will utilize about 16,577 Btu of solar-derived heat to dry zeolite during the day and cause 6 pounds of water to desorb (vaporize). These 6 pounds of vapor are to be condensed and removed from the system as pure water. During the night, 6 pounds of ice are to be sublimated and the vapor adsorbed into the zeolite. Each pound of ice sublimated will cause 8.4 pounds of water to freeze, for a total of 50.4 pounds of ice formation. A daily cycle then purifies 6 pounds of water by evaporation and 50.4 pounds of water by freezing. Because the total is still 50.4 pounds, the 6 pounds of water are first frozen and then sublimated through a double purification process.

This process is based on heat of sublimation of 1,218.7 Btu/pound and heat of fusion of 144 Btu/pound. The final result will be 50.4 pounds of purified water per 16,577 Btu of solar-derived heat, or 328.9 Btu per pound of water purified. A moderate efficiency low-temperature solar panel can collect 1,000 Btu/square feet a day, so 1 square foot of panel could process 3.0 pounds of water a day.

This solar-zeolite process can produce 50.4 pounds of purified water and 50.4 pounds of 32°F cooling--for the price of 16,571 Btu of solar-derived energy and 12,000 Btu of evaporative cooling.

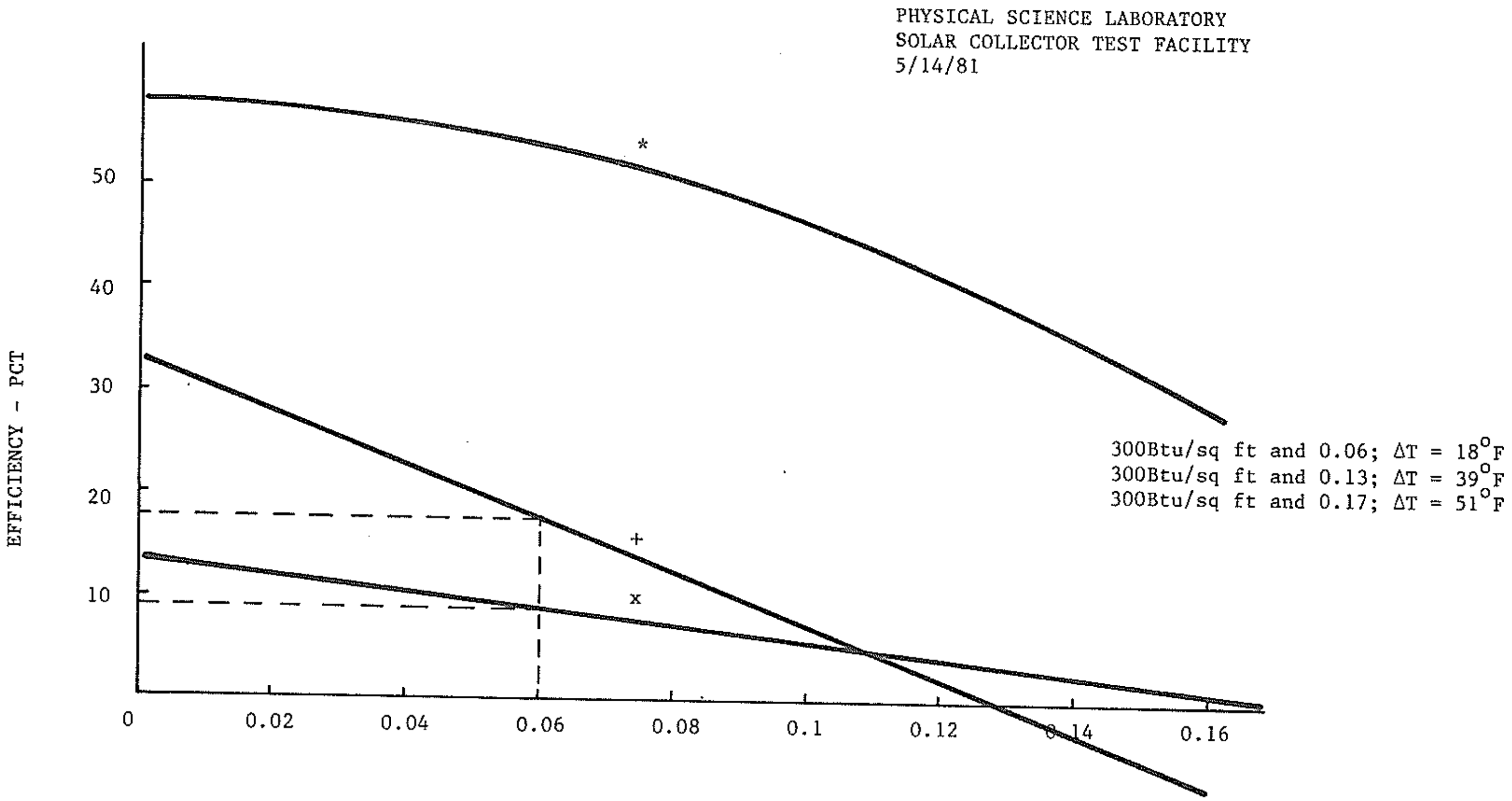
Solar-Driven Low-Pressure System, Theory

The simplified system tested uses low-cost nonglazed panels that are relatively efficient for low ΔTs between the input liquid and ambient air. Black-painted galvanized steel collectors have been tested at 58 percent efficiency for ΔT of 0°F, 40 percent efficiency for ΔT of 37°F, and 30 percent efficiency for ΔT of 48°F. The stagnation temperature was found to be 66°F above ambient temperature. These data are from figures 1 and 2, which were extracted from a report by George Conrad: The Design and Prototype Testing of a Solar Heating and Cooling Roof/Collector/ Radiation Module.

Unglazed panels also make good thermal radiators at night. Figure 3 is a plot of heat rejection at night from the black corrugated iron and circulating water. These data show heat rejection of 18 to 54 Btu/hour-feet^2 for variations of 0.3 to 2.0 in the ratio of $(2T_{inlet}-T_{ambient}-T_{sky})/T_{ambient}$. These data also were extracted from the Conrad report.

The above data show that corrugated metal painted black is a better solar collector than it is a radiator; however, it is still a good energy radiator. A system collecting solar-derived heat during the day and radiating that heat back out of the same collector at night would approach the stagnation temperature of 66°F above ambient by the end of the day. The system would normally be limited by the radiation.

An afternoon temperature of 90°F and early morning temperature of 70°F are used as an example. Sky temperature on a clear night is 10°F



F = AVG INLET FLUID TEMP LESS AMBIENT TEMP DIVIDED BY AVG INSOLATION (DEG F) (HR) (SQ FT) /BTU

PSL NO : 0117 SYMBOL: x EFF = 13.55 - 78.27xF EFF WITH AIR AT 1 SCFM/FT SQ
PSL NO : 0117 SYMBOL: + EFF = 32.92 - 256.78xF EFF WITH AIR AT 4 SCFM/FT SQ
PSL NO : 0117 SYMBOL: * EFF = 57.69 + (2.83xF) - 1156.40x(FxF) EFF WITH E G WATER AT 14.7 LBM/HR - FT SQ

Figure 1. Solar Collection Performance of Corrugated Steel Module.

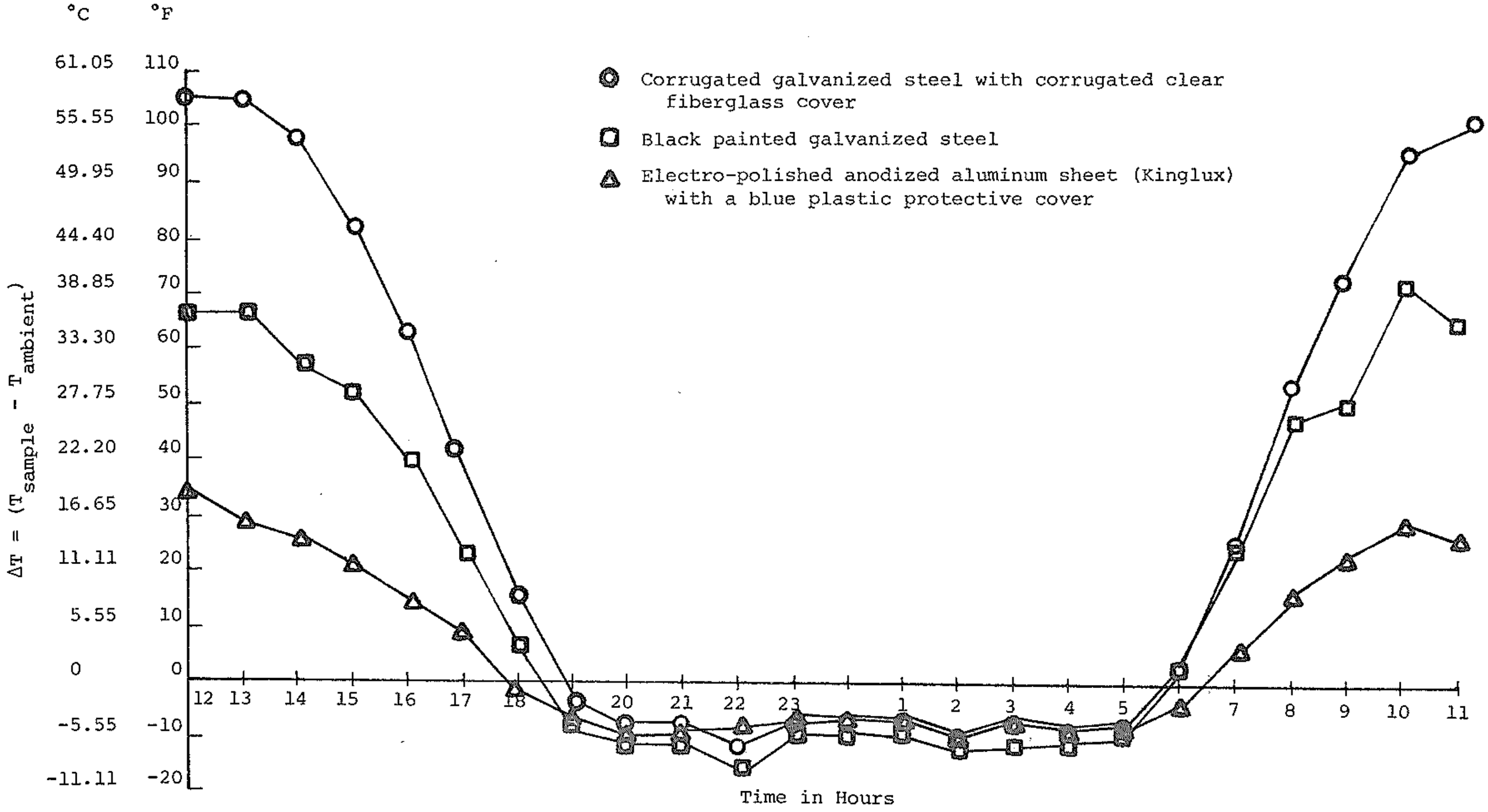


Figure 2. Variation of ΔT vs Time for the "Best Response" Materials

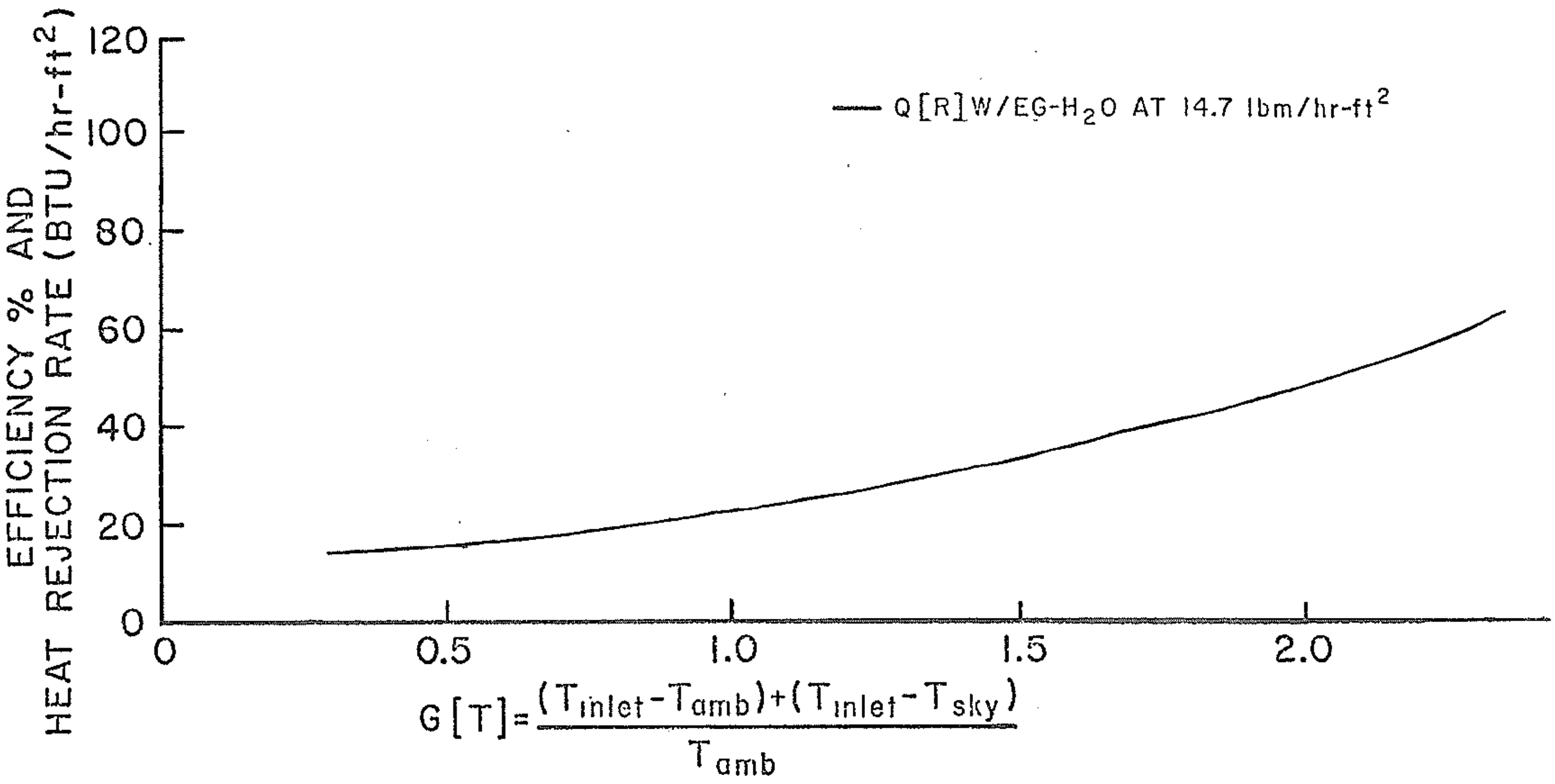


Figure 3. Corrugated Steel Module Nocturnal Cooling Performance

below ambient. The ratio for figure 3 is then ($2T_{inlet}$ - 70°F - 60°F)/ 70 = $\frac{2T_{inlet}-130}{70}$. The following table is then derived:

T_{inlet}(°F)	Ratio	Heat Rejection (Btu/hr-ft^2)
80	0.43	17
90	0.71	19
100	1.00	23
110	1.29	29
120	1.57	40
130	1.86	45
140	2.14	55
150	2.40	70

Based on conservative heating of a tank of water to 50°F above ambient during the day, the efficiency of the collector is about 28 percent, or 84 Btu/square foot-hour. Solar heating would drop to 13 percent and 39 Btu/square foot-hour at 60°F above ambient temperature. It would be expected to go to above a ΔT of 50°F and lower efficiency since 84 Btu/square foot-hour collection is well above the best radiation rate.

Temperatures at night are typically 20°F to 30°F below daytime temperatures. Using 70°F nocturnal, 90°F daily, and 60°F above ambient temperature water, the nocturnal heat rejection would be expected to go as high as 70 Btu/hour-square foot.

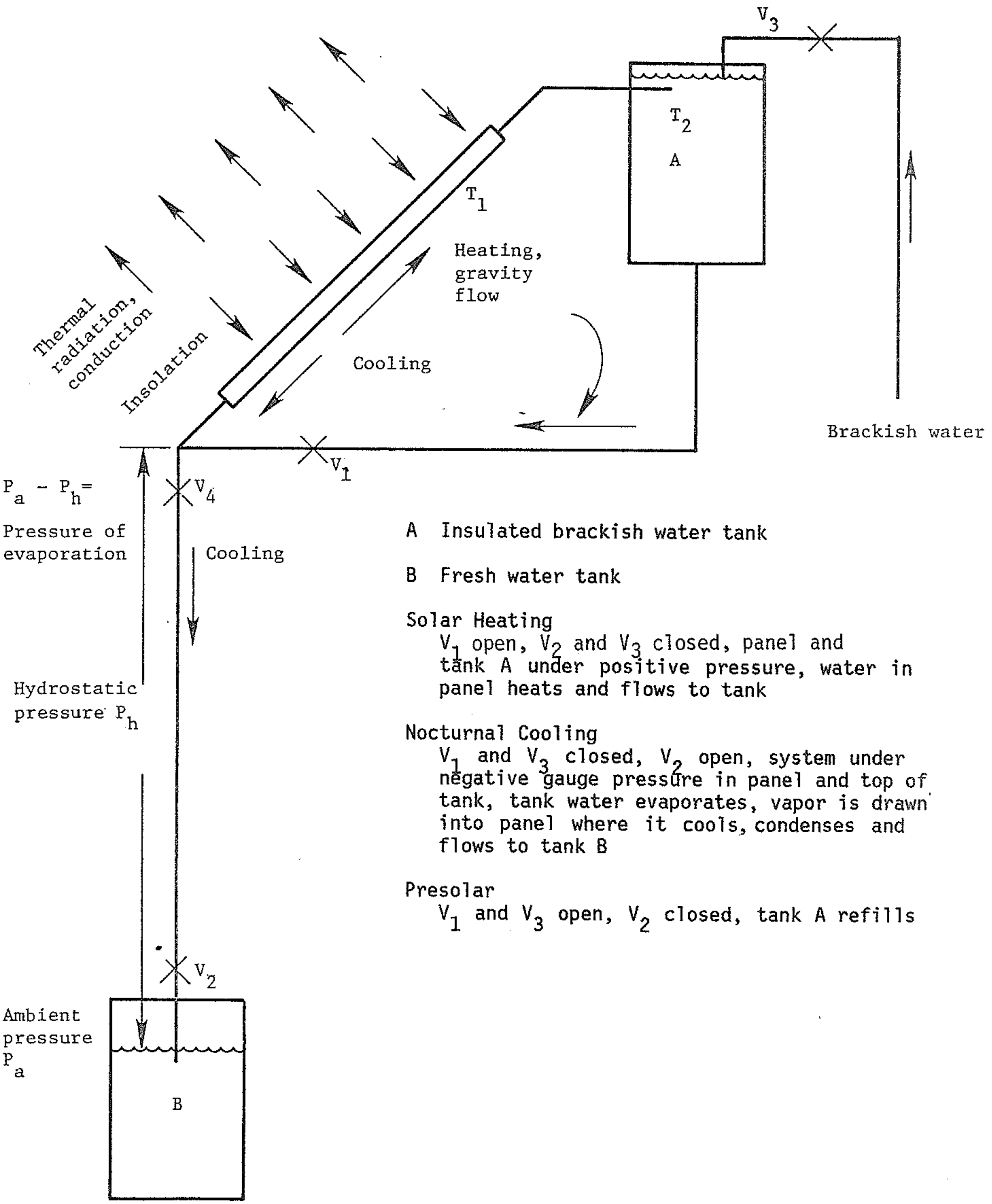
At 70 Btu/hour-square foot and 12 hours of radiation, the panel would radiate 840 Btu per square foot, or about enough energy to condense 0.81 pounds of vapor. A good solar evaporating pond gives 0.55 pounds/square foot day of purified water, so the 0.81 pounds compares favorably. The main advantages of the proposed low-pressure system over evaporating ponds are believed to be in cost of hardware and in ease of disposal of the salts. It should be noted that heat transfer in a condensing vapor-to-air system is normally more efficient than a water-to-air system. Therefore, and the heat exchange data herein are based on water to air.

The advantages of the proposed low-pressure system over the solar-driven reverse osmosis system are (1) it is far less complex and (2) it is simple to construct.

Solar-Driven Low-Pressure System, Test Findings

Figure 4 is a sketch of the system that was set up for test and evaluation. The solar-heated water thermosiphons through the solar panel, valve V_1, and tank A in the daytime, heating the water in tank A. At night, valves V_1 and V_3 are closed and V_2 and V_4 opened. The system is then sealed at the top and open only at the bottom. Water then flows out of the line into tank B until the pressure from the weight of the column of water in the pipe, plus pressure at the top of tank A, equals atmospheric pressure. The water at the top of the system vaporizes when the pressure drops sufficiently. The vapor fills the system from the pipe at the top of tank A, through the solar panel, and down the vertical pipe until the pressure balances.

The first vapor from the 150°F water in the tank would be at 150°F, and as it reaches the solar panel, the vapor gives up heat and condenses. The vapor rapidly cools, however, because the latent heat comes primarily from the surface of the water. The pressure and temperature in the panel and top of the tank, therefore, drop quickly to very low levels to keep the vapor as a vapor and to pressure balance the system. The vapor warms by obtaining heat from the panel and water in the tank until outside ambient temperature is reached. As the evening cools further, heat is radiated from the panel, cooling the vapor and condensing it. The condensate runs down the pipe toward tank B.



A Insulated brackish water tank

B Fresh water tank

Solar Heating
V_1 open, V_2 and V_3 closed, panel and tank A under positive pressure, water in panel heats and flows to tank

Nocturnal Cooling
V_1 and V_3 closed, V_2 open, system under negative gauge pressure in panel and top of tank, tank water evaporates, vapor is drawn into panel where it cools, condenses and flows to tank B

Presolar
V_1 and V_3 open, V_2 closed, tank A refills

Figure 4. Solar Water Purifier.

The water interfacing with the vapor at the top of the tank first becomes cold due to the evaporation. As heat conducts through the water and the heavy cold surface water circulates toward the bottom, the warm water goes toward the top and the surface warms; evaporation continues taking heat from the entire tank of water. An example of operation is as follows:

Weight of water in tank	250 pounds
Area of panel	32 square feet
Sundown to sunup	13 hours
Average radiation rate	45 Btu/hour square foot
Overnight change in water temperature	32 x 45 x 13/250 = 74.9°F

Starting at 150°F, the morning temperature would be 75.1°F. The overnight heat rejected would be 45 x 32 x 13 = 18,720 Btu, which is sufficient to process 18 pounds of water from tank A to tank B. This is 0.56 pounds of processed water per square foot of panel, somewhat less than initially proposed.

The next solar day would then return 18,720 Btu to the tank. At 2,000 Btu/square foot-day there would be 64,000 Btu on the panel. To return the 18,720 Btu, an efficiency of only 29 percent is necessary. During most of the solar day, the panel should give a much higher efficiency, indicating that the tank should warm up close to stagnation temperature. Increasing the tank A water to panel area ratio improves the water process rate because more energy will be stored in the tank for a given tank differential temperature between night and day.

The on-hand equipment used was a 30-gallon tank and a 32-square-foot panel. However, the system should process substantially more water by increasing tank size.

Since all desalination systems require tanks for raw water and processed water, one difference in this system is the substitution of low-cost solar collectors for a reverse osmosis system, electrodialysis system, or more expensive solar evaporation ponds. A second difference is that by using a tank with a large opening at the top, the salts can be deposited in a plastic liner while the water evaporates. This bag can be periodically removed to take out the salt.

The solar water purification system technique tested should furnish an average of 0.56 pounds of water per day per square foot of solar collector. On good insolation days, the brackish water tank temperature would be high, and water processing would be high. On cloudy days, the water processing would decrease, but as long as daytime temperatures are higher than nighttime temperatures, some water would be processed. Over a 20-year period, 1 square foot of panel is projected to process 4,088 pounds of water, or 490 gallons. This projection is based on very limited test data, and a prime objective of this project was to acquire more such data.

The low-temperature solar desalination system as sketched in figure 4 is far simpler than solar power towers and reverse osmosis; however, system cost per square foot of solar must not exceed $3 per square foot to match 20-year life cycle economy of the complex system. There are other benefits of the technique tested.

1. Salts are disposed of more easily.
2. No processing materials are required, such as the lime used in the Yuma project.
3. The system can be operated by untrained personnel.
4. Construction involves readily available materials.

DISCUSSION OF TESTS

The test system installed is shown in figure 4. A 30-gallon hot water tank was set on blocks to allow sufficient height for gravity flow of water through the FAFCO-manufactured plastic unglazed panel when heated above that in the tank. Tests were initiated on May 10, 1982, by filling the tank-panel system.

The following water temperature data* were obtained on May 11, 1982. The evaporation pressure data were then obtained from steam tables.

Time of Measurement	Water Temperature (°C)	(°F)	Evaporation Pressure† (psia)
0930	25	77	0.43
0945	31	87.8	0.59
1000	32	89.6	0.69
1020	35	95	0.81
1030	38	100.4	0.98
1040	39	102.2	1.04
1200	43	109.4	1.23
1330	46	114.8	1.47
1350	48	118.4	1.55
1430	49	120.2	1.78
1445	48	118.4	1.55

There were no clouds during the day. Two liters of water were added to the 30-gallon tank at the start of the above data collection to bring the water up into the sight glass.

On May 12 at 0750, the water temperature was measured to be 39°C (102.2°F). The tank was refilled by adding 1 liter of water. The tank

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*This test was run primarily to test the rate of solar heating with the unglazed solar panel.

†The evaporation pressures are the pressures that would cause evaporation to take place in the tank if the system were switched from solar heating to nocturnal cooling.

was insulated with 6 inches of fiberglass and covered with film plastic. This was in addition to insulation that came with the hot water tank. The following data were taken.

Time of Measurement	Water Temperature (°C)	Water Temperature (°F)	Evaporation Pressure (psia)
1100	37	98.6	0.98
1200	40	104.0	1.1
1450	46	114.8	1.47
1530	47	116.6	1.57

The day started out partly cloudy and ended up clear and windy.

On May 13 another liter of water was added to bring the water level up. The following data were recorded.

Time of Measurement	Water Temperature (°C)	Water Temperature (°F)	Evaporation Pressure (psia)
0815	40	104	1.09
0910	40	104	1.09
1020	39	102	1.02
1200	43	109	1.21
1300	49	120	1.78
1330	50	122	1.87
1630	51	124	2.00
1915	49	120	1.87

At 1930, valves V_1 and V_3 were closed and valves V_2 and V_4 were opened. The pressure was -14 inches of Hg (-6.94 psig, +5.84 psia). At this pressure, the water in the tank could not evaporate unless it was in the presence of sufficient air pressure to lower the partial pressure of vapor to 1.87 psia.

On the morning of May 14, 2.63 liters of water were measured in the collecting bucket. This collected water was most likely due to air leakage into the system because the system pressure by morning was 12.29 psia (atmospheric pressure: 12.78 psia).

On May 14, 1982, the following data were collected.

Time of Measurement	Water Temperature (°C)	Water Temperature (°F)	Evaporation Pressure (psia)
0800	36	96.8	0.88
0950	28	82.4	0.54 (water added)
1000	30	87.0	0.60
1100	42	107.6	1.22
1200	50	122.0	1.87
1242	54	129.2	2.27
1350	56	132.8	2.45
1930	60	140.0	2.86
1936	Valves 1, 3 closed, 2, 4 opened		
1940	Draining water continuously		

The system pressure measured at 1936 was 1.96 psia and some evaporation must have taken place. The pressure rose to 2.95 psia and then to 3.44 psia at 1951, indicating that any evaporation must have ceased or greatly diminished. On the morning of May 15, the system pressure was 0 psig, the water temperature was 42°C, and 3 liters of water had been collected. It is difficult to determine how much of the 3 liters of water was condensate and how much was released by air leaks. It appears that some air was trapped in the piping and in the water. As this air was released or expanded, it formed a partial pressure with the vapor. Data were not obtained to determine what the partial pressure of the vapor was. The free air in the system must have immediately expanded when the system was set for evaporation and condensation. If the free air was not too great, it only allowed the water to evaporate at a higher total pressure. Air leakage or outgassing from the water would, however, slow or stop the evaporation and eventually cause the system to drain.

The length of 3/4-inch PVC pipe below the level of the bottom of the solar panel was 31 feet long. This would give a hydrostatic pressure of 13.4 psia, or 0.65 psia greater than atmospheric pressure. The combine of 0.65 and 1.96 psia would cause the water level to drop about 6 feet down the 31-foot-long pipe. This left about 0.574 gallons of water, or 2.17 liters, in the pipe that drained down during the night. Data were not acquired to show when draindown occurred. Therefore, it is not known how long the system operated. The data indicate that 0.83 liter (0.574 gallon; 4.8 pounds) of vapor was condensed.

On May 17 and 18, the system was set for heating mode and no attempt was made to distill. The object was to remove some air that may have been in the water.

On May 19, 0.96 liter of water was added to the system to fill it and the following data were acquired.

Time of Measurement	Water Temperature (°C)	(°F)	Evaporation Pressure (psia)
0803	53	127.4	2.17
0930	44	111.2	1.36
1140	51	123.8	1.94*
1330	62	143.6	3.12
1500	61	141.8	3.0

*Some air was removed from solar panel.

At 1900 the water was 62°C and the system was set for distillation. The pressure in the system dropped to 1.96 psia, well below the evaporation point at 62°C. The water level must have dropped 8.76 feet down the 3/4-inch PVC pipe (to the 22.3-foot level), leaving 0.51 gallons, or 1.937 liters, in the pipe.

On the morning of May 20, the collection was 2.68 liters of water, of which 0.74 liter must have been condensate. The system was again at 0-gauge pressure.

Testing was then stopped to study the results and develop a plan to solve the air leakage or outgassing problem.

It was noted that a small leak was present on the face of the panel, so it was removed from the system. The pipes to the top of the tank and to the plumbing were capped. This left the system as shown in figure 5.

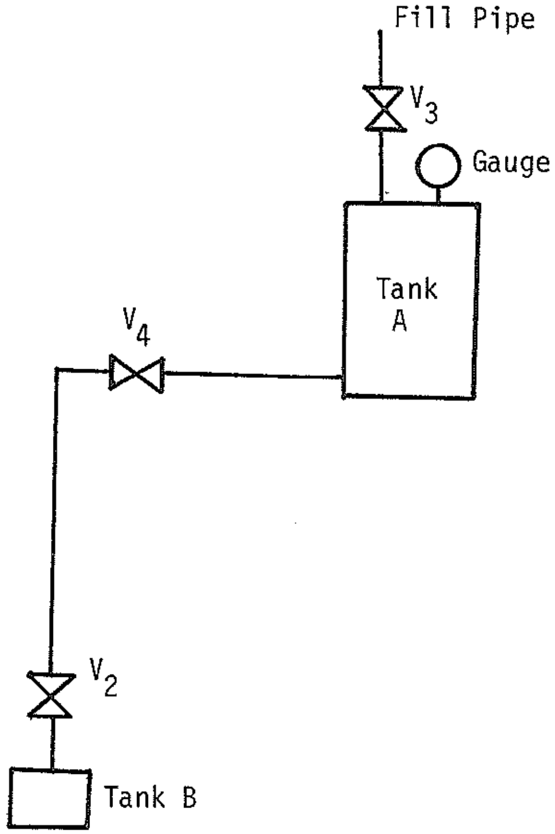

Figure 5. Hydrostatic Pressure Check One.

This system was filled with water on October 26, 1982. Valve V_3 was closed and valves V_2 and V_4 opened. Water flowed out the bottom just below V_2 and the pressure at the top of the tank went to -24.5 inch Hg gauge, or about 1.5 inches Hg absolute. The pressure reading stayed constant until the water ran out. It then returned to ambient pressure.

This demonstrated that the water column did drop the pressure at the top of the sealed system toward 0 absolute, as should have happened.

The system was then changed to move the plumbing to the top of tank A instead of the bottom as shown in figure 6.

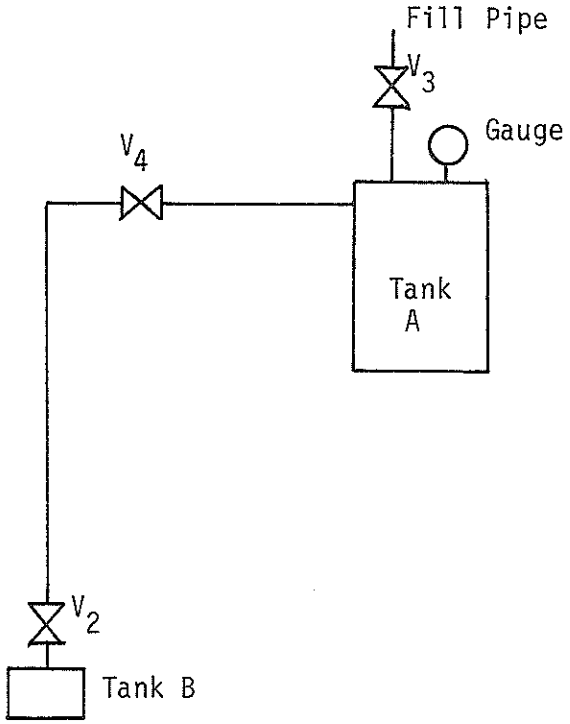

Figure 6. Hydrostatic Pressure Check Two.

A series of tests were run by filling the system with water, closing valve V_3 and opening valves V_2 and V_4. The gauge readings were about 5 inches Hg and did not appear reasonable.

The gauge was removed and found to have flakes of rust around the very small hole, which allowed some rust to enter the bourdan tube hole. The gauge was cleaned, but results still did not appear to be reasonable. A new gauge had been ordered, so tests were stopped until it arrived.

On January 12, 1983, tank A was again filled with water and the new gauge installed. Valve V_3 was closed and valves V_2 and V_4 opened. The pressure only dropped to -4 inches Hg. This indicated a continuing problem.

The insulation around the tank was then removed and all plumbing connections to the tank plugged except for the hot water connection. There had been short piping runs at several points.

On January 18, 1983, another run was made by filling the system with water, closing Valve V_3, and opening valves V_2 and V_4. The pressure dropped to -23.3 inches Hg. By the morning of the next day, it was at -5 inches Hg, which indicated that there was still a small air leak. All valves were removed except for V_2 and the sealing was improved at each joint by application of a wax-type material. The system was again filled and the fill pipe capped and sealed. When valve V_1 was opened, the pressure dropped to -23.3 inches Hg.

At 1348 on January 19, the pressure was still at -22.8 inches Hg, indicating that there were no air leaks and that outgassing was minor.

PRINCIPAL FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

The findings showed that the water could be heated via the unglazed solar panel during the day, evaporated at night in the raw water tank, and condensed in the solar panel.

Problems with the pressure gauge and air leaks were solved by obtaining a new gauge and careful sealing of the system.

It can be concluded that the technique works, but insufficient testing was done to determine how well it works. It is recommended that an improved system be constructed and tested using vacuum-type valves and a better solar panel.