DOE/NASA CONTRACTOR REPORT

DOE/NASA CR-150573

INDOOR TEST FOR THERMAL PERFORMANCE EVALUATION OF SUNWORKS (LIQUID) SOLAR COLLECTOR

Prepared by

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Solar Energy Systems Division
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Under subcontract to IBM Federal Systems Division, Huntsville, Alabama

Contract NAS8-32036

National Aeronautics and Space Administration
George C. Marshall Space Flight Center, Alabama 35812

For the U. S. Department of Energy

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This work was done under the technical supervision of Mr. Earle G. Harris, Marshall Space Flight Center, Alabama.

16. ABSTRACT

This report presents the test procedures used and test results obtained from an evaluation test program conducted on a Sunworks (S/N L1158G) single-covered liquid solar collector under simulated conditions. The Marshall Space Flight Center Solar Simulator was used in accordance with test requirements. The test article is a flat-plate solar collector using water as the heat transfer medium. The absorber plate is copper with copper tubes bonded by soft solder. The plate is coated with Enthone selective black with an absorptivity factor of .87~.92 and an emissivity factor of .10~.20. A time constant test and incident angle modifier test were conducted to determine the transient effect and the incident angle effect on the collector.

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1.0 PURPOSE

The purpose of this report is to present the test procedures used and the test results obtained during an evaluation test program. The test program was conducted to obtain thermal performance data on a Sunworks (S/N L1158G) single-covered liquid solar collector under simulated conditions. The tests were conducted utilizing the Marshall Space Flight Center Solar Simulator in accordance with the test requirements specified in Reference 2.1 and the procedures contained in Reference 2.2.

2.0 REFERENCES

2.1	ASHRAE-93-77	Method of Testing to Determine the Thermal Performance of Solar Collectors
2.2	MTCP-DC-SHAC-418	Test Procedure For The Performance Evaluation of the Sunworks (Liquid) Collector
2.3	MTCP-FA-SHAC-400	Procedure for Operation of the MSFC Solar Simulator Facility

3.0 MANUFACTURER

Sunworks
P. O. Box 1004
New Haven, Connecticut 06508

3.1 DESCRIPTION OF TEST SPECIMEN

The test article is a flat plate solar collector using water as the heat transfer medium. The absorber plate is copper and coated with Enthone selective black with absorptivity of .87 ~ .92; emissivity of .10 ~ .20. One-quarter inch (1/4") ID M-type copper tubes are bonded to absorber plate by soft solder with 6" center to center tube spacing. It has a single glass cover of 3/16" tempered glass with transmissivity of 0.92. The overall dimensions of the collector are 36" x 84" x 4". The gross surface area is 21 square feet with a glass area of 18.96 ft.^{2}, effective absorber area of 18.56 ft.^{2} and weighs approximately 115 pounds filled and 111 pounds empty. Figure 1 describes the details of the Sunworks liquid collector.

4.0 SUMMARY

This test program was conducted to evaluate the thermal performance of a Sunworks liquid collector under simulated conditions. The test conditions and the data obtained during the tests conducted on the simulator are listed in Table I for stagnation test and Tables II and III for thermal performance test. A graphic presentation of the data obtained is also presented in Figures 4 and 5. In addition, a time constant test and incident angle modifier test were conducted to determine the transient effect and the incident angle effect on the collector. The results of these tests are presented in Figures 6 through 8 and Table IV. Results of the collector load test are listed in Table V.

5.0 TEST CONDITIONS AND TEST EQUIPMENT

5.1 Ambient Conditions

Unless otherwise specified herein, all tests were performed at ambient conditions existing in Building 4619 at the time of the tests and listed in Tables I through IV.

5.2 Instrumentation and Equipment

All test equipment and instrumentation used in the performance of this test program comply with the requirements of MSFC-MMI-5300.4 C, Metrology and Calibration. The collector liquid loop flow diagram is shown in Figure 2. Instrumentation locations on the test loop and the collector are depicted in Figure 3. A listing of the equipment used in the tests follows.

Apparatus	Manufacturer/Model	Range/Accuracy
Platinum Resistance Thermometer	Supplied by Collector Manufacturer	0-500°F ± 2°F
Pyranometer	Eppley - PSP	0-800 $BTU/Ft^2 \cdot Hr$ ± 3%
Liquid Loop	MSFC Supplied	.1 - 1.2 GPM
Directional Anemometer	MSFC Supplied	0 - 30 MPH
Flowmeter	Foxboro/1/2-2 81T3C1	.1 - .91 ± 1% GPM
Platinum Resistance Thermometer	Minco Products	60-250°F ± .05°F
Strip Chart Recorder	Mosley 680	5-500 mv ± 2%
Floor Fan	MSFC Supplied	N/A
Solar Simulator	MSFC Supplied	See SHC 3006
Differential Pressure Sensor	Statham	0-10 PSID ± 1%
Platinum Resistance Thermometer	Hy-Cal	-50 - 400°F ± 1°F

6.0 REQUIREMENTS, PROCEDURES AND RESULTS

6.1 Collector Stagnation Test

6.1.1 Test Requirement

Utilizing the MSFC Solar Simulator, the stagnation tests shall be conducted at a collector tilt angle of 45 degrees from the horizontal. The collector panel shall be irradiated by the insolation rates of 275, 300 and 325 BTU/Hr·Ft^2 normal to the collector. The following data shall be recorded during the test at each test condition.

1. Insolation rate (BTU/Hr·Ft^2)

2. Ambient temperature (°F)

3. Absorber surface temperature - 4 locations (°F)

6.1.2 Test Procedure

1. Mount test specimen on test table at a 45° angle with respect to the floor.

2. Connect instrumentation leads to data acquisition system.

3. Assure that data acquisition system is operational.

4. Fill the collector flow passage with liquid; then close the hand valve (3), as shown in Figure 2, and shut off the liquid supply pump.

5. Power up simulator and establish the required solar flux level.

6. Monitor data until the surface temperatures reach steady state.

7. Data shall be recorded continuously during the test.

8. Repeat above steps as necessary to complete all the required test conditions.

9. Upon completion of testing, power down simulator and liquid loop.

10. Inform data control group that simulator operation has terminated.

6.1.3 Results

The results obtained during these tests are contained in Table I.

6.0 REQUIREMENTS AND PROCEDURES (Continued)

6.2 Collector Thermal Efficiency Test

6.2.1 Test Requirements

Thermal performance evaluation data shall be obtained at inlet temperatures of 0, 25, 50 and 100°F above ambient temperature at liquid flow rates of 285 and 158 lb/hr at insolation rates of 240 and 300 BTU/Hr·Ft^2 and a wind speed of 7.5 mph. The following data shall be recorded during the test at each test condition.

1. Ambient temperature.
2. Collector inlet liquid temperature.
3. Collector outlet liquid temperature.
4. Collector differential temperature.
5. Differential pressure across collector.
6. Liquid flow rate.
7. Insolation rate.
8. Wind speed.

6.2.2 Test Procedure

1. Mount test specimen on test table at a 45° angle with respect to the floor.
2. Assure that simulator lamp array is adjusted to an angle of 45° with respect to the floor.
3. Align the test table so that the test specimen's vertical centerline coincides with the vertical centerline of the lamp array and the distance from the top of the test specimen to the lens plane of the lamp array is 9 feet.
4. Insulate all pipes.
5. Assure that data acquisition system is operational.
6. Start liquid flow loop and establish a flow rate of 285 Lb/Hr.
7. Establish the wind speed of 7.5 mph.
8. Power up simulator and establish a solar flux level of 240 BTU/Ft^2·Hr.

6.0 REQUIREMENTS AND PROCEDURES (Continued)

6.2.2 Test Procedure (Continued)

9. Determine the ambient air temperature.

10. Adjust the inlet temperature of the collector to the ambient air temperature value.

11. After steady state conditions have been established, record data for a minimum of five minutes.

12. Repeat steps 8, 9, 10 and 11, changing the flux level and liquid inlet temperature as necessary until data has been obtained for each test condition specified in Paragraph 6.2.1.

13. Repeat steps 7, 8, 9, 10, 11 and 12 with flow rate of 158 lb/hr.

14. Upon completion of testing, power down simulator and liquid loop.

15. Inform data control group that simulator operation has terminated.

6.2.3 Test Results

The results obtained during these tests are contained in Figures 4 and 5 and Tables II and III.

6.0 REQUIREMENTS AND PROCEDURES (Continued)

6.3 Collector Time Constant Test

6.3.1 Test Requirements

In accordance with ASHRAE 93-77, the time constant test shall be conducted by abruptly reducing the flux level to zero. Inlet temperature shall be kept to within ± 2°F of ambient, with a liquid flow rate of 285 Lb/Hr. The differential temperature across the collector shall be recorded to determine the time required to reach the condition of

$$\frac{Te - Ti}{Te_{ini} - Ti} = .368$$

where

Te = Outlet temperature

Te_{ini} = Initial outlet temperature

Ti = Inlet temperature

The following data shall be recorded during the test:

1. Absorber surface temperature - 4 locations.
2. Ambient temperature.
3. Collector inlet temperature.
4. Collector outlet temperature.
5. Collector differential temperature.
6. Differential pressure across collector.
7. Liquid flow rate.
8. Insolation rate.

6.3.2 Test Procedure

1. Mount the collector on test table at 45° from the horizontal and assure that solar simulator surface is parallel to the collector surface.
2. Assure that data acquisition system is operational.
3. Adjust the liquid flow rate to 285 Lb/Hr.
4. Adjust the liquid inlet temperature to within ± 2°F of ambient.

6.0 REQUIREMENTS, PROCEDURES AND RESULTS (Continued)

6.3.2 Test Procedure (Continued)

5. Adjust the flux level to 250 $BTU/Ft^2 \cdot Hr$.

6. Monitor the differential temperature across the collector.

7. Allow the system to stabilize at above conditions for at least 5 minutes.

8. Turn off the solar simulator.

9. Monitor the differential temperature until the ratio of $\frac{Te - Ti}{Te_{ini} - Ti}$ is less than .30.

10. Upon completion of testing, power down simulator and liquid loop.

11. Inform data control group that simulator operation has terminated.

6.3.3 Test Results

The results obtained during this test are shown in Figure 6.

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6.0 REQUIREMENTS, PROCEDURES AND RESULTS (Continued)

6.4 Collector Incident Angle Modifier Test

6.4.1 Test Requirement

The collector incident angle modifier test shall be conducted at north-south radiation incident angle of 45 degrees. The east-west radiation incident angles shall be 23, 45 and 60 degrees. The liquid flow rate shall be 285 lb/hr with inlet temperature controlled to within ± 2°F of ambient at the insolation rate of 300 BTU/Ft^2·Hr and 0 mph wind. The following data shall be recorded during the test at each test condition.

1. Ambient temperature.
2. Collector inlet liquid temperature.
3. Collector outlet liquid temperature.
4. Collector differential temperature.
5. Liquid flow rate.
6. Insolation rate.

6.4.2 Test Procedure

1. Mount the collector on the test table at incident angle of 23°.
2. Adjust the liquid flowrate to 285 lb/hr.
3. Adjust the solar simulator flux level to 300 BTU/Hr·Ft^2.
4. Adjust the inlet temperature to ambient ± 2°F.
5. Measure the flux level at 9 locations on the test plane.
6. Record data for 5 minute stabilized period.
7. Repeat above steps for incident angles of 45° and 60°.
8. Upon completion of testing, power down simulator and liquid loop.
9. Inform data control group that simulator operation has terminated.

6.4.3 Test Results

Data obtained from this test program were analyzed according to ASHRAE 93-77 and reported in Table IV and graphic format in Figures 7 and 8.

6.0 TEST REQUIREMENTS, PROCEDURES AND RESULTS (Continued)

6.5 Collector Load Test

6.5.1 Test Requirements

One solar collector shall be subjected to load testing. The specified load requirements are listed in Table V. The collector shall be mounted as indicated in Figure 9 but oriented such that the glazing is horizontal. Uniform loads shall be applied by means of a transparent flexible diaphragm which can be covered with a uniform layer of transparent liquid of varying depths to obtain the desired load variations.

6.5.2 Test Procedure

1. Mount the collector in the horizontal plane.

2. Place the load frame with liner over the collector.

3. Fill the load frame liner with water to a level corresponding to the Step 1 load of Table V and let stand for five minutes.

4. Drain and remove the load frame.

5. Flush the collector exposed surface with water and inspect for leaks.

6. If the collector leaked or was damaged due to the load, record and indicate what the load level is.

7. If the collector does not leak and is not damaged, record the load level and repeat steps 3 through 5 for the next load level.

6.5.3 Test Results

The results of this test are tabulated in Table V.

7.0 ANALYSIS

7.1 Thermal Performance Test

The analysis of data contained in this report is in accordance with the National Bureau of Standards recommended approach. This approach is outlined below.

The efficiency of a collector is stated as:

$$\eta = \frac{q_u/A}{I} = \frac{\dot{m}\, C_{tf}\left(t_{f,e} - t_{f,i}\right)}{I} \tag{1}$$

where:

q_u = rate of useful energy extracted from the Solar Collector (BTU/Hr)

A = Gross collector area (Ft^2)

I = Total solar energy incident upon the plant of the solar collector per unit time per unit area ($BTU/Hr \cdot Ft^2$)

$\dot{m}$ = Mass flow rate of the transfer liquid through the collector per unit area of the collector ($Lbm/Ft^2 \cdot Hr$)

C_{tf} = Specific heat of the transfer liquid (BTU/Lb·°F)

$t_{f,e}$ = Temperature of the transfer liquid leaving the collector (°F)

$t_{f,i}$ = Temperature of the transfer liquid entering the collector (°F)

Rewriting Equation (1) in terms of the total collector area yield:

$$\eta = \frac{(\dot{m}A)\, C_{tf}\left(t_{f,e} - t_{f,i}\right)}{(IA)} = \frac{\dot{M}\, C_{tf}\left(t_{f,e} - t_{f,i}\right)}{P_i} \tag{2}$$

Notice that:

P_i = IA = Total Power Incident on the Collector.

$\dot{m}A = \dot{M}$ = Total Mass Flow Rate through the Collector.

Therefore $\dot{M}\, C_{tf}(t_{f,e} - t_{f,i})$ = Total Power Collected by the Collector.

7.0 ANALYSIS (Continued)

7.1 Thermal Performance Test (Continued)

Substitution in Equation (2) results in:

$$\eta = \frac{Pabs}{Pinc} \qquad (3)$$

where:

Pabs = Total collected power

Pinc = Total incident power

This value of efficiency is expressed as a percentage by multiphying by 100. This expression for percent efficiency is:

$$\text{Collector Efficiency} = \frac{Pabs}{Pinc} \times 100 \qquad (4)$$

or from Equation (2), collector efficiency is defined by the equation:

$$\%\ \text{Eff.} = \frac{\dot{M}\ C_{tf}\ (t_{f,e} - t_{f,i})}{Pi} \times 100 \qquad (5)$$

Each term in Equation (5) was measured and recorded independently during the test. The calculated values of efficiency were determined at sixty-second intervals. The mean value of efficiency was determined over a five-minute period during which the test conditions remained in a quasi-steady state. Each five-minute period constitutes one "data point" as is graphically depicted on a plot of percent efficiency versus

$$\left((t_i - t_a /I \right)$$

where:

t_i = Liquid inlet temperature (°F)

t_a = Ambient temperature (°F)

I = Incident flux per unit area ($BTU/Hr \cdot Ft^2$)

The abscissa term $\left((t_i - t_a) /I \right)$ was used to normalize the effect of operating at different values of I, t_i and t_a. The results are found in Figures 4 and 5.

The result of second order polynomial analysis is shown in Figures 4 and 5. The second order polynomial to best describe the test results is:

$$\%\ \text{Efficiency} = a_0 + a_1\tau + a_2\tau^2$$

7.0 ANALYSIS (Continued)

7.1 Thermal Performance Test (Continued)

where:

$$\mathcal{T} = (t_i - t_a)\ I$$

and the coefficients are determined to be:

Flow Rate (Lbm/hr)	285	158
a_0	66.38	63.04
a_1	-86.45	-78.21
a_2	-80.04	-111.5

7.0 ANALYSIS (Continued)

7.2 Time Constant Test

Two methods are proposed by ASHRAE 93-77 for conducting a time constant test. However, due to facility limitations, only the first method could be used. This method consisted of shutting down the simulator and maintaining a constant flow rate and inlet temperature while obtaining data.

According to the definition of time constant given in 93-77, it is the time required for the ratio of the differential temperature at time τ to the initial differential temperature to reach .368. It can be expressed as:

$$\frac{T_{f,e\,\tau} - T_{f,i}}{T_{f,e,ini} - T_{f,i}} = .368 \qquad (1)$$

if the inlet liquid temperature can be controlled to equal the ambient air temperature,

where:

$T_{f,e,\tau}$ = Exit liquid temperature at time

$T_{f,i}$ = Inlet liquid temperature

$T_{f,e,ini}$ = Initial exit liquid temperature.

From Figure 6 the time constant was determined to be 1 minute and 32 seconds.

7.0 ANALYSIS (Continued)

7.3 Incident Angle Modifier Test

Two methods are proposed by ASHRAE 93-77 for incident angle modifier tests. For the MSFC Solar Simulator Facility, only method 1 (tilting the collector) is applicable. The collector was adjusted so that the incident radiation angles were 23°, 45° and 60° to the normal of the collector surface.

According to 93-77, the incident angle modifier is defined as

$$K_{\alpha\tau} = \frac{\eta}{F_R(\tau\alpha)n} \qquad (1)$$

where η = efficiency at tilted angle

$F_R(\alpha\tau)n$ = Intercept of efficiency curve at normal incident angle

For equation (1) to be applicable, the inlet liquid temperature must be controlled to within ± 2°F of the ambient air temperature.

The results of this computation are shown on Table IV and plotted against incident angle in Figure 7 and plotted against $\frac{1}{\cos\theta i} - 1$ in Figure 8.

TABLE I

STAGNATION TEST DATA

Collector Side °F										
Collector Back °F										
Outer Cover °F										
North Surface °F	283	303	312							
Center Surface °F	292	314	322							
East Surface °F	283	303	313							
South Surface °F	264	285	294							
Ambient °F	73	73	73							
T_{in} °F										
T_{out} °F										
ΔT										
Solar Flux BTU/Hr·Ft^2	275	300	325							
Flow Rate LB/Hr	0	0	0							
Wind Speed MPH	0	0	0							
Efficiency %										
(Ti-Ta) /I °F·Hr·Ft^2/BTU										

TABLE II

Sunworks Liquid Collector
Thermal Performance Test Data

285 Lbm/Hr. Flow Rate

Ambient °F	75	76	77	80	80	76	78	79		
T_{in} °F	75	76.4	115	116	126.7	127.5	173.3	174		
T_{out} °F	87.2	91.0	124.5	128	136	138	177.7	180.3		
ΔT °F	12.2	14.6	9.5	120	9.3	10.5	4.4	6.3		
Solar Flux BTU/Hr·Ft^2	250	300	250	300	250	300	250	300		
Flow Rate Lb/Hr	288	284	283	287	283	289	276	285		
Wind Speed MPH	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5		
Efficiency %	66.8	65.7	51.2	54.6	50.1	48.2	23.1	28.5		
(Ti-Ta)/I°F·Hr·Ft^2/BTU	0	0.001	0.152	0.120	0.187	0.172	0.381	0.317		

TABLE III

Sunworks Liquid Collector
Thermal Performance Test Data

158 Lbm/Hr. Flow Rate

Ambient °F	76	76	78	81	80	80	79	80		
T_{in} °F	76	76.3	114.5	116	127.4	127.3	171.7	172.1		
T_{out} °F	96.8	101	131.0	136.5	142.5	146	178	183.6		
ΔT °F	20.8	24.7	16.5	20.5	15.1	18.7	6.3	115		
Solar Flux BTU/Hr·Ft^2	250	300	250	300	250	300	250	300		
Flow Rate Lb/Hr	160	160	158	160	155	159	155	157		
Wind Speed MPH	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5		
Efficiency %	63.4	62.7	49.8	52.0	44.6	47.2	18.6	28.6		
(Ti-Ta)/I°F·Hr·Ft^2/BTU	0	0.001	0.146	0.117	0.190	0.158	0.371	0.307		

TABLE IV

Test Data for Sunworks
Incident Angle Modifier Test

Incident Angle	0	23	45	60						
Ambient °F	80	82	82.3	83						
T_{in} °F	80	83	82	82.5						
T_{out} °F	93.8	95.6	91.5	88.8						
ΔT °F	13.8	12.6	9.5	6.3						
Solar Flux BTU/Hr·Ft^2	290	268	213	148						
Flow Rate Lb/Hr	290	288	290	289						
Wind Speed MPH	0	0	0	0						
Efficiency %	65.8	64.4	61.7	58.6						
$K_{\alpha\tau}$	1	0.980	0.938	0.890						

TABLE V

Service Load Steps and Test Results

Step No.	Load (Lb/Ft^2)	Pass/Fail	Comments
1	10	Pass	No leaks
2	20	Marginal	Small leak in gasket upper left side
3	30	Marginal	Same
4	50	Fail	Leak in upper left side, larger
5	80	Fail	Same
6	120	Fail	Additional large leak upper right side gasket

Tested By B Henderson

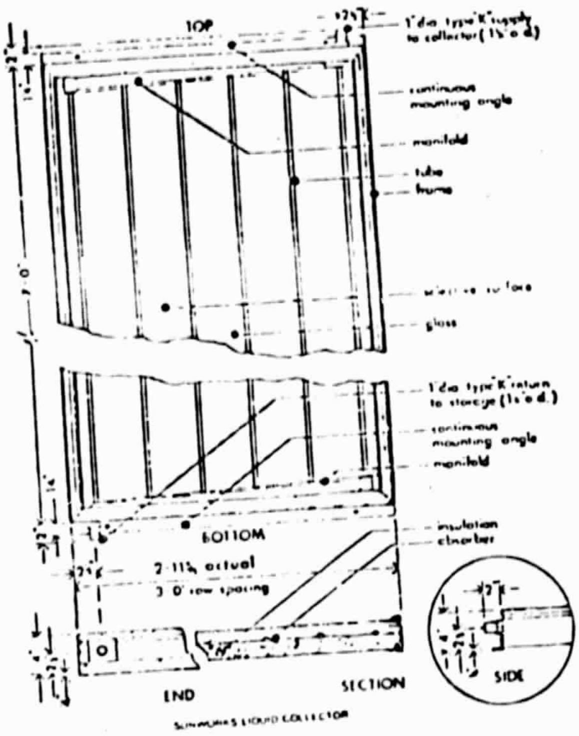

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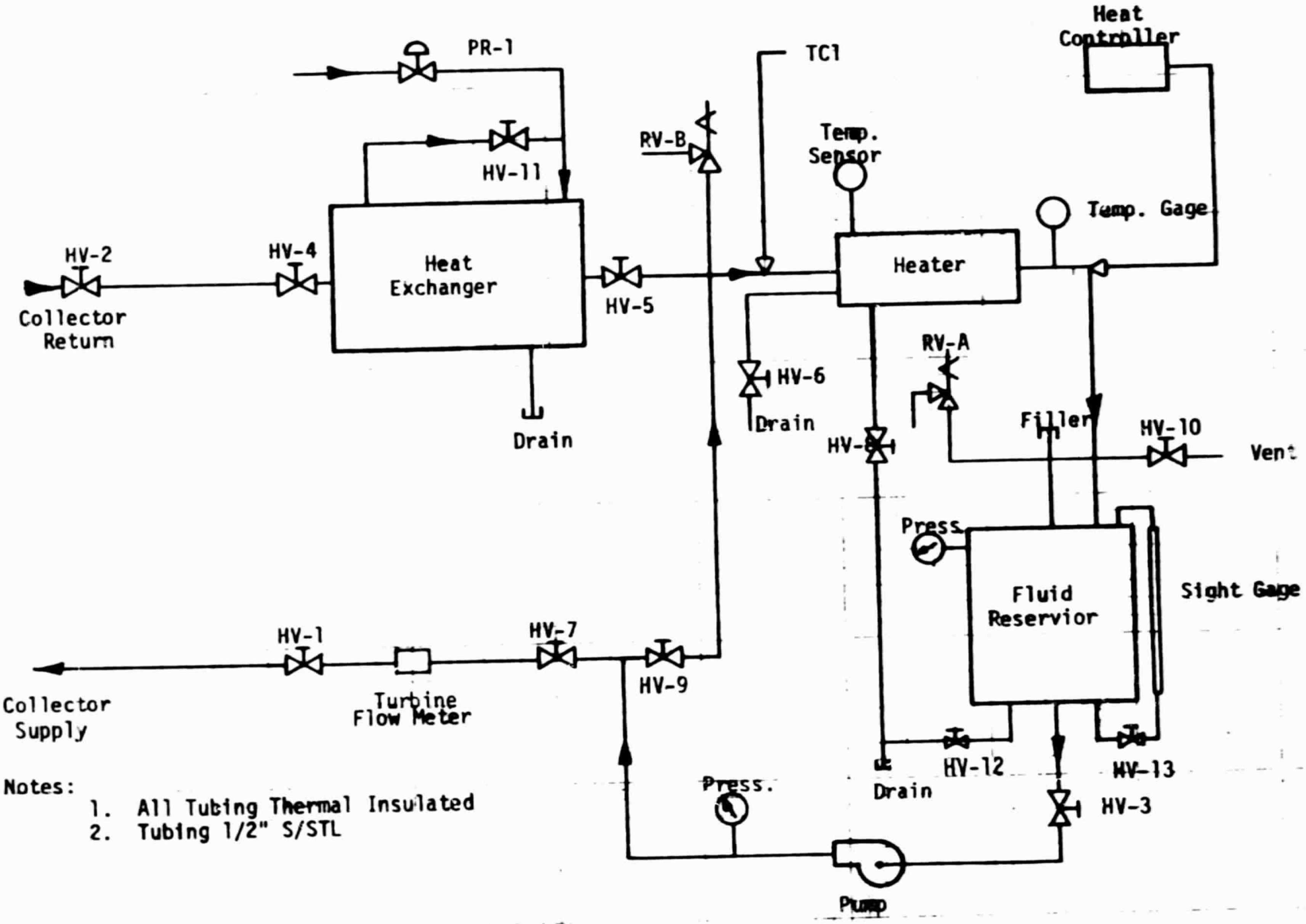
FIGURE 1. Detail Drawing of Sunworks (Liquid) Collector



Notes:
1. All Tubing Thermal Insulated
2. Tubing 1/2" S/STL

FIGURE 2. Collector Liquid Test Loop Flow Diagram

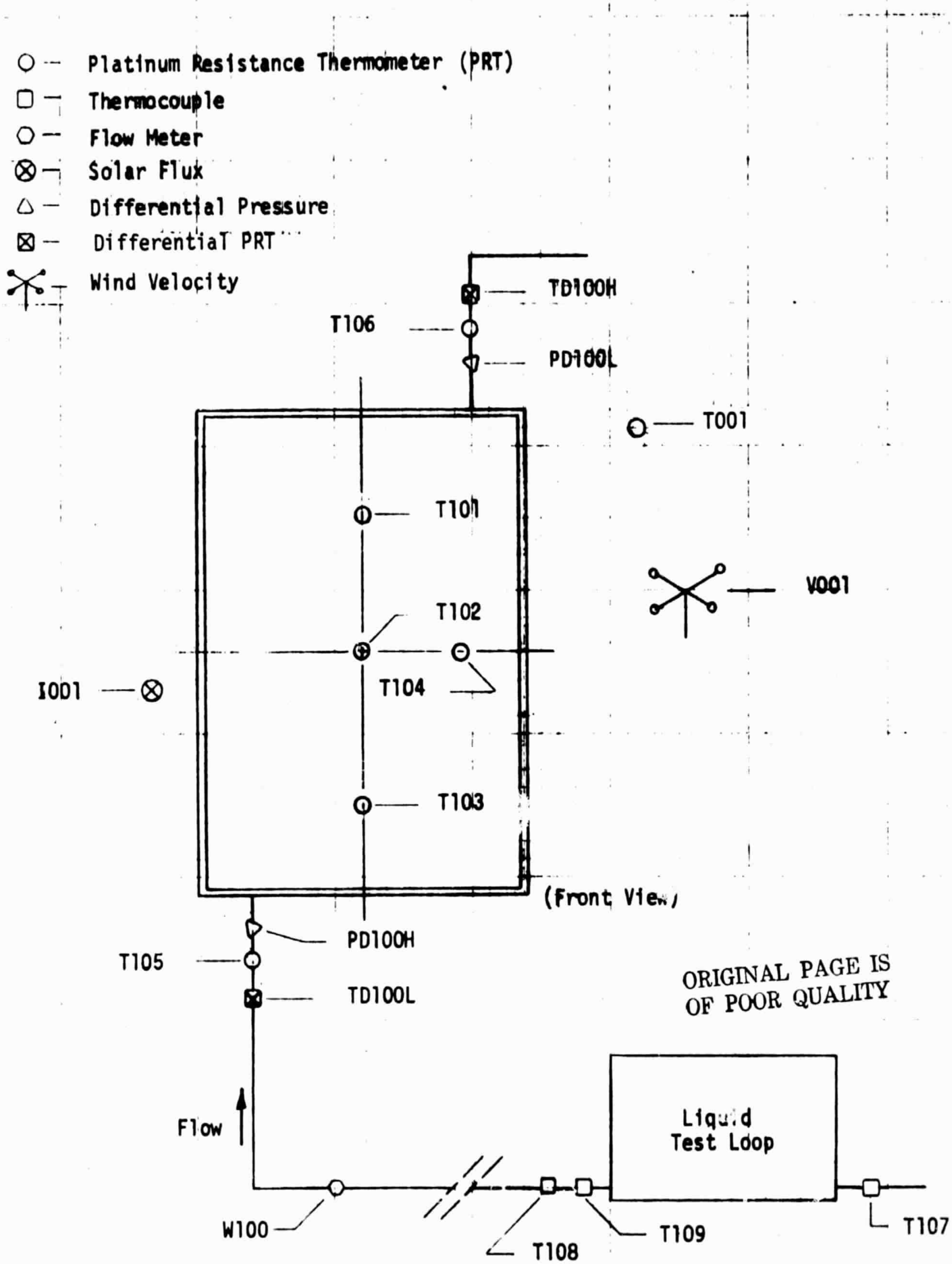


Figure 3. Instrumentation Locations for Sunworks (Liquid) Collector Test

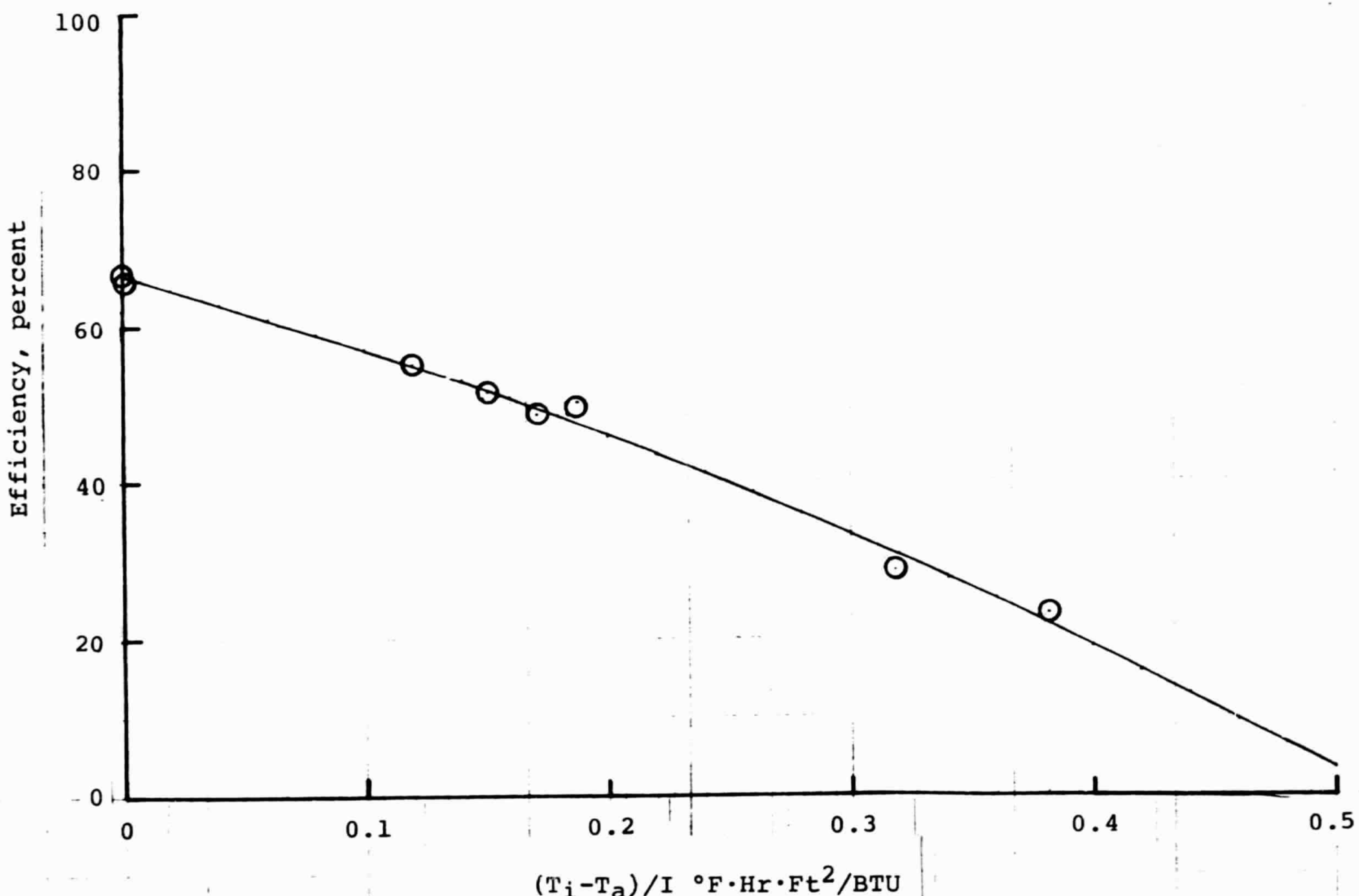


FIGURE 4. Thermal Performance of Sunworks Liquid Collector with Flow Rate of 285 Lbm/Hr.

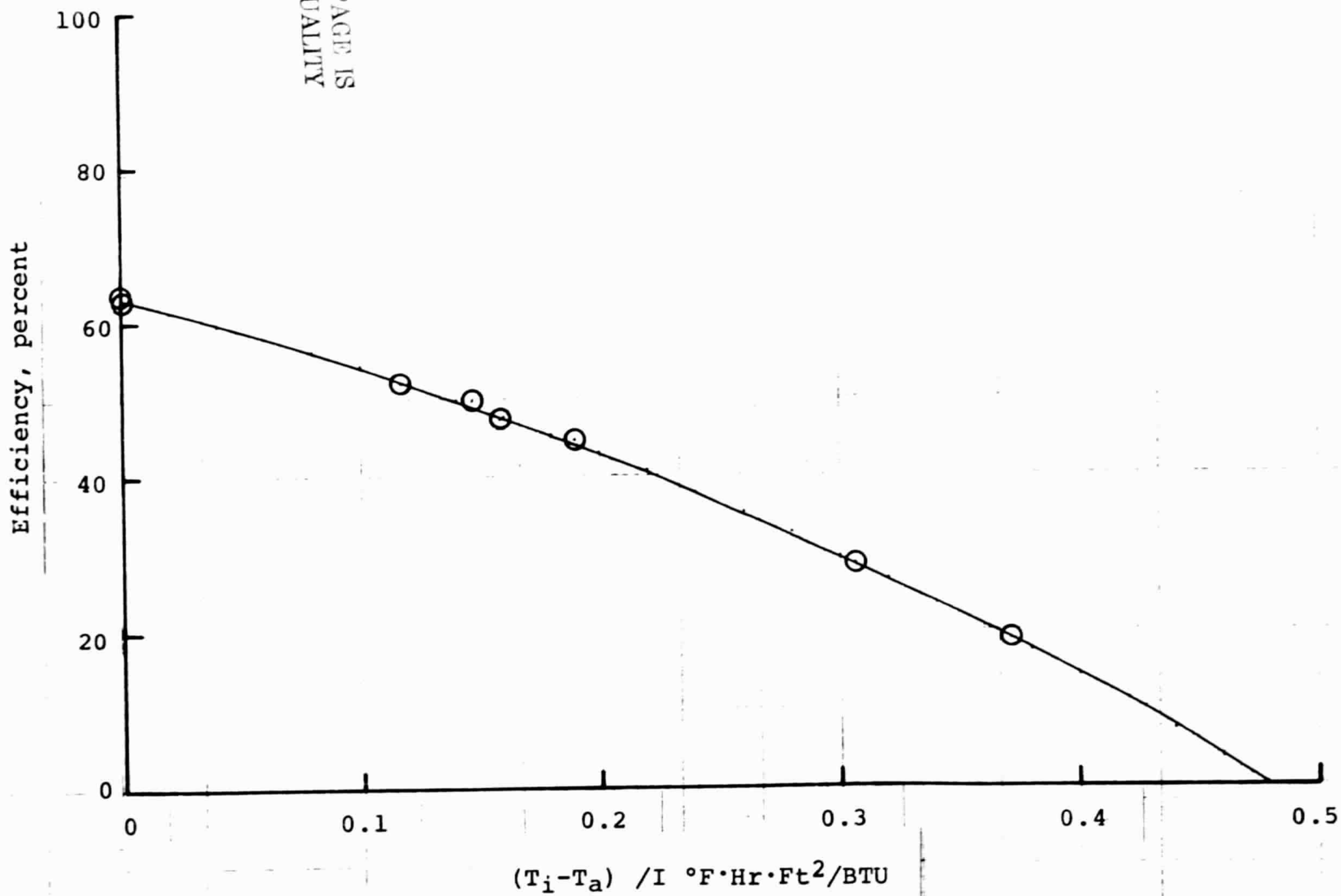


FIGURE 5. Thermal Performance of Sunworks Liquid Collector with Flow Rate of 158 Lbm/Hr.

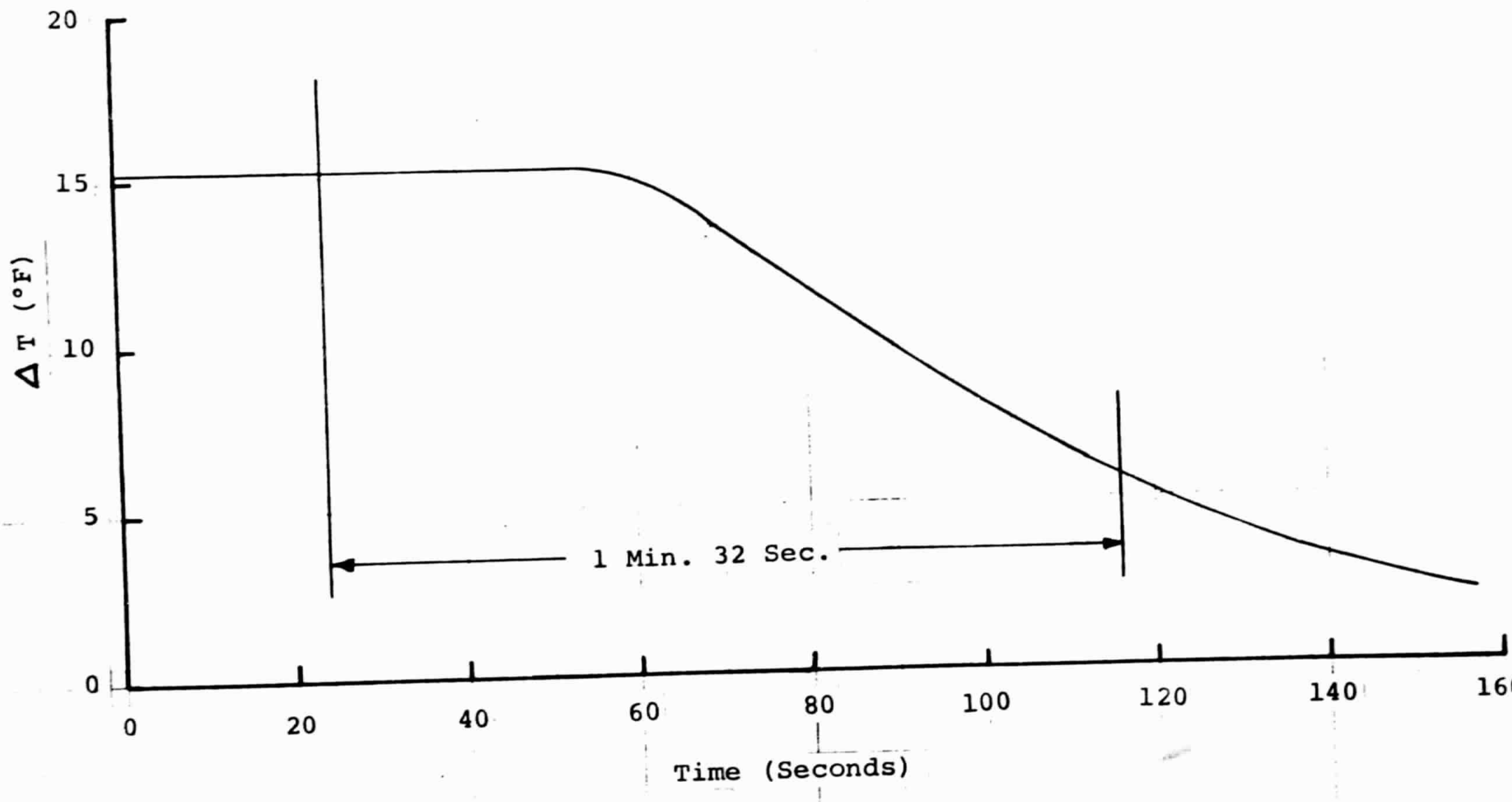


FIGURE 6. Time Constant Test of Sunworks Liquid Collector

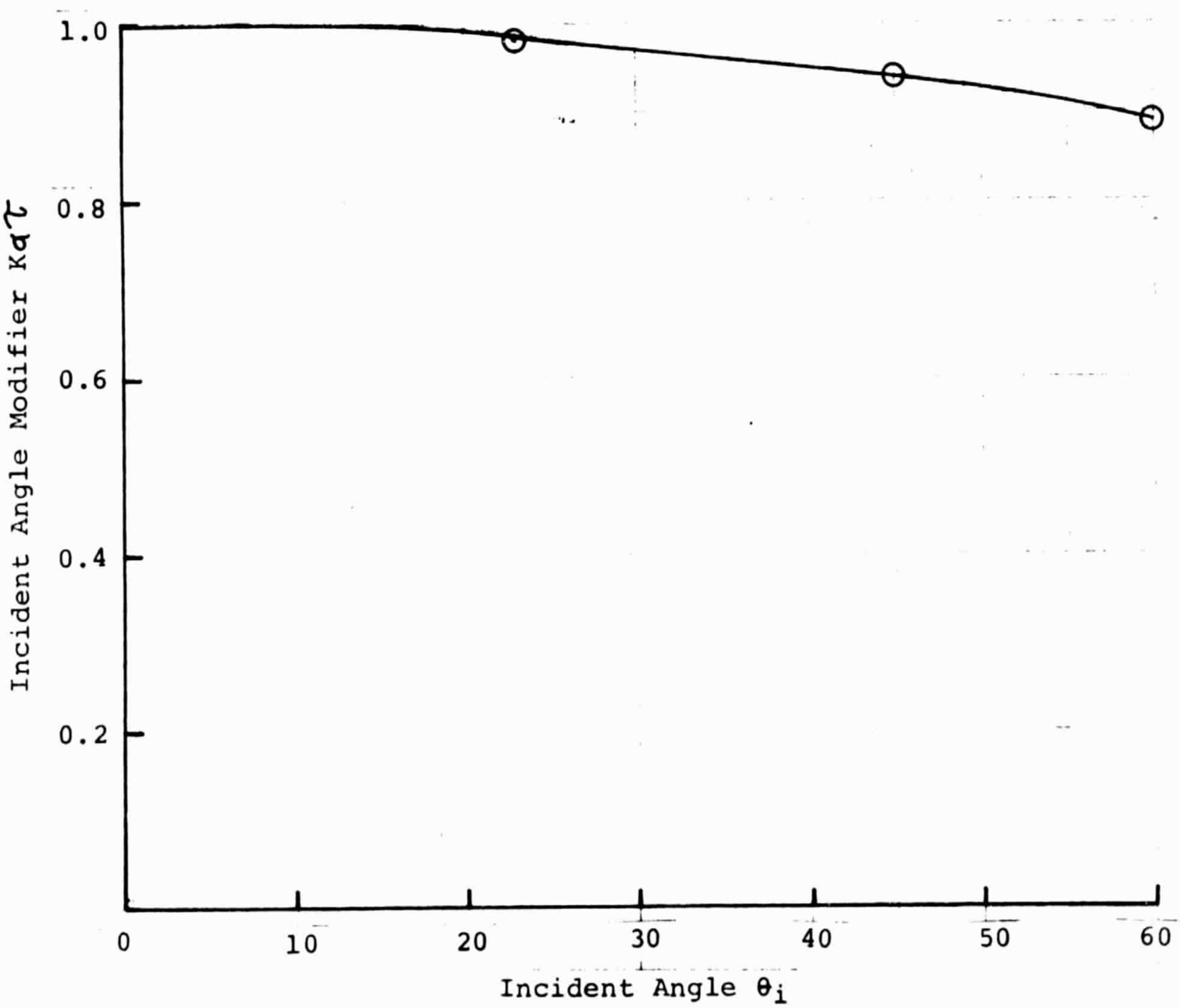


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FIGURE 7. Incident Angle Modifier vs Incident Angle

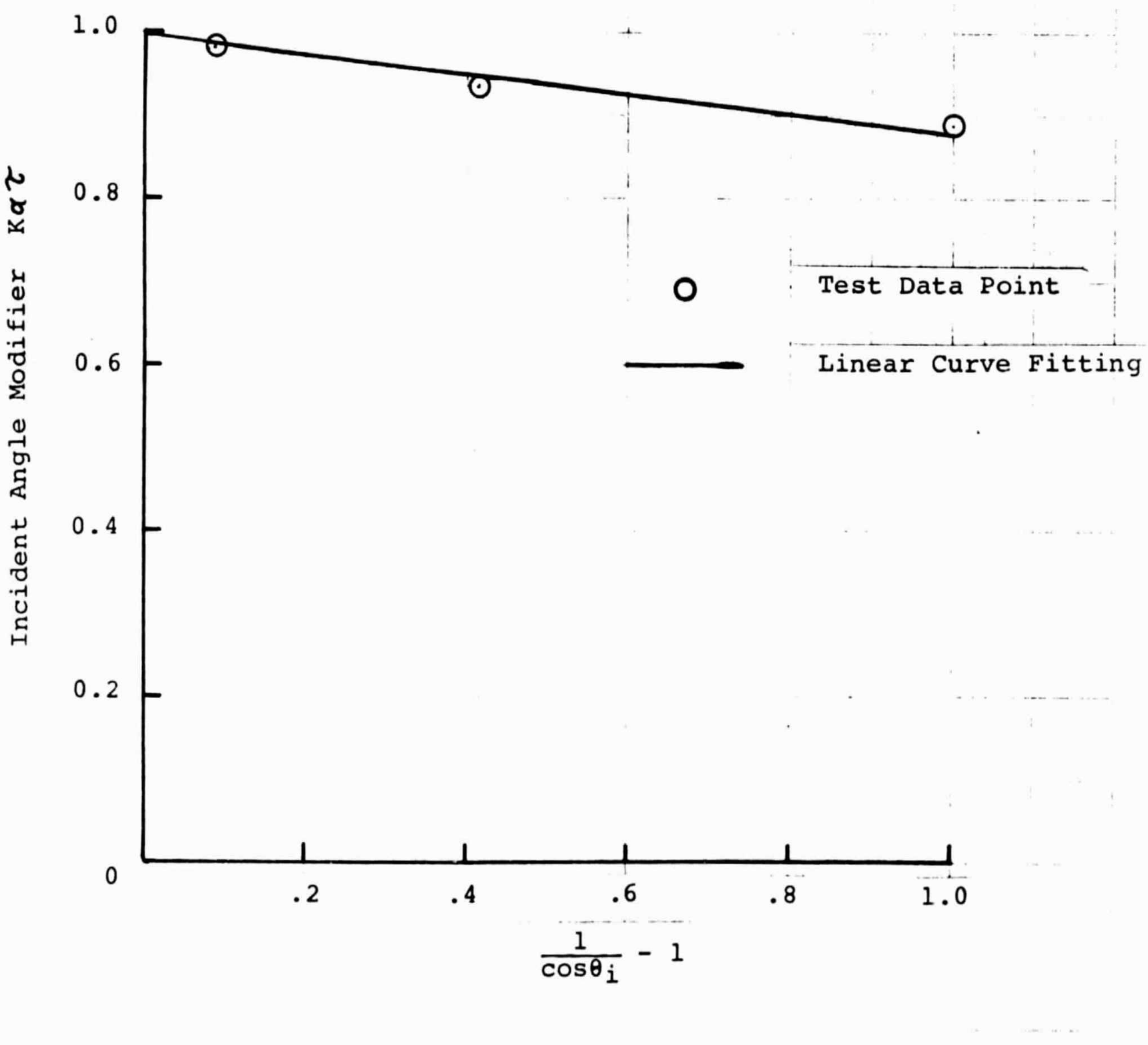


FIGURE 8. Incident Angle Modifier vs $\frac{1}{\cos\theta_i} - 1$

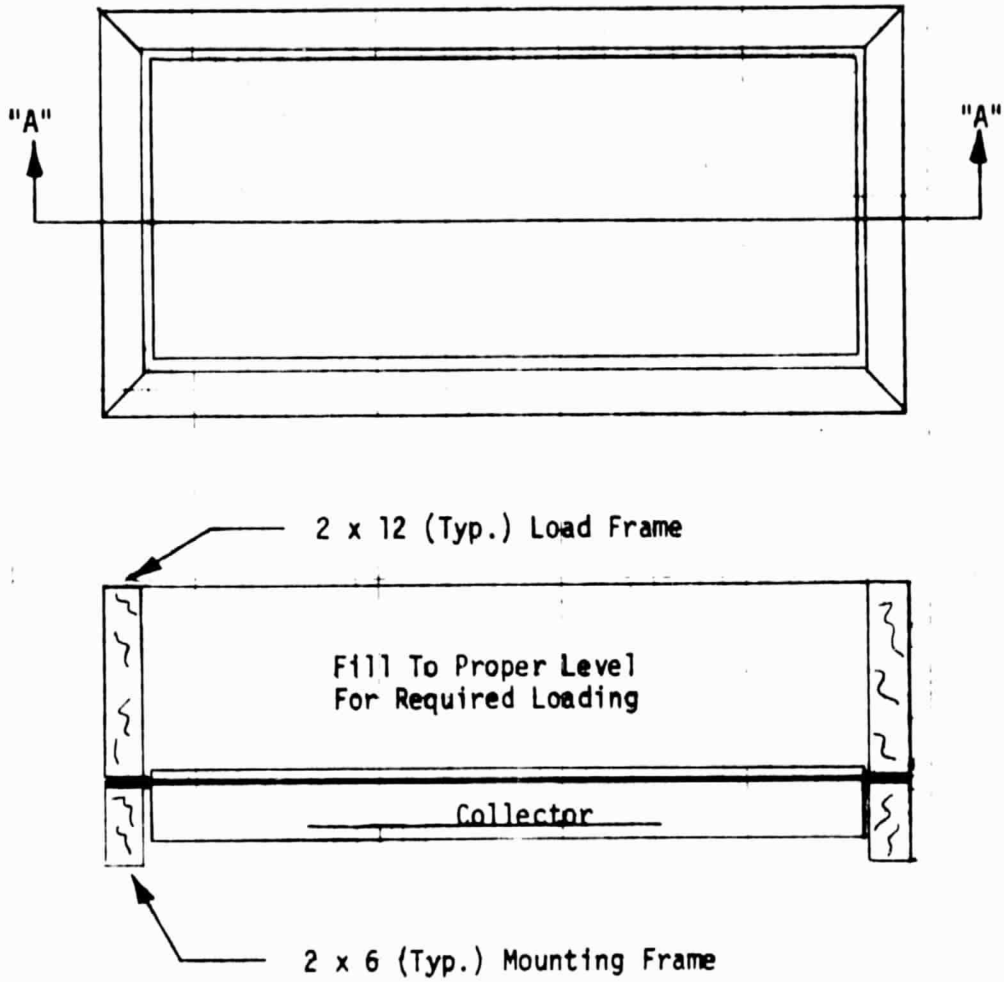
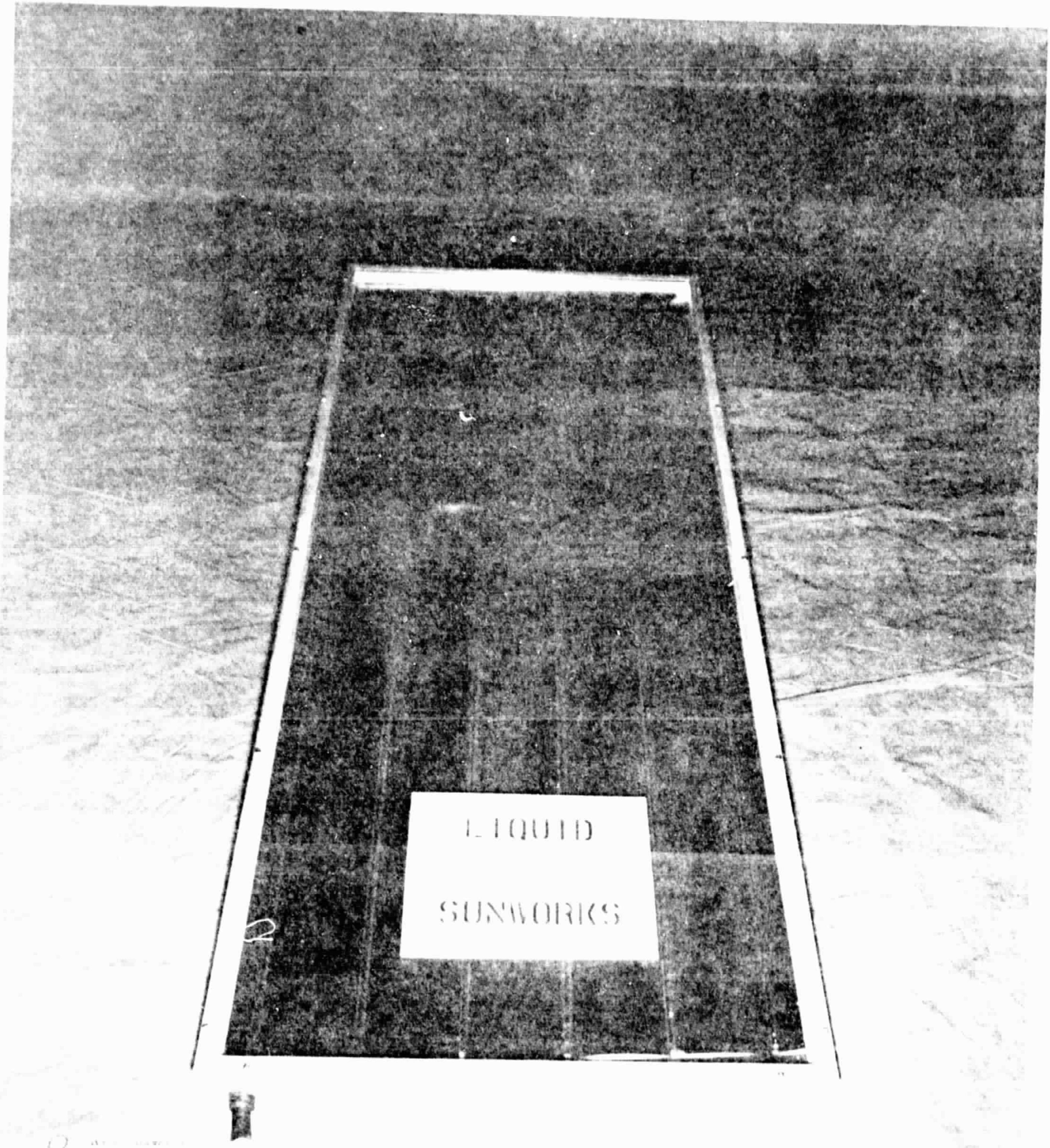


FIGURE 9. Test Setup for Static Loads



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