DOE/NASA CONTRACTOR REPORT

DOE/NASA CR-150819

THERMAL PERFORMANCE EVALUATION OF THE CALMAC (LIQUID) SOLAR COLLECTOR

Prepared by

Wyle Laboratories
Solar Energy Systems Division
Huntsville, Alabama 35805

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

U.S. Department of Energy

Solar Energy

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1.0 PURPOSE

The purpose of this document is to present the procedures used and the test results obtained during an evaluation program. The test program was conducted to obtain the following performance data and information on the Calmac solar collector:

- Thermal performance data under simulation conditions.
- Structural behavior of the collector under static loading conditions.
- Effects of long-term exposure to natural weathering elements.

The tests were conducted utilizing the MSFC 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-FA-SHAC-400	Procedure for Operation of the MSFC Solar Simulator Facility

3.0 COLLECTOR DESCRIPTION

Manufacturer: Calmac Manufacturing Corporation

Manufacturer's Address: 150 South Van Brunt Street
Englewood, N.J. 07631

Model Number: None shown.

Serial Number: 01

Type: Flat Plate

Working Fluid: Water

Gross Collector Area, ft^2: 34.33 ft^2

Overall external dimensions:
- Width, inches: 50.31"
- Length, Inches: 98.25"
- Thickness, Inches: 3.75"
- Aperture area, ft^2: 29.3 ft^2

3.0 COLLECTOR DESCRIPTION (Continued)

Collector glazing: Single (.040 Fiberglas reinforced Polyester (Kalwall)

Weight, lbs: Empty: 78.5 lbs.
Full: 83.5 lbs.

Absorber Plate: .002" aluminum plate with plastic tubes coated with Urethane Black.

4.0 SUMMARY

Results of performance evaluations of collector efficiency, thermal response time, and incident angle modifier are presented in Section 6. Graphical presentations of the collector thermal response time, collector efficiency and incident angle modifier are contained in Figures 3 through 5.

Measurements of stagnation temperature during the preconditioning evaluation and structural load evaluations were not performed during this test program due to the collector construction.

It is noted that the manufacturer limits the maximum operating temperature to 210°F and the maximum operating pressure is specified to be 20 psig.

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.

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-5300.4C, Metrology and Calibration. Table I contains instrumentation identification and data acquisition connection data. Instrumentation locations on the test loop and collector are depicted in Figure 1. A listing of the equipment used in each test follows.

Apparatus	Manufacturer/Model	Range/Accuracy
Platinum Resistance Thermometer	Supplied by Collector Manufacturer	0-500°F ± 0.5°F
Pyranometer	Eppley - PSP	0-800 $BTU/Ft^2 \cdot Hr$ ± 3%
Liquid Loop	MSFC Supplied	.1 - 2.5 GPM
Directional Anemometer	Supplied by AMC	0 - 30 MPH
Flow Meter	Fischer & Porter/ 10A3565SZ	.1 - 2.2 ± .01 GPM
Platinum Resistance Thermometer	Hy-Cal	0-500°F ± 0.5°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 Transducer	Statham	0 - 10 PSID ± 1%

All transducers with the exception of the Eppley PSP pyranometer used in recording test data are calibrated by either NASA or AMC calibration laboratories as required by MSFC MMI 5300.4C. The PSP pyranometer was calibrated by the manufacturer. The stated accuracy of individual transducers reflects the overall expected accuracy through the data acquisition system.

5.0 TEST CONDITIONS AND TEST EQUIPMENT (Continued)

5.3 Data Systems

Test data obtained during simulator tests are transmitted from MSFC Building 4619 (test site) through primary data acquisition system #3 to the real time data link and the DDP-224 computer located in Building 4646. A separate data link between Building 4646 and 4619 provides for printout of real time data at the test site. A listing of all instrumentation by function, type and corresponding data recording system is indicated in Table I.

The end-to-end accuracy of data derived from system testing is subject to an error analysis which accounts for all inaccuracies in the transducer, signal conditioning, signal transmission and computer processing methods. Since a formal systems error analysis will not be done, confidence in printout accuracies are established by installing calibrated "parallel" transducers and direct readouts at key points in the system and performing comparison checks from time to time before, during and after tests. The results of such checks together with a review of the data for anomalies indicate that the data presented is suitable for the purpose intended.

6.0 TEST REQUIREMENTS AND PROCEDURES

6.1 Collector Preconditioning and Stagnation Test

Tested By B. Henderson
Started 4/10/78
Completed 4/13/78

6.1.1 Requirement

The collector shall be mounted on an outdoor passive test stand at an angle of 45° from the horizontal and facing south. The inlet and outlet ports to the collector shall be capped to prevent flow. The upper cap shall contain a small vent hole. The preconditioning shall consist of at least three days exposure during which the mean incident solar radiation measured in the plane of the collector shall be 1500 BTU/Ft^2·day. During this preconditioning, the following data shall be recorded within two hours of solar noon when the insolation is constant and above a minimum of 200 BTU/Hr·Ft^2 in the plane of the collector. Data recorded shall be the average for at least a 20 minute period at quasi-steady state conditions.

1. Insolation rate.
2. Ambient temperature.
3. Wind Velocity and direction.
4. Absorber surface temperature at either 4 or 5 locations. (Not instrumented)

6.1.2 Procedure

1. Mount test specimen as described above.
2. Connect instrumentation.
3. Record data as described above.

6.1.3 Results

The following data sheet shall be used to record these stagnation conditions.

Date	Time	Insolation Rate BTU/Ft^2·Hr	Ambient Temperature. °F	Wind Dir/Vel deg/mph	Absorber Plate Temp., °F				
					T101	T102	T103	T104	T105*
	Total exposure 3 days at				Not	instrumented			
	1500 BTU/day.				due	to collector			
					construction.				

* T105 is an optional temperature sensor installed by some manufacturers.

6.C TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Collector Time Constant Test

Tested By B. Henderson
Started 5/22/78
Completed 5/22/78

6.2.1 Requirements

The collector time constant shall be determined by abruptly reducing the solar flux to zero. This will be done with the inlet temperature adjusted to within ± 2°F of ambient while the liquid is flowing at 14.7 lbm/hr·ft^2. These are recommended flowrates. The manufacturer's flowrates should be used when specified. The differential temperature across the collector shall be monitored to determine the time required to reach the condition of:

$$\frac{\Delta T(t)}{\Delta T_i} = .368$$

where $\Delta T(t)$ is the differential temperature at time t after the solar flux is reduced to zero and ΔT_i is the differential temperature prior to the power down of the solar simulator. The liquid to be used as the collector heat transfer medium shall be as specified by the manufacturer. If this liquid is not specified, use water as the fluid.

The following data will be recorded for the test:

(1) Solar flux.
(2) Ambient temperature.
(3) Inlet liquid temperature.
(4) Collector differential temperature.
(5) Liquid flow rate.
(6) Specified heat transfer medium.

6.2.2 Procedure

1. Adjust the liquid flow rate to 999.6 lbm/hr.*

2. Adjust the inlet temperature to ambient ± 2°F.

3. Power up the solar simulator and establish a solar flux level of 260 BTU/Ft^2·Hr.

4. Establish wind speed of 7.5 mph.

* These are recommended flowrates. The manufacturer's flowrates should be used when specified.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Collector Time Constant Test (Continued)

6.2.3 Results

The thermal response time of the Calmac collector was determined to be 1 minute and 44 seconds. Experimental results are shown graphically in Figure 3. Data analysis methods are described in Section 7.1.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.3 Collector Thermal Efficiency Test

Tested By	R. Heinisch, Jr.
Started	5/1/78
Completed	5/1/78

6.3.1 Requirements

Utilizing the MSFC Solar Simulator and the portable liquid loop, parametric performance evaluation data shall be recorded of the following test variables and conditions. The liquid to be used is the manufacturer's recommended heat transfer fluid. If not specified, the test shall be performed using water as the working fluid.

Variable/Condition	Requirement
(1) Collector inlet liquid temperature differential above existing ambient temperature level	0°F, 25°F, 50°F, 75°F and 100°F
(2) Collector outlet liquid temperature	Measured data
(3) Incident solar flux level liquid	250, 300 $BTU/Hr \cdot Ft^2$ °F
(4) Liquid flow rate through collector (Ref. 2.1, area based on aperture)	14.7 $lbm/hr \cdot ft^2$
(5) Wind speed	7.5 MPH
(6) Ambient air temperature	Existing room condition

6.3.2 Procedure

1. Mount test specimen on test table at a 45° angle with reference to the floor.
2. Assure that simulator lamp array is adjusted to an angle of 45° with reference to the floor.
3. Using the procedure contained in Reference 2.3, align the test table so the test specimen's vertical centerline coincides with the vertical centerline of the lamp array and the distance from the loop of the test specimen to the lens plane of the lamp array is 9 feet.
4. Insulate all liquid lines.
5. Connect instrumentation leads to data acquisition system in accordance with Table I.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.3 Collector Thermal Efficiency Test (Continued)

6.3.2 Procedure (Continued)

6. Assure that data acquisition system is operational.

7. Perform sensor accuracy verification tests.

8. Establish required wind speed.

9. Start liquid flow loop and establish the required flow rate.

10. Establish the required inlet temperature.

11. Power up solar simulator in accordance with Reference 2.2 and establish the required solar flux level.

12. Record data for a minimum of five minutes at these stabilized conditions.

13. Repeat Steps 9 through 12 as necessary to complete all the required test conditions with independent tests as specified below:

Test No.	Inlet Liquid Temperature Differential Above Existing Ambient Temp., °F	Solar Flux BTU/Hr·Ft^2 °F	Liquid Flow Rate LBM/HR	Wind Speed, MPH
1	0	250	999.6	7.5
2	0	300	999.6	7.5
3	25	250	999.6	7.5
4	25	300	999.6	7.5
5	50	250	999.6	7.5
6	50	300	999.6	7.5
7	75	250	999.6	7.5
8	75	300	999.6	7.5
9	100	250	999.6	7.5
10	100	300	999.6	7.5

6.3.2 Procedure (Continued)

14. Upon completion of testing, power down simulator and liquid loop in accordance with Reference 2.2.

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

6.3.3 Results

Results of thermal efficiency tests are depicted graphically in Figure 4. Supporting data obtained during the test are presented in Table II. The methods of data analyses are described in Section 7.2.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.4 Incident Angle Modifier Test

Tested By B. Henderson
Started 5/2/78
Completed 5/2/78

6.4.1 Requirements

The collector incident angle modifier shall be determined by tilting the collector at 30°, 40°, 50° and 60° with respect to the solar simulator surface. The liquid flow rate shall be 999.6± 2 lbm/hr with the inlet temperature controlled to within ± 2°F of ambient. The insolation rate shall be 250 BTU/Ft^2·Hr. The liquid to be used is the manufacturer's recommended fluid. If not specified, the tests shall be performed using water as the heat transfer medium. The following data shall be recorded during the tests.

(1) Collector tilt angles.

(2) Ambient air temperature.

(3) Collector inlet liquid temperature.

(4) Collector outlet liquid temperature.

(5) Collector differential temperature.

(6) Collector differential pressure.

(7) Incident solar flux level.

(8) Liquid flow rate through the collector.

6.4.2 Procedure

1. Set up collector at required tilt angle.
2. Establish required flowrate.
3. Establish required inlet temperature.
4. Establish solar simulator flux level at 250 BTU/Ft^2·Hr and measure the flux levels at 9 locations on the collector surface and record on data sheet.
5. Record data for five minutes at above stabilized conditions.
6. Repeat above steps as necessary to obtain required data for each tilt angle.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.4 Incident Angle Modifier Test (Continued)

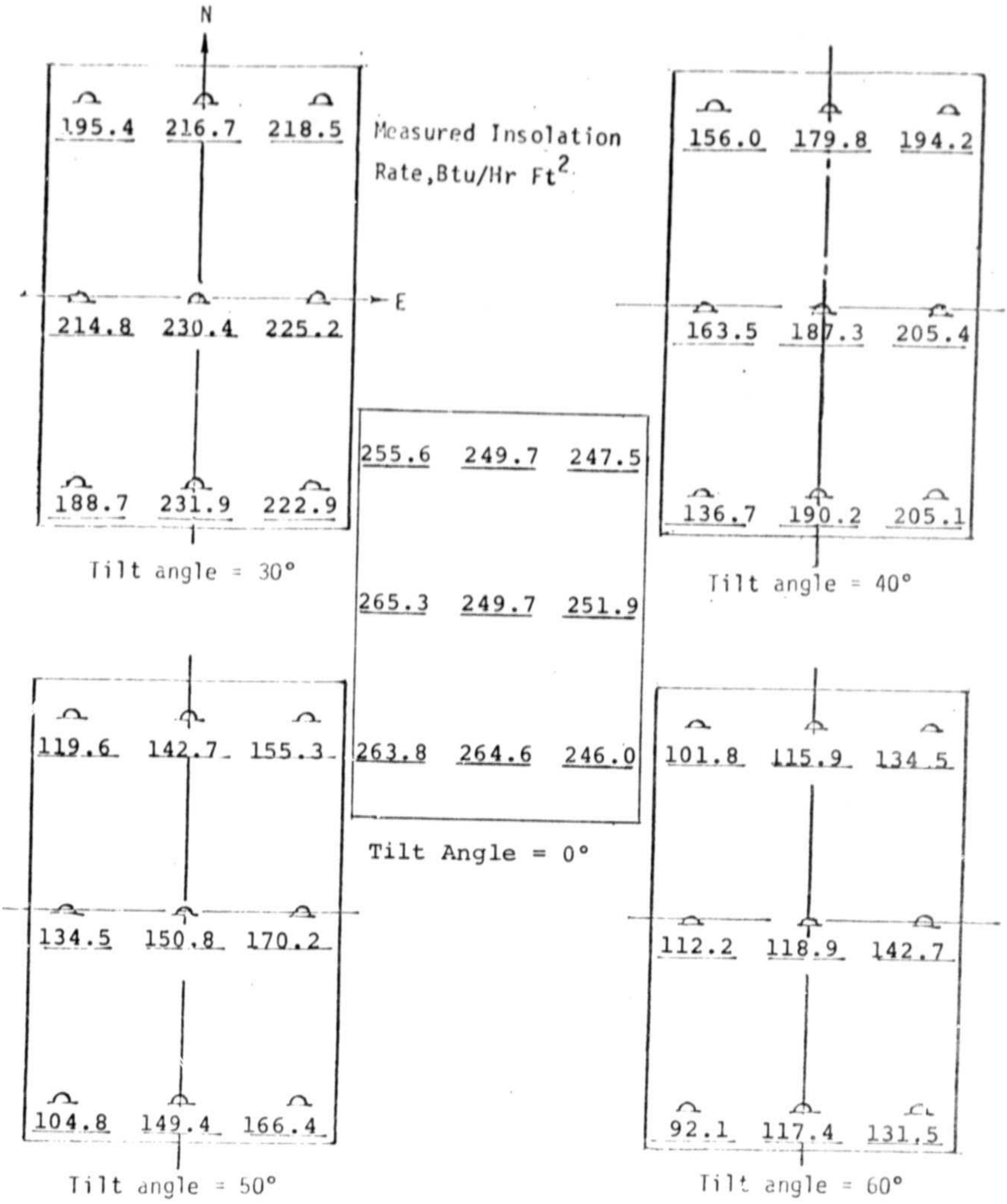
6.4.3 Results

The following data sheet was utilized to record steady state data for the incident angle modifier test.

Collector Tilt Angle, Degrees	30	40	50	60	0
Average Solar * Insolation Rate, $BTU/Hr \cdot Ft^2$	216.0	179.8	143.7	118.5	255.0
Ambient Air Temperature, °F	72.2	72.1	71.2	72.5	71.1
Collector Inlet Temperature, °F	73.0	73.0	72.7	73.3	73.1
Collector Outlet Temperature, °F	78.0	77.1	75.9	75.9	79.0
Collector Differential Temperature, °F	5.0	4.1	3.2	2.6	5.9
Flowrate through Collector, lbm/hr.	999.6	999.6	999.6	999.6	999.6
Collector Differential Pressure, in. water	NOT MEASURED				
Incident Angle Modifier, $K_{\alpha\tau}$	1.0	.99	.966	.95	1.0

* Data measured to obtain average insolation rates are to be recorded on the following sheet.

The resulting incident angle modifier values are shown graphically in Figure 5 as a function of the angle of incidence. Methods of data analysis are described in Section 7.3.



MEASURED INSULATION RATES AS A FUNCTION OF COLLECTOR TILT ANGLE

7.0 ANALYSIS

7.1 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 3 the time constant was determined to be 1 minute and 44 seconds.

7.0 ANALYSIS (Continued)

7.2 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:

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

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 ($BTU/Lb \cdot °F$)

$t_{f,e}$ = 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:

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

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)

7.2 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 result of second order polynomial analysis is shown in Figure 4. 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)

7.2 Thermal Performance Test (Continued)

where:

$$\tau = (t_i - t_a)/I$$

and the coefficients are determined to be:

$$a_0 = 62.67; \ a_1 = -101.90, \text{ and } a_2 = -9.19$$

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

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

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 in Section 6.4.3 and are plotted against incident angle in Figure 5.

TABLE I
DESIGNATION OF INSTRUMENTATION FOR SIMULATOR TESTS

Meas. No.	Sensor Location	Instrument Output Range	Meas. Range	Serial No.	Model No.
T101	Collector Absorber Plate 1	20 MV	-50 - 400°F	Mfg.*	RTS-4175-100
T102	Collector Absorber Plate 2	"	"	"	"
T103	Collector Absorber Plate 3	"	"	"	"
T104	Collector Absorber Plate 4	"	"	"	"
T107	Collector Absorber Plate 5	"	"	"	"
T105	Collector Fluid Inlet	"	60 - 250°F	35	RTS-4135-100
T106	Collector Fluid Outlet	"	60 - 250°F	85	RTS-4135-100
T109	Ambient Air	"	40 - 100°F	100	RTS-4135-100
F001	Fluid Flow Rate/ Pressure Transducer	0 - 5 VDC	35 - 130 ACFM	71712-1	52D0010AM6
I001	Solar Flux	0 - 20 MV	0 - 743 BTU/ $Hr \cdot Ft^2$	14134F3	PSP
T008	Nozzle Temperature	0 - 20 MV	60 - 250°F	50	RTS-4135-100
PD100	Across Collector	-	0 - 10 PSID	Statham Differential Pressure Transducer	
TD100	Across Collector	0 - 20 MV	0 - 140°F	12261	TP-6T-180-240-1027

* Installed by Collector Manufacturer.

TABLE II

CALMAC LIQUID COLLECTOR
THERMAL PERFORMANCE TEST DATA

Ambient Air Temperature (T_a), °F	67.6	67.6	67.3	67.8	67.7	68.0	63.5	65.4	63.9	65.0
Fluid Inlet Temperature (T_i), °F	69.0	70.3	92.0	92.4	114.6	117.2	139.9	142.9	163.9	164.0
Fluid Outlet Temperature (T_{out}), °F	74.3	67.3	96.6	98.3	118.5	122.3	142.6	146.8	166.0	167.75
Differential Fluid Temperature (ΔT), °F	5.3	6.7	4.6	5.9	3.9	5.1	2.7	3.9	2.1	3.15
Solar Flux, BTU/Hr·Ft^2	256.6	307.8	256.0	307.8	256.6	307.8	256.6	308.8	256.6	307.8
Flow Rate, lb/hr	998.6	998.6	995.6	995.6	989.6	988.6	983.6	983.6	977.6	977.6
Windspeed, MPH	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Efficiency, %	60.1	63.3	52.0	55.6	43.8	47.7	30.1	35.4	22.5	29.2
(T_i - T_a)/I, °F·Hr·Ft^2/BTU	.005	.008	.096	.079	.187	.159	.297	.251	.389	.321

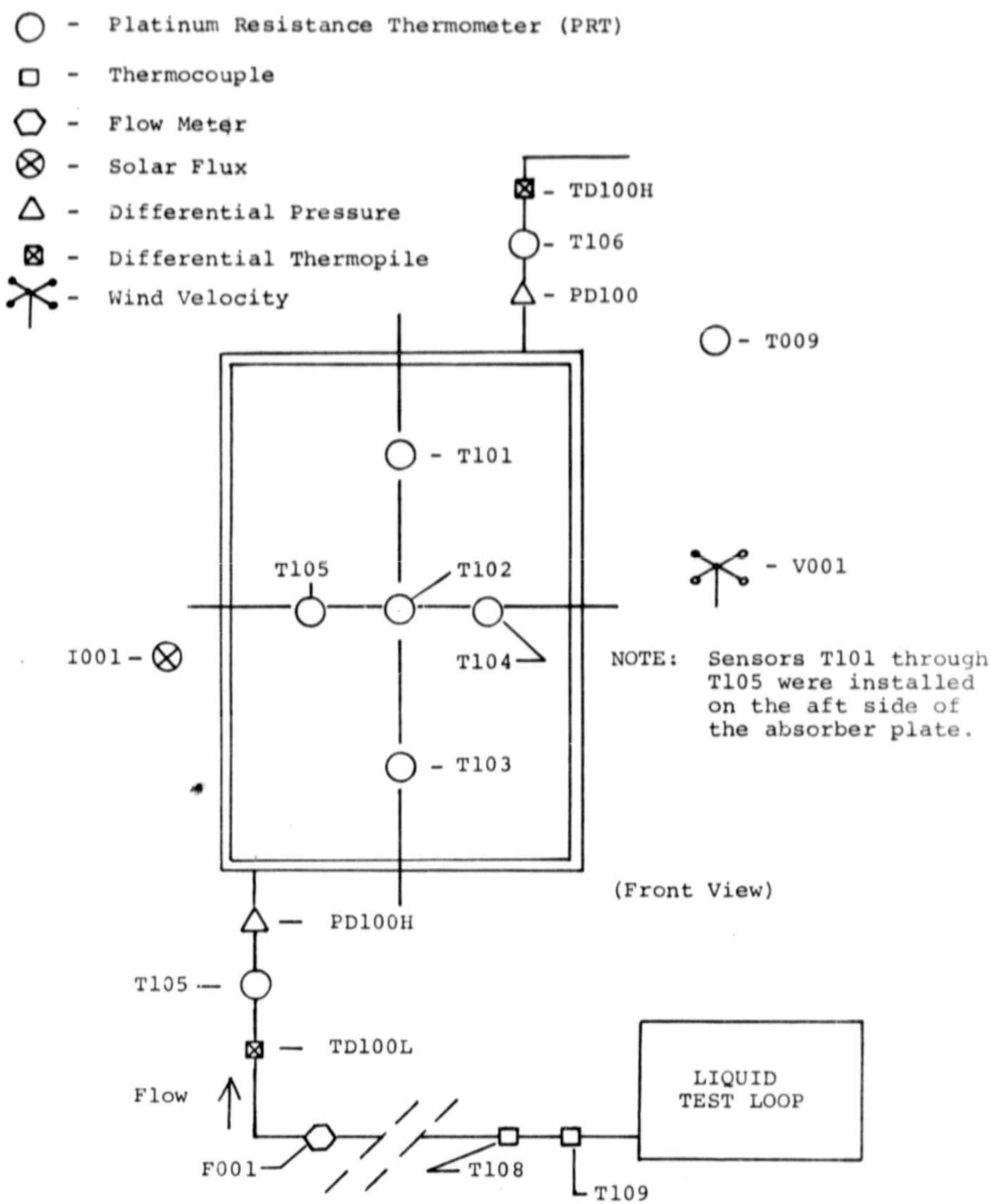


Figure 1. Instrumentation Locations for Liquid Collector Test

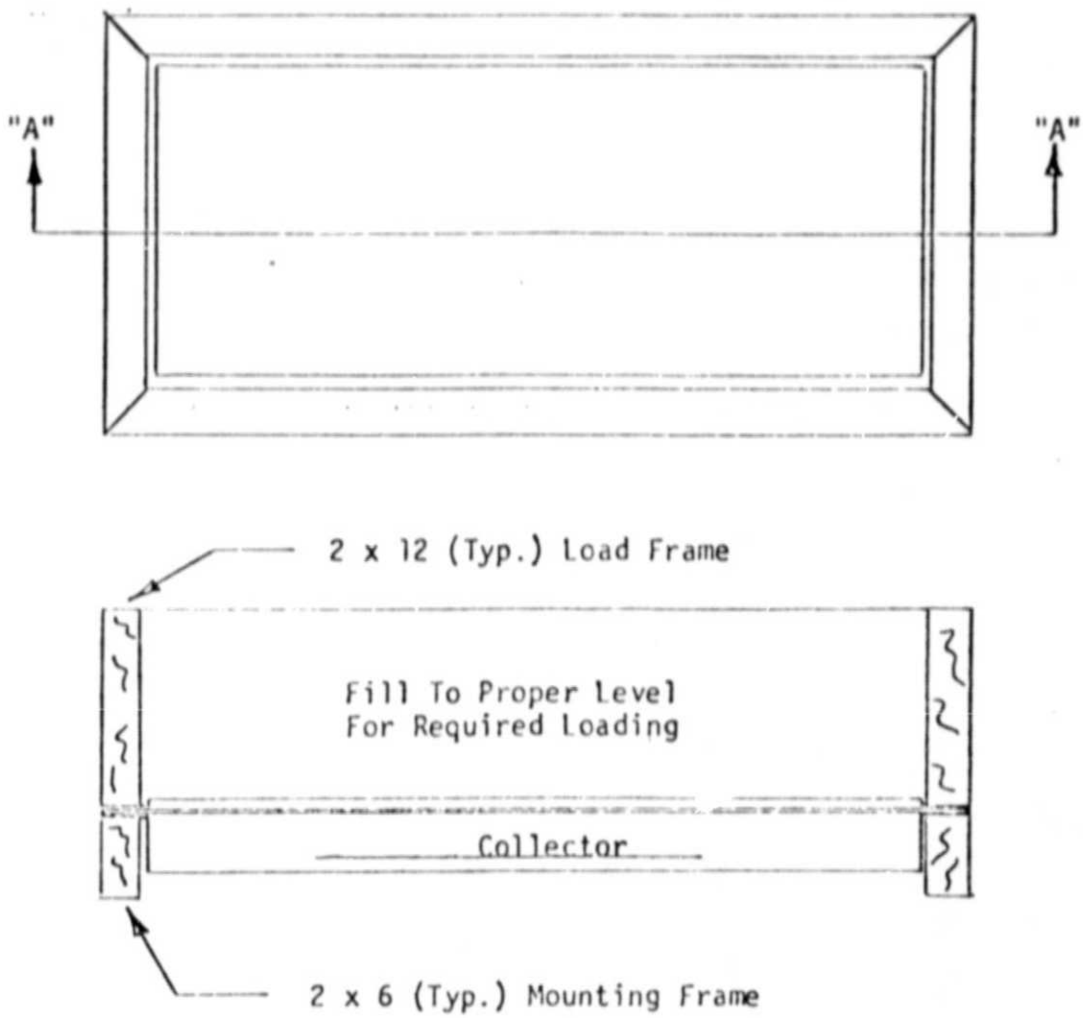


FIGURE 2. Test Setup for Static Loads.

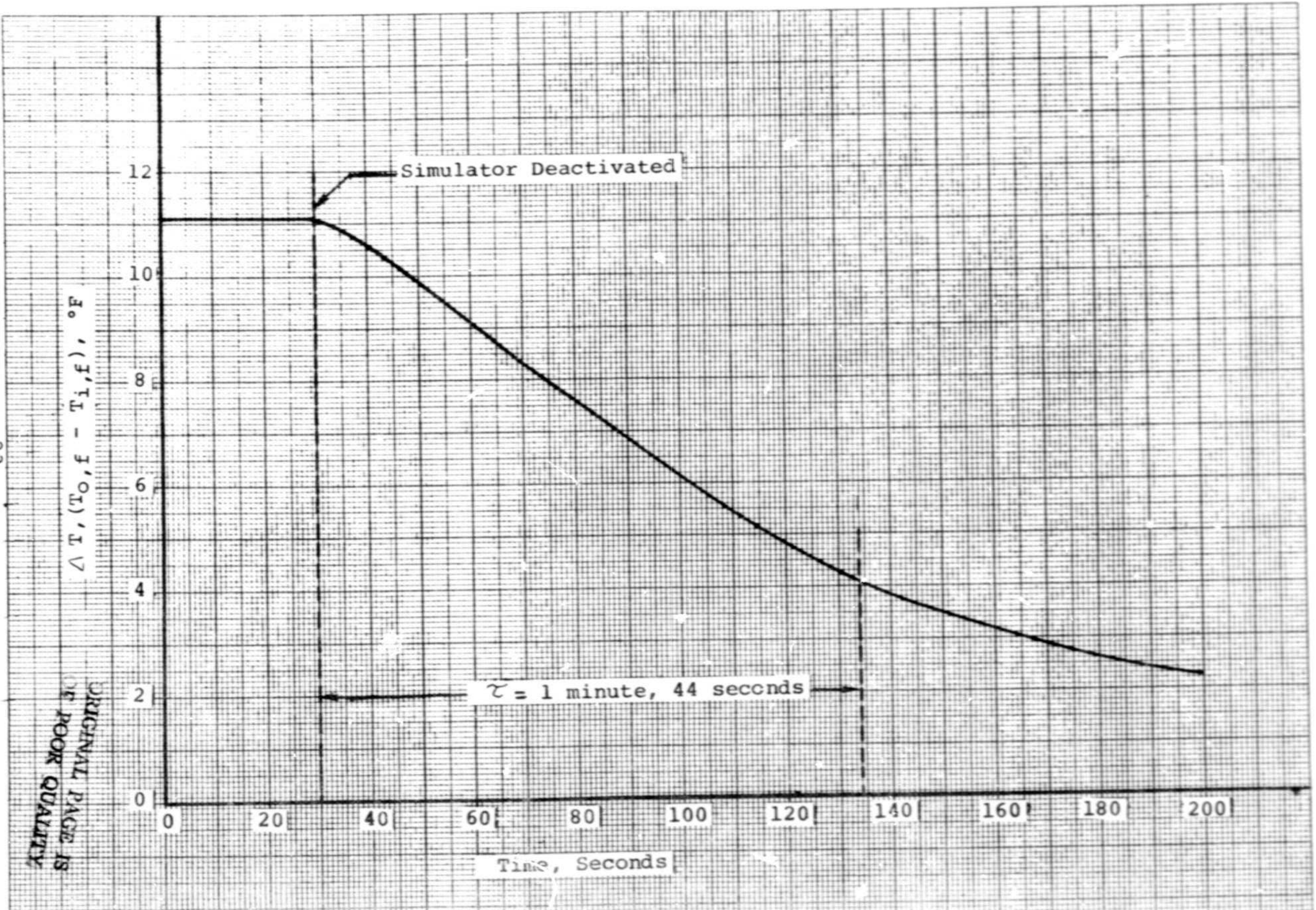


Figure 3. Time Constant Test of Calmac Collector

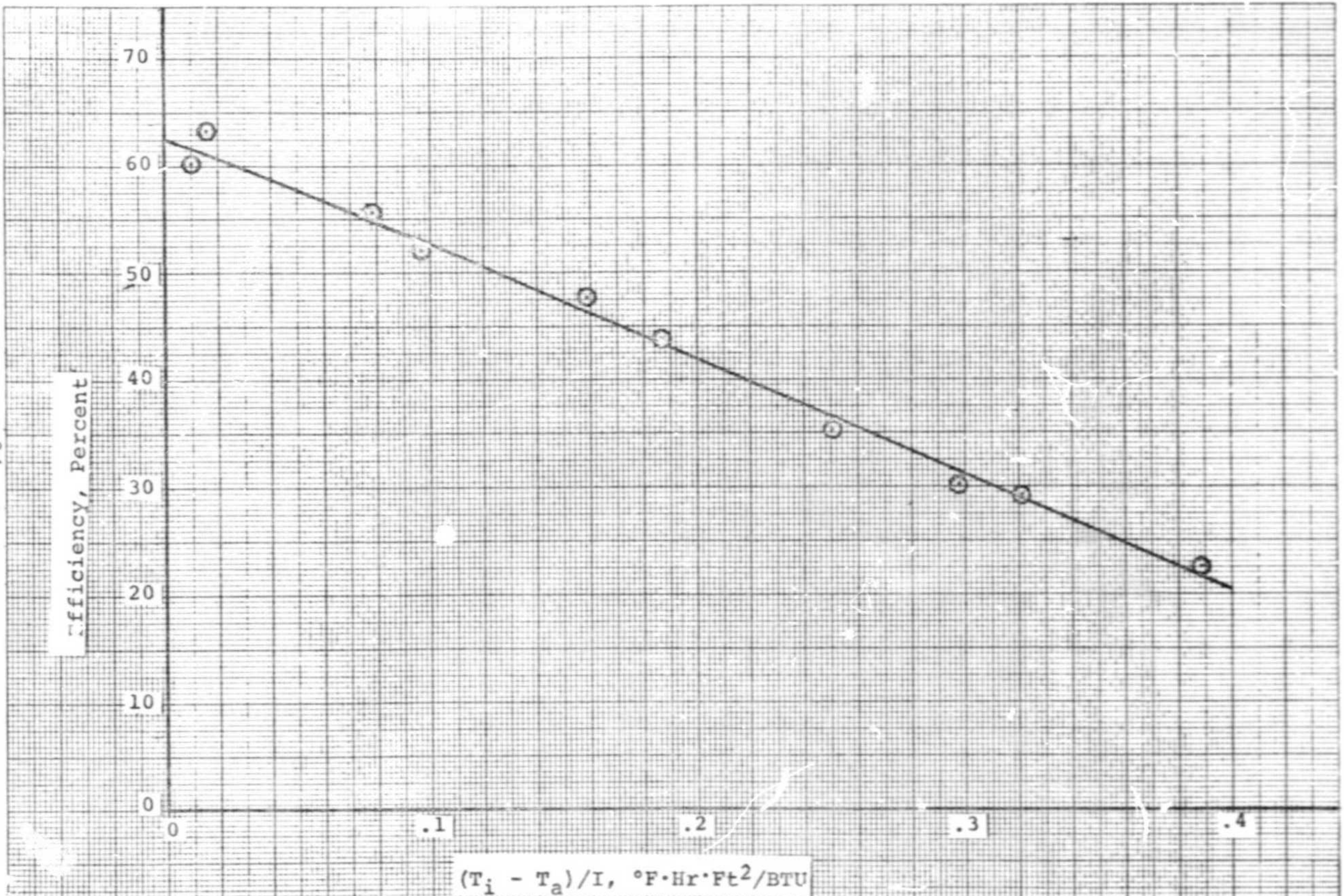


Figure 4. Thermal Efficiency of Calmac Liquid Collector

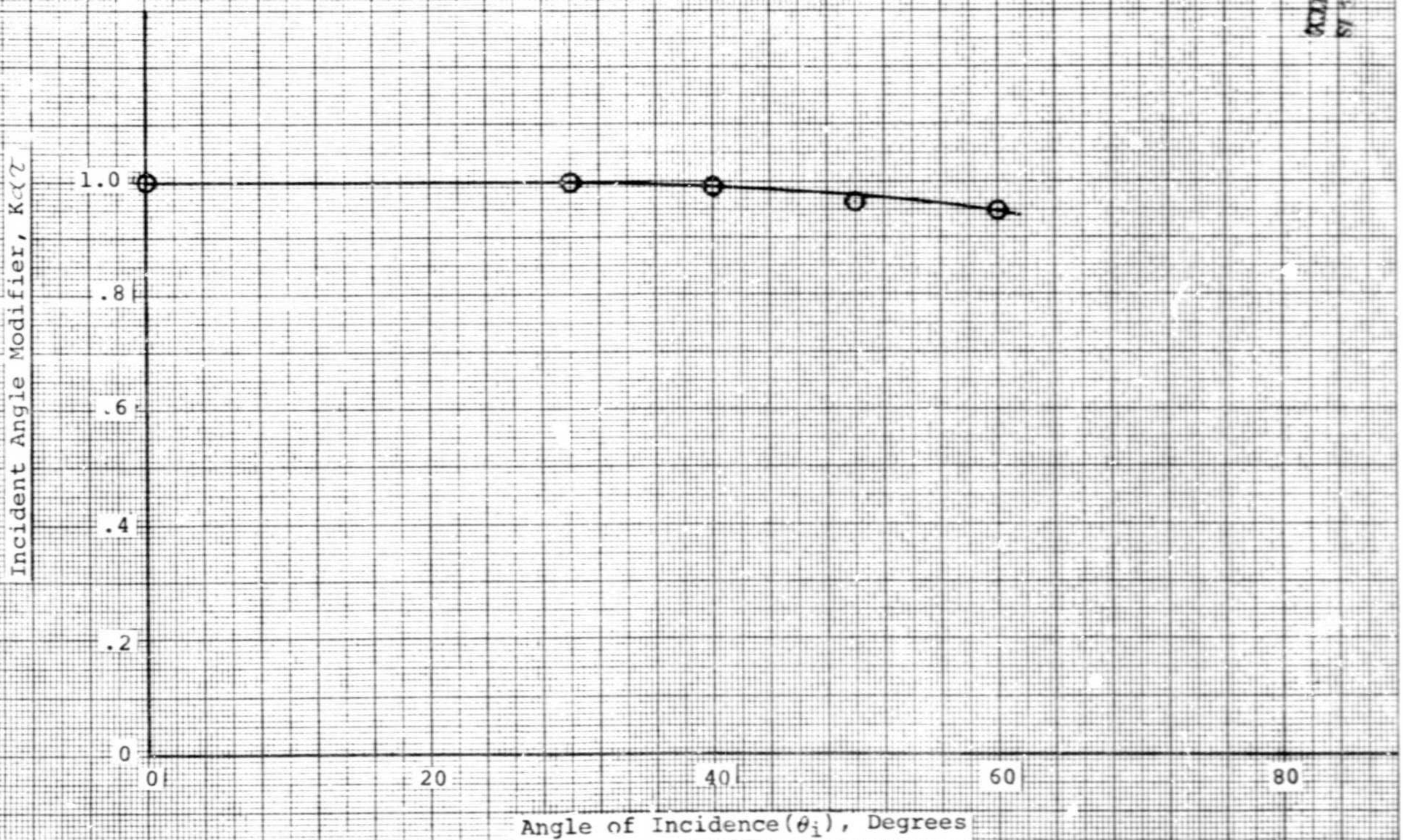


Figure 5. Incidence Angle Modifier Versus Angle of Incidence

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