THE DESIGN, CONSTRUCTION, AND EVALUATION OF A THERMOSIPHON SOLAR WATER HEATER

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APPROVAL PAGE

TITLE	The Design, Construction, and Evaluation of a Thermosiphon Solar Water Heater
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III. OBJECT

The purpose of this senior project was to design, construct and evaluate a thermosiphon solar water heater. The project was to be used as a department demonstration of a passive solar water heating system. Overall maximum dimensions of the system needed to be maintained to insure the system's transportability through doors and corridors.

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IV. THEORY

The main force which creates the flow of fluid in a thermosiphon system is the, difference in densities of the low temperature fluid in the tank and the high temperature fluid in the collector. This buoyancy pressure can be calculated by multiplying the density difference of the two points by the buoyancy difference. This will be the pressure difference. This pressure difference is what drives flow through the system.

The flow rate of the fluid is determined by the pressure drop in the system due to friction and fitting losses. When the flow rate produces a pressure drop equal to the buoyancy pressure rise, the system will maintain a constant flow.

The flow rate of the system is very sensitive to pressure drop because the buoyancy pressure rise is so small. A major contributor to frictional pressure drop is the system piping. This is closely related to pipe size as shown in a study done by Lawrence Berkeley Laboratory (LBL). At solar noon, peak solar input, the study shows maximum flow was obtained. Flow through a 1" tube was three times that of a ½" tube. Also contributing to the frictional pressure drop are fittings and flow control devices.

The system efficiency is also affected by flow rate. A low flow rate through the collector produces a larger temperature rise in the collector which raises plate and pipe temperatures, thus increasing losses. A high flow rate therefore can remove and store more energy than a slow rate of flow.

V. DESIGN-BUILD

The system was designed and built as a demonstration of passive solar water heating. The system consists of a 14.3 square foot collector, a nominal 30-gallon storage tank, support frame and connecting piping.

The maximum allowable height for the system was six feet, nine inches. This insured clearance of the system through most institutional doors. A three feet, six inches width clearance was also maintained. This maximum height forced the bottom of the tank to be below the top of the collector. As stated in the LBL study, this had the effect of reducing flow rate during operating hours and causing reverse thermo-siphoning in non-sunlit hours. Reverse siphoning can be prevented by the use of a check valve. Since this system was only designed to be a demonstration project, the check valve was not installed. Scaled schematics showing the height and width of the system are shown in Figures 1 and 2.

The frame for the tank and collector is constructed of one and one-half inch schedule 40 black steel and one inch steel angle with welded connections. The frame needed considerable structural integrity to support and transport the water-filled system. Complete construction details can be obtained from Figures 1 and 2.

The system was piped with three-quarter inch copper water

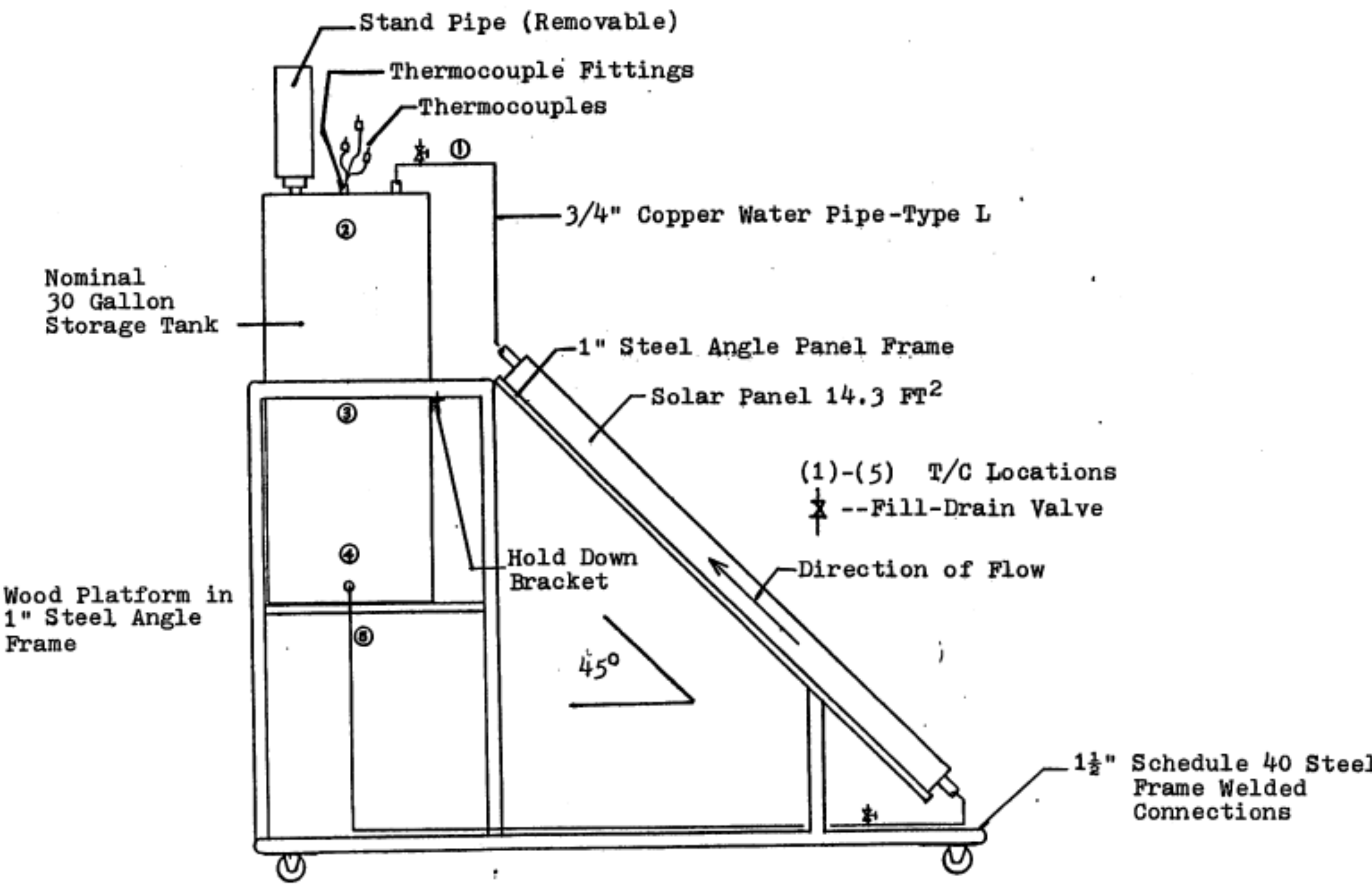

FIGURE 1 : LEFT SIDE VIEW OF SYSTEM
Scale : 3/4" = 1'0"

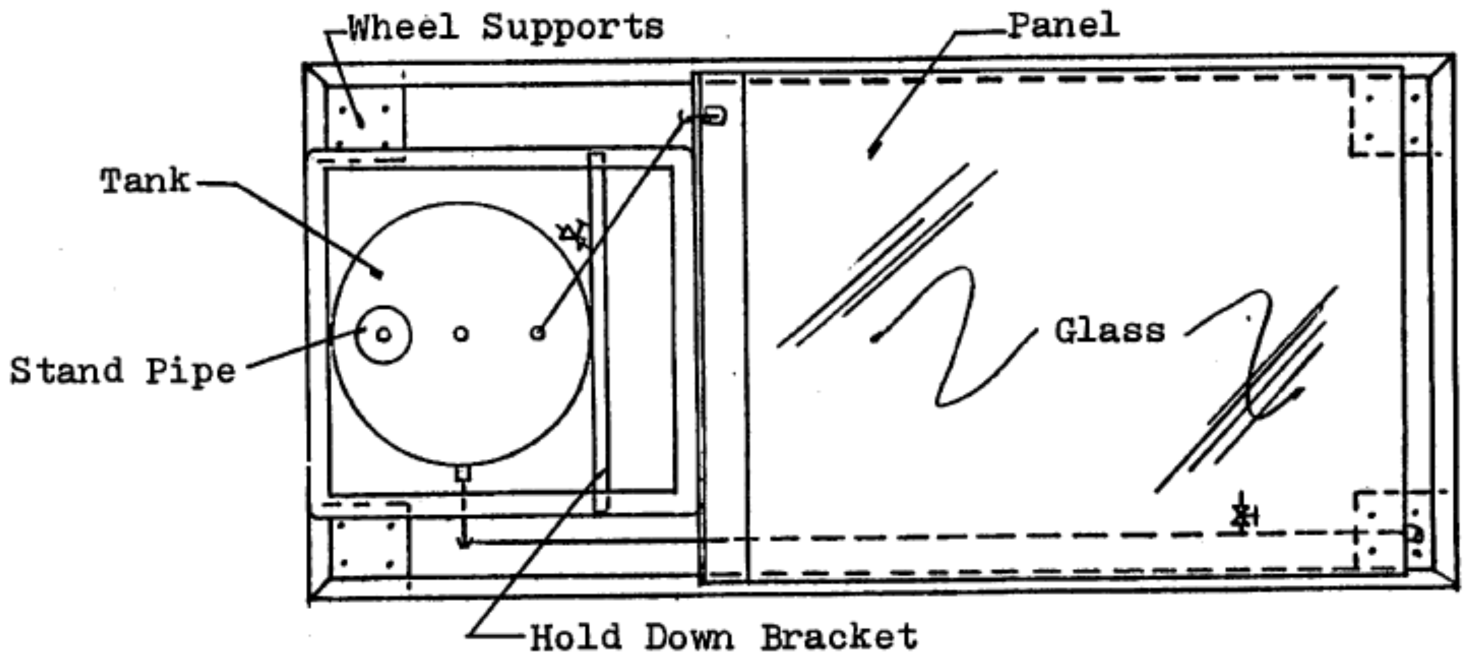

FIGURE 2 : TOP VIEW OF SYSTEM
Scale : 3/4" = 1'0"

pipe, type L, with soldered fittings. Two valves were placed in the piping system, one at the low point for filling and draining and one at the high point for air venting.

To minimize construction costs, the system was designed as an open system. During operation, the system was always at atmospheric pressure. Since the system was a thermosiphoning system, there could not be any breaks in the fluid circuit; that is, the system must always be full, and there can be no air gaps in the system. A one foot high by four inch diameter standpipe was used to keep the system full and allow for fluid expansion.

Measurement of flow by conventional means (i.e., orifice or velocity flowmeter) required a mechanical connection to the fluid. This would produce a pressure drop which would reduce considerably, or more likely prevent, flow in the system. Therefore, no flowmeter was used. A hope for the future is to obtain a flowmeter which uses a temperature difference over a known length of pipe to calculate the flow. This flowmeter would be completely external.

For temperature measurement, five type "T" (copper-constantan) thermocouples were placed in the system, as shown in Figure 1. Three thermocouples were placed inside the tank to check stratification and obtain an average tank temperature.

VI. MATERIALS AND EQUIPMENT

A list of the equipment used to collect data for the analysis of the system is shown in Table II.

The Honeywell Strip chart recorder was used to transduce and record the data from the six type "T" thermocouples placed on the system. The Micromax strip chart recorder was used for recording the voltage output of the Eppley Pyranometer in units of gram-cal/min cm2. The equipment recorded the data precisely, but their accuracy was not checked. The value of the data collected was close to anticipated values.

The system equipment, the tank and panel, were not ideal for application in a solar thermosiphon water heater, but they seemed to perform reasonably well. The tank was a standard 30-gallon nominal electric water heater converted for use as a solar storage tank. The tank did not have the proper connections to be used as a solar storage tank. Since the system was to be run under no load, no water had to be drawn off or added to the tank, so the available fittings were sufficient for use. The tank was also poorly insulated. There was no insulation on the top and bottom of the tank, and the side had only one inch of fiberglass.

The solar panel was manufactured by Sun Works and had 14.3 square feet of single sheet, etched glazing. The panel itself was back painted copper tubing with copper plate and backside insulation. Dimensional data is shown in Table II.

The materials used in the construction were selected for their availability in the department. Fortunately what was available was sufficient for the structural frame. One inch angle iron was used for the collector frame and the tank platform frame.

All. connections were arc-welded. The welding of the frame took much longer than anticipated due to the difficulty of welding pipe.

Nominal three-quarter inch copper water pipe was used for all the plumbing, as opposed to five-eighths inch pipe which was also available, because the larger diameter would produce a smaller pressure drop. All connections were soldered. The piping was insulated with one-half inch of polyurethane with glued connections.

VII. ANALYSIS AND CALCULATIONS

The solar energy incident upon a south-facing surface tilted at 45 degrees was calculated from the solar data in Table I. This data had already been converted from the pyranometer output of gram-cals/min cm^2 to BTU/$hrft^2$ by the following conversion:

$$(X)\left(\frac{\text{gram-cal}}{\text{min cm}^2}\right)\left(\frac{221.2(\text{BTU/hrft}^2)}{(\text{gram-cal/min cm}^2)}\right) = (Y)\left(\frac{\text{BTU}}{\text{hrft}^2}\right)$$

Since instantaneous values for incident solar energy were recorded every 15 minutes., for seven hours, each value was multiplied by 15 minutes and the total incident was:

$$S = 24{,}114 \text{ BTU}$$

The heat into the tank was calculated by multiplying the total fluid mass in the system by the temperature rise over the test period as shown below

$$Q = (M)(CP)(DT)$$

$$M = (27.5 \text{ gal})\left(\frac{8.34 \text{ lb}}{\text{gallon}}\right) = 230 \text{ lb.}$$

$$DT = 58^{\circ}F$$

$$Q = (230 \text{ lb})(1 \text{ BTU/lb}^{\circ}F)(58^{\circ}F) = 13{,}340 \text{ BTU}$$

Efficiency was 55 percent using this equation:

$$\text{Efficiency} = \frac{Q}{S}\ \frac{(\text{output})}{(\text{input})}$$

A computer simulation of the system was also used. The measured values of solar input and ambient temperature were used in the program. Besides environmental data, the input to the program was as follows:

AC = 14.3, ft^2

UL = 5.0, BTU/hrft^2°F

FPRIME = 0.85

TAUALF = 0.85

ST01 = 27.5, gallons

UASI. 5.0,

BTU/hr°F TCW =

68°F

ALAT = 35°

TILT = 45°

NHRF = 1

NHRL = 8

HR = 5, ft

DR = 0.25 in

XNR = 6

DP = 0.75 in

FP = 17 ft

HP = 2 ft

The program utilization and variables are explained and defined in·Appendix I, page 20 and 21.

VIII. RESULTS

The results of the system test are shown in Figures 3 and 4. The temperature profiles shown in Figure 3 represent the time variations of the temperature of the points as indicated below:

T1 - Tank inlet
T2 - Top third of tank
T3 - Middle third of tank
T4 - Bottom third of tank
T5 - Tank outlet
T6 - Ambient temperature

The locations of thermocouples 1-5 are shown in Figure 1. The graph shows the effects of stratification. T3 lags behind T2 by about an hour and T4 lags behind T3 also by an hour. At 9:00, when the test was started, the average tank temperature was about 68°F and at 41:00, at the end of the test, the tank average was 126^{0}F. As the tank heated up, the temperature rise across the collector was reduced. The higher temperature of the water flowing through the panel caused more losses and decreased heat transfer because the temperature difference between plate and fluid was reduced.

Figure 4 shows a profile of the incident solar energy as a function of solar time. Solar input peaked at 12:45, 272 BTU/hrft^2. The graph shows the effect of facing the collector south, rather than having it track the sun. If the collector

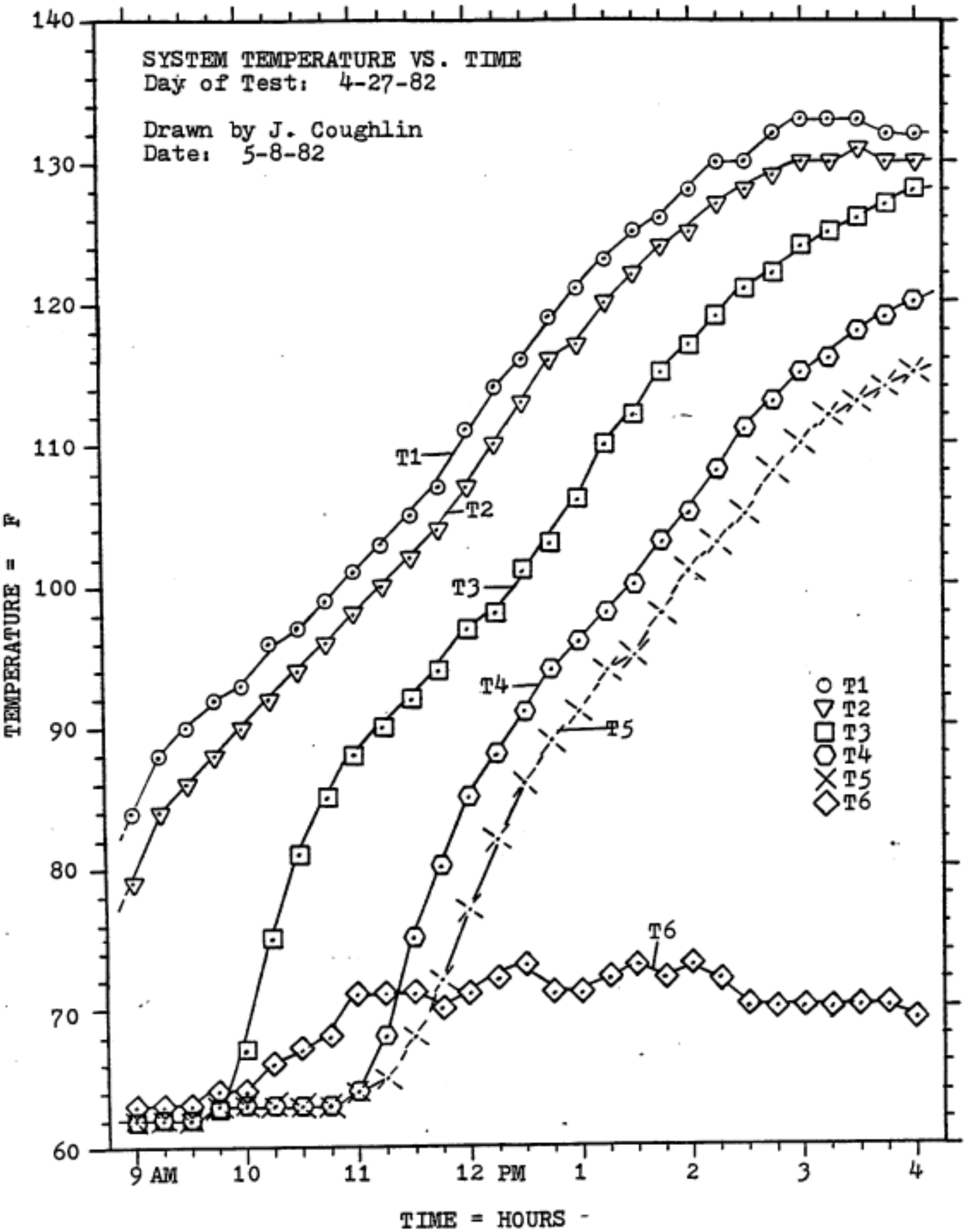

FIGURE 3 : SYSTEM TEMPERATURES VS. TIME

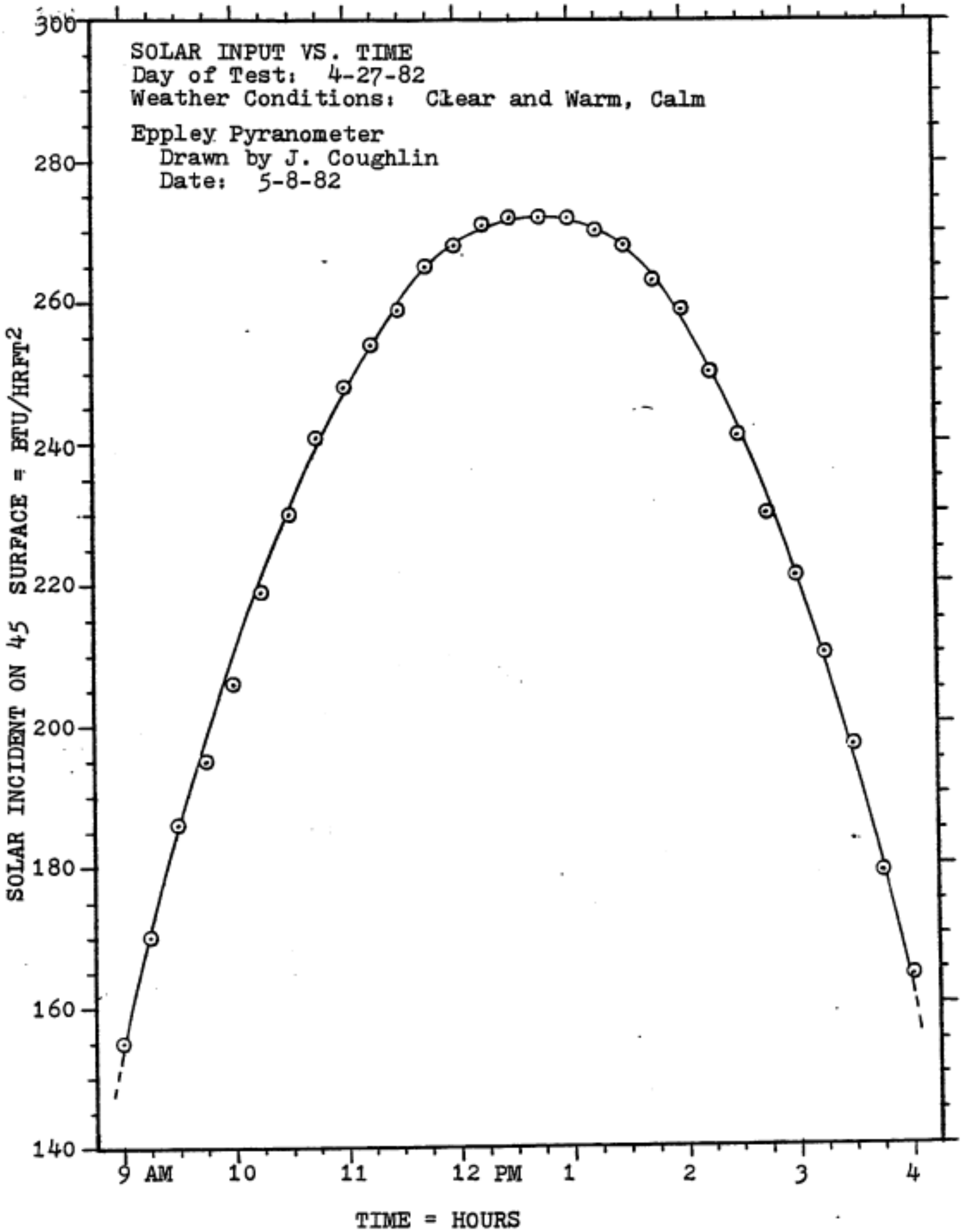

FIGURE 4 : INCIDENT INSOLATION VS. TIME

tracked the sun, the intensity profile would have been flatter. By 4:00 p.m., the sun was so far west it was no longer contributing any usable heat to the tank.

The solar and temperature data are shown in tabular form in Table I.

The same solar and ambient air temperature as measured were used as input for the computer simulation. The total amount of solar energy incident upon the collector and stored as measured and as simulated by the computer are as follows:

Solar incident: S = 24,114 BTU
Stored (measured): Q = 13,340 BTU
Stored (computer): Q = 6,348 BTU

The measured tank temperature rise was 58°F while the computer simulation predicted only a 27.5°F rise. The efficiencies are as follows:

Measured efficiency: 55%
Computer efficiency: 26%

TABLE I : EXPERIMENTAL DATA

TIME	T1*	T2	T3	T4	T5	T6	SOLAR*
9:00	84	79	62	62	62	63	155
9:15	88	84	62	62	62	63	170
9:30	90	86	62	62	62	63	186
9:45	92	88	63	63	63	64	195
10:00	93	90	67	63	63	64	206
10:15	96	92	75	63	63	66	219
10:30	97	94	81	63	63	67	230
10:45	99	96	85	63	63	68	241
11:00	101	98	88	64	64	71	248
11:15	103	100	90	68	65	71	254
11:30	105	102	92	75	68	71	259
11:45	107	104	94	80	72	70	265
12:00	111	107	97	85	77	71	268
12:15	110	110	98	88	82	72	271
12:30	115	113	101	91	86	73	272
12:45	119	116	103	94	89	71	272
1:00	121	117	106	96	91	71	272
1:15	123	120	110	98	94	72	270
1:30	125	122	112	100	95	73	268
1:45	126	124	115	103	98	72	263
2:00	128	125	117	105	101	73	259
2:15	130	127	119	108	103	72	250
2:30	130	128	121	111	105	70	241
2:45	132	129	122	113	108	70	230
3:00	133	130	124	115	110	70	221
3:15	133	130	125	116	112	70	210
3:30	133	131	126	118	113	70	197
3:45	132	130	127	119	114	70	179
4:00	132	130	128	120	115	69	164

*Temperature = ^{o}F
Solar Input = $BTU/hrft^2$

IX. DISCUSSION AND CONCLUSIONS

Due to the fact that this project only involved the design, construction, and evaluation of one variation of a thermosiphon system, it is hard to make any conclusions about the best system configuration for maximum performance. Due to the need for this system to be transportable, it was not designed for best performance. This project does prove that a thermosiphon system will heat water with reasonable efficiency.

In a report on thermosiphon water heaters by LBL (ref. 2), some general conclusions are drawn:

- Reverse flow can be prevented if the tank is completely above the top of the collector.
- No significant performance advantage results from having the tank above the top of the collector other than preventing reverse flow.
- System performance is essentially independent of flow resistance (pipe size) over a wide range of values.

Tank elevation, tube and pipe size do have a substantial effect upon flow rate, but the flow rate has little effect on performance.

There appears to be some problem in the simulation program (ref. 1) used to simulate the system performance. The measured efficiency of 55 percent does not compare closely with the computer generated efficiency of 26 percent. The measured solar data appears to be accurate when compared with tabulated data from Duffie and Beckman (ref. 3).

The computer seems to predict excessive losses. The system input parameters were conservative estimates since actual values were not known. This seems to support the idea that the computer program used does not accurately predict a thermosiphon system.

If a flow meter could be obtained, a better comparison could be made to the computer simulation because an important portion of the program depends upon the computer predicting a flow rate. The program's prediction could be checked against the actual flow, thus giving one more checkpoint.

This system as designed and built would be too small for the average residential application. Using twenty gallons of hot water per person for a family of four, or 80 gallons, twice the storage and twice the panel area would be needed. Thermosiphon systems would seem to have a lot of potential for areas where no power is available, and there is periodic, rather than continuous, usage.

X. APPENDIX

APPENDIX I: EXPLANATION OF SIMULATION PROGRAM

The computer program that was used was a simulation program that calculates the monthly performance of a thermosiphon system based upon a weather tape. This program was developed as a senior project by Tom Barrington (ref. 1) and has been slightly modified since, by Mr. Niles of the Environmental Engineering Department.

The program as written had several operations which did not fit this system and test method. The program had to be modified to fit for use in this project. The first problem was that the system was a single tank with no load. This was a simple problem to solve by setting the demand, the backup set point, the mixing set point, and the backup tank heat loss coefficient to zero. The backup tank size could not be set to zero, because the computer would have to divide by zero, so the tank size can be set to any number other than zero.

The most difficult modification to the program was to use synthetic weather tape that was made from the test data of the experiment. Since the data collected was the total insolation on the collector, the part of the subroutine, Insol, that calculates the total insolation from the diffuse and horizontal insolation had to be deleted from the program. The line that reads the weather tape had to be modified to read only the hour, outdoor temperature and total insolation.

The input variables were as follows:

AC - Total collector area, ft^2
UL - Collector overall loss coefficient, $BTU/hrft^2$
FPRIME - Collector efficiency coefficient
TAUALF - Effective tau-alpha product
STO1 - Solar storage tank size, gal.
STO2 - Backup tank size, gal.
UAS1 - Solar storage tank heat loss coefficient, $BTU/hrft^2$
UAS2 - Backup tank heat loss coefficient, $BTU/hrft^2$
TBUSP - Thermostat setting on backup heater, ^oF
TMIXSP - Mixing valve setting, ^oF
TR - Ambient temperature to which tanks were exposed, ^oF
DEMAND - Hot water demand, gal./day
TCW - City water temperature, ^oF
ALAT - Latitude of location, degrees
TILT - Collector tilt angle from horizontal, degrees
NHRF - First hour of test
NHRL - Last hour of test
HR - Length of collector risers, ft.
DR - Inside diameter of collector risers, in.
XNR - Number of collector risers
DP - Inside diameter of piping to and from collector, in.
FP - Equivalent length of piping to and from collector, includings fittings, valves, and dynamic losses in collector headers, ft.
HP - Height difference from top of collector to return fitting of solar storage tank, ft.

With these modifications to the program and the input data, the program could be run to fit our system and weather tape.

APPENDIX II

TABLE II: EQUIPMENT LIST

1. Honneywell strip chart recorder
   Type "T" thermocouples
   Range: 0-150°F
   Least Count: 1.0°F
   CP #77271

2. Micromax strip chart recorder
   Leed and Northrup Co.
   Philadelphia, PA
   Range: 0-2 gram-cal/min cm^2
   Least count: 0.1 gram-cal/min cm^2

3. Eppley Pyranometer
   Model 10, No. 2312
   Eppley Laboratores, Inc.
   Newport, RI
   Millivolts/gram-cal/min cm^2

XI. REFERENCES

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[2]A. Mertol, W. Place, T. Webster, and R. Greif, "Thermosiphon Water Heaters with Heat Exchanges," Lawrence Berkeley Laboratory Report, LBL-100JJ, 1980.

[3]J. Duffie and W. Beckman, Solar Energy Thermal Processes. John Wiley and Sons, New York, 1974.

[4]W. Place, M. Daneshyar, and R. Kammerud, "Mean Monthly Performance of Passive Solar Water Heaters," Lawrence Berkeley Laboratory Report, LBL-9295, 1979,