DOE/NASA CONTRACTOR REPORT

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INDOOR TEST FOR THERMAL PERFORMANCE OF THE SUNMASTER EVACUATED TUBE (LIQUID) SOLAR COLLECTOR

Prepared by

Wyle Laboratories
Solar Energy Systems Division
Huntsville, Alabama 35805

Under subcontract with IBM, Federal Systems Division, Huntsville, Alabama 35807

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For the U. S. Department of Energy

(NASA-CR-161306) INDOOR TEST FOR THERMAL PERFORMANCE OF THE SUNMASTER EVACUATED TUBE (LIQUID) SOLAR COLLECTOR (Wyle Labs., Inc.) 40 p HC A03/MF A01 CSCL 10A

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1.0 PURPOSE

The purpose of this document is to present the test procedures used during the performance of an evaluation test program to obtain performance data on the Sunmaster solar collector under simulated conditions.

The test was performed utilizing the MSFC solar simulator in accordance with the test requirements specified in Reference 2.1 and the procedures contained in Reference 2.2, except where noted in the test procedure to accommodate test requirements peculiar to the Sunmaster collector.

2.0 REFERENCES

2.1 ASHRAE 93-77		Method of Testing to Determing the Thermal Performance of Solar Collectors
2.2 MTCP-FA-SHAC-400		Procedure for Operation of the MSFC Solar Simulator Facility
2.3 NBSIR 78-1305A		Provisional Flat Plate Solar Collector Testing Procedures: First Revision

3.0 COLLECTOR DESCRIPTION

Manufacturer:	Sunmaster Corporation	
Manufacturer's Address:	12 Spruce Street Corning, New York 14830	
Model Number:	Sunmaster DEC-8 (Original) Sunmaster DEC-8A (Modified)	
Serial Number:	DEC-8 DEC-8A	000118 002949
Type:	Evacuated Tube	
Working Fluid:	Water	
Gross Collector Area, Ft^2:	17.17	
Overall external dimensions:	Width, inches Length, inches Thickness, inches Aperture area, ft^2	48.0 51.5 7.8 14.0
Collector glazing:	Evacuated tube	
Weight:	Empty, lbs. Water Filled, lbs.	65.0 90.0

4.0 SUMMARY

This test program was conducted to evaluate the performance of a Sunmaster liquid, evacuated tube solar collector under simulated conditions. A schematic of the collector array is shown in Figure 1. The test conditions and the data obtained for the thermal performance tests are listed in Tables I and II. Table I contains results for the DEC-8 configuration, which had a one-inch diameter outlet manifold with copper orifices. During the testing, erratic flow was observed at the inclination angle of 6 degrees, corresponding to the latitude of a special application. The manufacturer was aware of problems at this inclination angle and supplied a modified version, DEC-8A, which has a 1-1/4 inch diameter outlet manifold and pyrex glass orifices. Table II contains the test data for the DEC-8A configuration. The DEC-8 configuration was tested in an open loop and the DEC-8A configuration was tested in a closed loop at 15 PSIG. Graphic presentations of the data contained in Tables I and II are shown in Figures 2 and 3 for the DEC-8 configuration and in Figures 4 and 5 for the DEC-8A configuration. A time constant test and an incident angle modifier test were also performed to determine the transient effects of the solar incidence angle on the collector. The results of these tests are shown in Figures 6 and 7, respectively, with the incident angle modifier test data given in Table III. Several special tests were requested for this collector. A non-standard stagnation test was performed to determine maximum tube temperatures for various levels of solar insolation. Figure 8 contains the transient tube responses for the stagnation test. Each evacuated tube operates as an independent flat plate; therefore, a three-point flux map was performed for each tube. A typical flux map is shown in Figure 9, indicating that non-uniformities are well within the allowable limits for solar simulators. A hot fill test was conducted to determine the possibility of breakage in the event of an accidental hot fill. Several breakages did occur, but all were at conditions above typical operation. Table IV shows the hot tube fill condition, and Figure 10 provides a summary of the hot fill test results. In the event that a particular delta temperature promotes the tube breakages, Table IV was developed by interpolating for tube temperatures from the stagnation plots in Figure 8. Although there is no apparent relationship between flow rate and breakage, all of the breakages did occur at a delta temperature of more than 600°F.

The standard configuration for the Sunmaster collector is with no cover. However, a Lexan cover was used to cover the tubes in case of breakage during the hot fill test. The indicated solar flux levels are corrected values compensating for the transmissivity loss through the Lexan cover.

The only common ground for comparing overall collector performance should be the "all day efficiency" rather than $F_R \alpha \tau$. No standard practice has been established, but each collector should be evaluated for space heating, domestic hot water and solar cooling or process heat applications at a nominal location. This would assist the solar designer in choosing the most efficient collector for a particular application. Evacuated tube collectors are effective for solar cooling applications; therefore, according to the procedure in NBSIR 78-1305A, an all day efficiency for the Sunmaster was calculated for a typical solar cooling application. The selected site dependent data in conjunction with test results used in this determination are shown 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.

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. Figure 1 contains instrumentation identification and data acquisition connection data. Instrumentation locations on the test loop and collector are also depicted in Figure 1. A listing of the equipment used in each test follows.

Apparatus	Manufacturer/Model	Range/Accuracy
Pyranometer	Eppley - PSP	0-800 BTU/Ft^2· Hr Class I
Liquid Loop	MSFC Supplied	.1 - 1.2 GPM
Directional Anemometer	Supplied by AMC	0 - 30 MPH
Flow Meter	Foxboro/1/2-2 82098B	.1 - 1.12 ± 1% GPM
Thermocouples	Type T	-100 + 700 ± 2°F
Platinum Resistance Thermometer	Hy-Cal	0 -1000°F ± 0.5°F
Strip Chart Recorder	Mosley 680	5-500 MV ± 2%
Fans	MSFC Supplied	N/A
Solar Simulator	MSFC Supplied	See SHC 3006
Pressure Gauge	U. S. Gauge Co/Ashcroft	0 - 60 PSIG ± 1 PSIG

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

A Doric Digitrend 220 digital output data logger was used to record all test data. A formal systems error analysis was not done; confidence in printout accuracies was established by installing calibrated "parallel" transducers and direct readouts at key points in the system and comparison checks were performed from time to time before, during and after tests. The results of such checks together with a review of the data for anomalies indicated that the data presented is suitable for the purpose intended.

6.0 TEST REQUIREMENTS AND PROCEDURES

6.1 Collector Preconditioning and Stagnation Test

6.1.1 Requirement

Preconditioning of the Sunmaster collectors is not required. Rather than monitor temperatures for a standard stagnation test, maximum tube temperatures at steady-state conditions for several insolation levels were obtained.

6.1.2 Procedure

1. Mount test specimen on test table at a 6° angle with reference to the floor.

2. Assure that the simulator lamp array is adjusted to an angle of 6° with reference to the floor.

3. Using the procedure contained in Reference 2.2, align the test table such that the test specimen and lamp array centerlines coincide and the distance between the specimen and the plane of the lamp array lenses is nine feet.

4. Insulate all liquid lines.

5. Connect instrumentation leads to data acquisition system in accordance with Figure 1.

6. Assure that the data acquisition system is operational.

7. Perform sensor accuracy verification tests.

8. Power up the solar simulator according to Reference 2.2 and perform a flux map at top, middle and bottom of each tube.

9. Establish a solar flux level of approximately 300 BTU/Hr-Ft^2.

10. Record data at one minute intervals until steady state conditions are achieved.

11. Repeat steps 9 and 10 with approximate flux levels of 325, 350, and 375 BTU/Hr-Ft^2.

12. Upon completion of testing, power down the simulator according to Reference 2.2.

6.1.3 Results

The results for the special stagnation test are shown graphically in Figure 8.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Collector Time Constant Test

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 0.175 GPM.

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 (water) flow rate to 0.175 GPM.*

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

3. Power up the solar simulator and establish a solar flux level of 300 $BTU/Ft^2 \cdot Hr$.

4. Establish wind speed of 7.5 mph.

5. Record data for ten minutes at above stabilized conditions.

6. Power down solar simulator.

7. Record the change of ΔT across the collector.

* This is the manufacturer's recommended flowrate for this test.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2.3 Results

The results obtained during the time constant test are shown in Figure 6.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.3 Collector Thermal Efficiency Test

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	250, 300, and 350 $BTU/Hr \cdot Ft^2$ °F
(4) Liquid flow rate through collector	0.175 GPM
(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 6° angle with reference to the floor.

2. Assure that simulator lamp array is adjusted to an angle of 6° with reference to the floor.

3. Using the procedure contained in Reference 2.2, align the test table so the test specimen's vertical center-line 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 Figure 1.

6. Assure that data acquisition system is operational.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.3 Collector Thermal Efficiency Test (Continued)

6.3.2 Procedure (Continued)

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, performing a flux map at top, middle and bottom of each tube.
12. Record data for a minimum of five minutes at these stabilized conditions.
13. Repeat Steps 9 through 12 for all inlet temperatures.
14. Obtain sufficient data at 10, 15 and 45° inclination angles to determine effect on performance.
15. Upon completion of testing, power down simulator and liquid loop in accordance with Reference 2.2.

6.3.3 Results

The thermal efficiency tests were conducted for the DEC-8 and DEC-8A configurations. The results for these tests are contained in Tables I and II and are presented graphically in Figures 2 through 5. The DEC-8 collector was tested in an open loop system. The DEC-8A collector was tested in a closed loop at 15 PSIG.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.4 Incident Angle Modifier Test

6.4.1 Requirements

Due to flow and drain down requirements, the collector could not be tilted; therefore, the lamp array was adjusted to 15°, 30° and 45° with respect to the solar collector surface. The liquid flow rate shall be 0.175 GPM with the inlet temperature controlled to within ± 2°F of ambient. The insolation rate shall be 300 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) Lamp array 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 lamp array at required tilt angle.

2. Establish required flowrate.

3. Establish required inlet temperature.

4. Establish solar simulator flux level at 300 BTU/Ft^2·Hr and measure the flux levels at 24 locations on the collector surface and record on data sheet.

5. Record data for ten minutes at above stabilized conditions.

6. Repeat above steps as necessary to obtain required data for each tilt angle.

6.4.3 Results

The results of the incident angle modifier test are presented in Table III and are shown graphically in Figure 7.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.5 Fill and Drain and Hot Fill Test

6.5.1 Requirements

The test will be performed utilizing the solar simulator. The collector will be mounted at a 6° inclination angle with respect to horizontal, such that the outlet is 1/8 inch lower than the opposite side to allow the manifold to drain. Utilizing special tubes with an observation window, fill the collector, with no solar insolation, at flow rates of 0.35 GPM and 0.075 GPM, monitoring the time required to fill the collector. Drain the full collector, monitoring the drain time, as a result of gravity drain. After the fill and drain times have been determined, bring the empty collector to stagnation steady-state temperatures at flux levels of 300, 325 and 375 BTU/Hr·Ft^2, and fill the collector with ambient temperature water at flow rates of 0.20, 0.25, 0.30, and 0.35 GPM. Data to be recorded is listed below:

1. Insolation rate.
2. Ambient temperature.
3. Inlet temperature.
4. Absorber surface temperatures at 3 or 4 locations.
5. Flow rate.

6.5.2 Procedure

1. Mount test specimen as described above.

2. Connect and check out instrumentation.

3. Record above data.

6.5.3 Results

Results of the fill time tests were 9.2 minutes and 38 minutes for 0.35 and 0.075 GPM flow rates, respectively. The drain time was six minutes, but will vary with suction heads on the inlet and with the collector inclination angle.

The hot fill tests were performed with two different sets of tubes. The first set had gone through stagnation testing, and five were broken as a result of the hot fill. A new set of tubes was installed, and three more tubes broke. The results of the hot fill tests are shown in Figure 10. Table IV lists the flux levels, flow rates and temperature difference between the inlet liquid and the tube stagnation temperature at the conditions when breakage occurred.

7.0 ANALYSIS OF RESULTS

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:

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

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 plane 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:

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

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 AND RESULTS (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 multiplying 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:

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

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 ten minute period during which the test conditions remained in a quasi-steady state. Each ten -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·Ft^2)

The abscissa term $\left((t_i - t_a)/I\right)$ was used to normalize the effect of operating at slightly different values of I, t_i and t_a. The results are found in Figures 2 and 4. Due to the excellent insulative properties of the evacuated tube, and considerable data scatter, the best curve fit is a first order polynomial given by:

$$\text{Efficiency} = a_0 + a_1 \Gamma$$

7.0 ANALYSIS (Continued)

7.1 Thermal Performance Test (Continued)

where:

$$J' = (T_i - T_a)/I$$

and the coefficients are determined to be:

Flow Rate (GPM)	0.175	
a_0	0.411	DEC-8
a_1	-0.145	
a_0	0.391	DEC-8A
a_1	-0.224	

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, the first method was used. This method consisted of shading the collector 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, when solar insolation is reduced to zero. 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 cannot be controlled to equal the ambient air temperature, then the following equation must be used

$$\frac{F_R U_L \ (T_{f,i}-T_a) + \frac{\dot{m}Cp}{Ag} \ (T_{f,e,\tau} - T_{f,i})}{F_R U_L \ (T_{f,i}-T_a) + \frac{\dot{m}Cp}{Ag} \ (T_{f,e,ini}-T_{f,i})} = .368 \qquad (2)$$

where:

$T_{f,e,\tau}$	Exit liquid temperature at time τ
$T_{f,i}$	Inlet liquid temperature
$T_{f,e,ini}$	Initial exit liquid temperature
$\dot{m}$	Liquid mass flow rate, Lb/Hr
C_p	Specific heat of liquid, BTU/Lb·°F
A_g	Gross collector area, ft^2
$F_R U_L$	Negative of the slope determined from the thermal efficiency curve

The inlet temperature was maintained within ± 2°F of the ambient, hence equation (1) was used for evaluation. From Figure 6 the time constant was determined to be 12 minutes.

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. However, due to the flow and drain down design of this collector, it was necessary to tilt the solar array instead of the collector. The lamp array could not be adjusted to 60°; therefore, the angles of 0°, 15°, 30° and 45° to the normal of the collector surface were used.

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 without a cover plate

For equation (1) to be applicable, the inlet liquid temperature must be controlled to within ± 2°F of the ambient air temperature. In cases where the inlet liquid temperature cannot be controlled to within ± 2°F, the following equation must be used to evaluate the incident angle modifier.

$$K\alpha\tau = \frac{\eta + F_R U_L \dfrac{T_{f,i} - T_a}{I}}{F_R(\alpha\tau)\ n} \qquad (2)$$

where

$F_R U_L$ is the negative of the slope determined from the thermal efficiency curve, without a cover plate.

Table III shows that the inlet liquid temperatures were all within ± 2°F of ambient air temperature. Hence, equation (1) was used for evaluation.

$$K\alpha\tau = \frac{\eta}{0.414}$$

The results of this computation are shown on Table III and plotted against incident angle in Figure 7.

7.3 Incident Angle Modifier Test (Continued)

The purpose of the incident angle modifier is to allow a designer or analyst to predict the total daily energy output from the collector, as the sun tracks from east to west. Most collectors are more efficient at normal incidence than at other angles, but some are even more efficient at angles other than normal. The only common ground for comparing collectors should be the "all day efficiency" rather than $F_R\alpha\tau$. However, the prospective application of the collector also influences the value of "all day efficiency." That is, for low temperature applications such as space heating or domestic hot water, a typical flat plate collector may have an all day efficiency of 40%, but for solar cooling applications the all day efficiency might be 20%. Therefore, criteria should be established to rate each collector for space heating, domestic hot water, and solar cooling at a nominal location, because efficiencies are also dependent on outdoor ambient temperatures.

Evacuated tubes are effective for solar cooling applications; therefore, according to the procedure in NBSIR 78-1305A the all day efficiency of the Sunmaster collector is 33 per cent for a typical solar cooling application. The selected site dependent data in conjunction with test data used in these determinations is shown in Table V. No standard criteria has been established for "all day efficiency"; and these calculations are dependent on system operating parameters, site data, time of year and daily weather; therefore, the above information should be viewed as interesting but not conclusive.

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TABLE I

THERMAL PERFORMANCE TEST DATA FOR THE DEC-8 SUNMASTER COLLECTOR

Sheet 1 of 2.

Ambient Air Temperature (T_a), °F	68.5	68.5	71.4	69.8	73.2	73.7	69.8	70.5	71.1	73.0	68.8	77.2	77.7	77.0	76.6
Fluid Inlet Temperature (T_i), °F	66.9	71.1	73.4	70.7	73.7	73.3	112.6	113.4	114.1	112.9	114.0	148.7	149.3	149.0	149.5
Fluid Outlet Temperature (T_e), °F	90.1	86.0	95.9	88.9	99.7	94.5	113.7	136.2	132.6	142.0	134.5	166.7	164.0	169.5	166.5
Differential Fluid Temperature (ΔT), °F	23.2	14.9	22.5	18.2	26.0	21.2	21.1	22.8	18.5	29.1	20.5	18.0	14.7	20.5	17.0
Total Solar Flux (I), $BTU/Hr \cdot Ft^2$	249.4	248.6	304.4	304.4	348.7	348.7	249.4	300.9	300.9	346.4	341.9	248.6	248.6	298.1	298.1
Flow Rate, GPM	.18	.244	.193	.246	.189	.246	.175	.175	.25	.160	.25	.192	.240	.190	.238
$(T_i - T_a)/I$ $°F \cdot Hr \cdot Ft^2/BTU$	0	0.0105	0.006	0.003	0.001	0	0.172	0.143	0.143	0.115	0.132	0.288	0.288	0.242	0.244
Efficiency (η), %	43.3	42.6	41.5	42.8	41.0	43.5	39.0	34.9	40.8	39.1	40.1	40.5	41.3	38.0	39.5
Inclination Angle	6°	6°	6°	6°	6°	6°	6°	6°	6°	6°	6°	6°	6°	6°	6°

TABLE I
(Continued)

THERMAL PERFORMANCE TEST DATA
FOR THE DEC-8 SUNMASTER COLLECTOR

Sheet 2 of 2.

Ambient Air Temperature (T_a), °F	74.5	74.6	70.4	70.5	70.4	70.0	74.7	69.4	66.4	73.1	75.8	76.1	77.3	79.9	79.2
Fluid Inlet Temperature (T_i), °F	148.5	149.0	184.3	186.9	184.4	186.7	184.6	185.8	68.2	108.6	152.0	182.2	80.8	110.3	147.5
Fluid Outlet Temperature (T_e), °F	174.4	168.7	201.4	199.8	205.3	202.4	207.2	204.0	92.6	131.1	173.1	201.4	105.2	132.7	169.0
Differential Fluid Temperature (ΔT), °F	25.9	19.7	17.1	12.9	20.9	15.7	22.6	18.2	24.4	22.5	21.1	19.2	24.4	22.4	21.5
Total Solar Flux (I), $BTU/Hr \cdot Ft^2$	346.4	346.4	254.0	254.0	301.1	301.1	348.7	351.6	297.2	302.4	302.4	302.4	305.9	305.9	305.9
Flow Rate, GPM	.171	.245	.178	.245	.180	.240	.181	.232	.185	.182	.176	.181	174	.177	.171
$(T_i-T_a)/I$ $°F \cdot Hr \cdot Ft^2/BTU$	0.214	0.215	0.448	0.458	0.379	0.388	0.315	0.331	0.006	0.117	0.252	0.351	0.011	0.099	0.223
Efficiency (η), %	37.2	40.6	34.9	36.2	36.4	36.4	34.1	35.0	44.2	39.5	35.6	33.5	40.4	37.6	34.9
Inclination Angle	6°	6°	6°	6°	6°	6°	6°	6°	15°	15°	15°	15°	45°	45°	45°

TABLE II

THERMAL PERFORMANCE TEST DATA
FOR THE DEC-8A SUNMASTER COLLECTOR

Sheet 1 of 2

Ambient Air Temperature (T_a), °F	84.1	85.0	78.2	80.4	85.9	81.6	81.0	79.3	80.9	81.9	81.12	81.11	81.2	81.6
Fluid Inlet Temperature (T_i), °F	85.3	85.4	82.8	115.9	180.4	194.2	216.2	81.5	110.0	109.5	126.8	127.0	149.5	189.0
Fluid Outlet Temperature (T_e), °F	108.0	107.8	105.1	137.2	200.4	211.4	234.3	104.5	131.3	131.5	146.5	146.8	168.5	207.1
Differential Fluid Temperature (ΔT), °F	22.7	22.4	22.3	21.3	20.0	17.2	18.0	23.0	21.3	22.0	19.7	19.8	19.0	18.1
Total Solar Flux (I), BTU/Hr·Ft^2	289.9	282.9	298.2	298.2	298.2	296.8	293.1	302.6	297.6	302.6	297.6	297.6	297.6	297.6
Flow Rate, GPM	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179
$(T_i-T_a)/I$ °F·Hr·Ft^2/BTU	.004	.001	0.01	.12	0.32	0.38	0.46	0.01	0.10	0.09	0.15	0.15	0.23	0.36
Efficiency (η), %	40.6	41.1	38.8	36.7	33.9	29.1	30.6	39.4	35.9	37.5	34.1	34.1	32.6	30.5
Inclination Angle	6°	6°	6°	6°	6°	6°	6°	10°	10°	10°	10°	10°	10°	10°

TABLE II

THERMAL PERFORMANCE TEST DATA
FOR THE DEC-8A SUNMASTER COLLECTOR

Sheet 2 of 2

Ambient Air Temperature (T_a), °F	70.7	84.73	84.7	86.3	77.6	77.7	76.8	77.4	80.72
Fluid Inlet Temperature (T_i), °F	76.1	110.38	110.4	126.6	147.0	146.8	176.4	176.5	199.7
Fluid Outlet Temperature (T_e), °F	97.0	131.6	132.1	146.2	165.7	165.8	196.4	196.7	216.1
Differential Fluid Temperature (ΔT), °F	20.9	21.3	21.7	19.6	18.7	19.0	20.0	20.2	16.4
Total Solar Flux (I), BTU/Hr·Ft^2	299.9	298.9	298.9	298.9	303.2	303.2	299.9	299.9	299.9
Flow Rate, GPM	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179
$(T_i - T_a)/I$ °F·Hr·Ft^2/BTU	.02	.09	.09	.13	.23	.23	.33	.33	.40
Efficiency (η), %	32.6	36.7	37.4	33.6	31.5	31.9	33.9	34.0	27.4
Inclination Angle	15°	15°	15°	15°	15°	15°	15°	15°	15°

TABLE III

INCIDENT ANGLE MODIFIER TEST DATA
FOR THE DEC-8A SUNMASTER COLLECTOR

Angle	0°	15°	30°	45°		
Ambient Air Temperature (T_a), °F	85.0	78.4	79.2	75.9		
Fluid Inlet Temperature (T_i), °F	85.4	79.6	79.6	77.3		
Fluid Outlet Temperature (T_e), °F	107.8	104.8	104.6	97.6		
Differential Fluid Temperature (ΔT), °F	22.4	25.2	25.0	20.3		
Total Solar Flux (I), BTU/Hr·Ft^2	282.9	295.3	277.5	229.2		
Flow Rate, GPM	0.180	0.180	0.180	0.180		
Efficiency (η), %	41.4	44.3	46.8	45.7		
Adjusted Efficiency Ratio $K\alpha\tau$	1.00	1.070	1.130	1.104		

TABLE IV

SUNMASTER DEC-8

HOT FILL TUBE BREAKAGE CONDITIONS

BTUH ($BTU/Hr \cdot Ft^2$)	Flow Rate (GPM)	ΔT (°F)
421.5	0.20	(721-63) = 658
343.0	0.20	(698-63) = 635
321.0	0.25	(682-63) = 619
348.0	0.25	(700-63) = 637
367.0	0.30	(708-63) = 645
389.0	0.30	(716-63) = 653
406.5	0.30	(720-63) = 657
396.0	0.35	(718-63) = 655

TABLE V
SUNMASTER COLLECTOR
CALCULATED ALL DAY EFFICIENCY

CALCULATION STEPS	HOUR OF THE DAY, SOLAR TIME												DAILY TOTAL
	6-7	7-8	8-9	9-10	10-11	11-12	12-1	1-2	2-3	3-4	4-5	5-6	
1. Inlet fluid temp. to collector, $t_{f,i}$	185	185	185	185	188	190	193	194	200	200	200	200	
2. Ambient air temp., t_a	73	74	79	82	86	90	92	93	94	94	92	90	
3. Incident radiation on collector plane, I_T (Table A2, ASHRAE 93-77)	6	60	132	197	249	281	292	281	249	197	132	60	2144
3a. $T_{fi}-T_a/I_T$	18.0	1.87	.80	.52	.41	.36	.35	.37	.43	.54	.82	1.8	
4. Collector thermal efficiency at normal incidence, determined in accordance with Sections 8.3.2 and 8.5 of ASHRAE 93-77 and using data from Lines 1, 2 and 3		.12*	.26*	.32	.34	.35	.35	.35	[illegible]	.32	.26*	.12*	
5. Incident angle between direct solar beam and outward drawn normal to collector plane, θ d	90	75	60	45	30	15	15	30	45	60	75	90	
6. Incident angle modifier, determined in accordance with Sections 8.3.3 & 8.6 of ASHRAE 93-77 and using the value of θ from Line 5	0	.65*	.94*	1.11	1.14	1.08	1.08	1.14	1.11	.94*	.65*	0	
7. Energy output from collector [Line 3 x Line 4 x Line 6]		4.7	32.3	70.0	96.5	106.2	110.3	112.1	94.0	59.3	22.3	0	707.7
8. Collector thermal efficiency, Line 7/Line 3													33.0

Example: 32°N Lat.
42° Tilt
Avg. - Clear Skies

* Estimated or extrapolated values

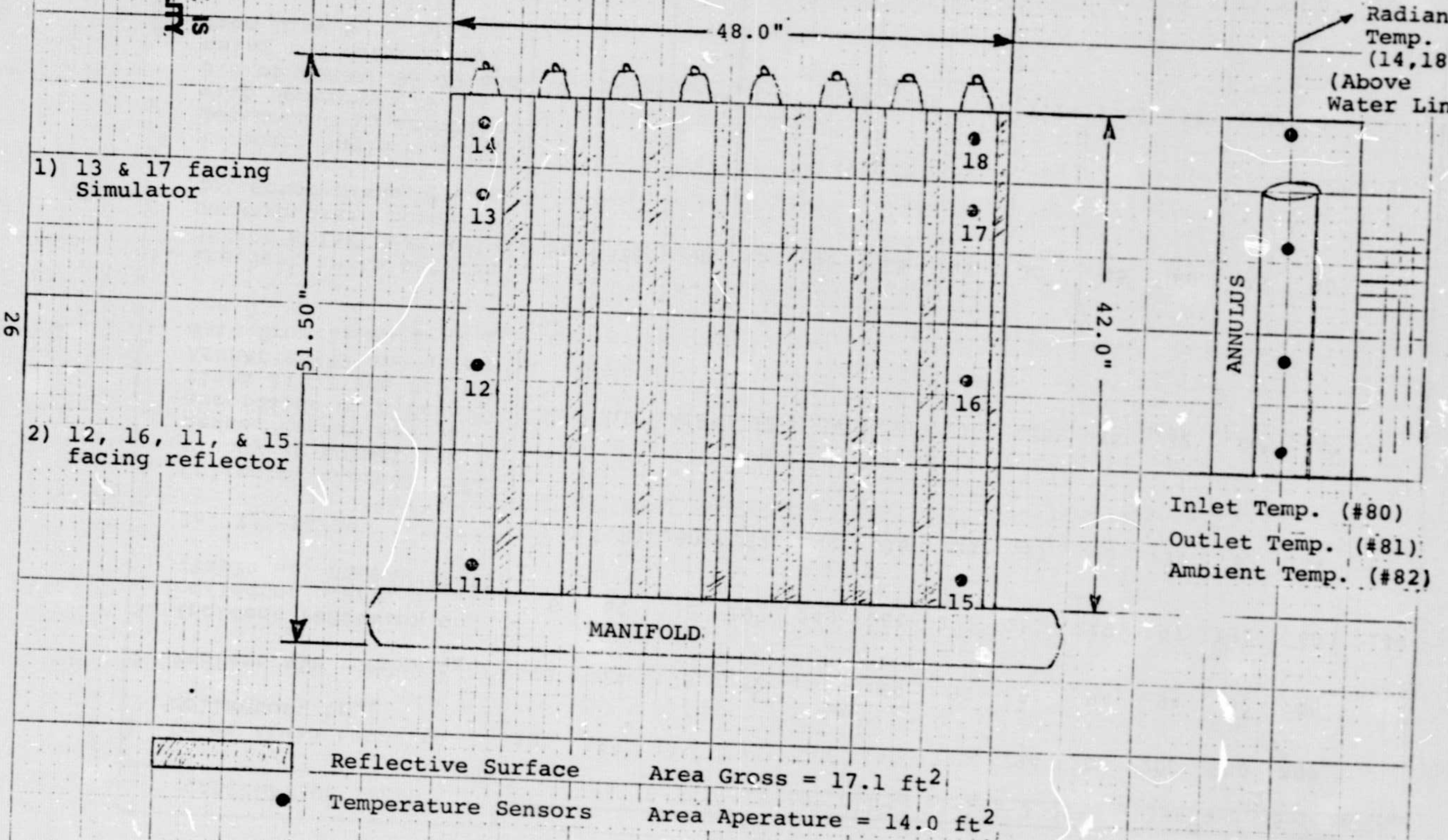

Figure 1. Schematic of the Sunmaster Collector, Indicating Instrumentation

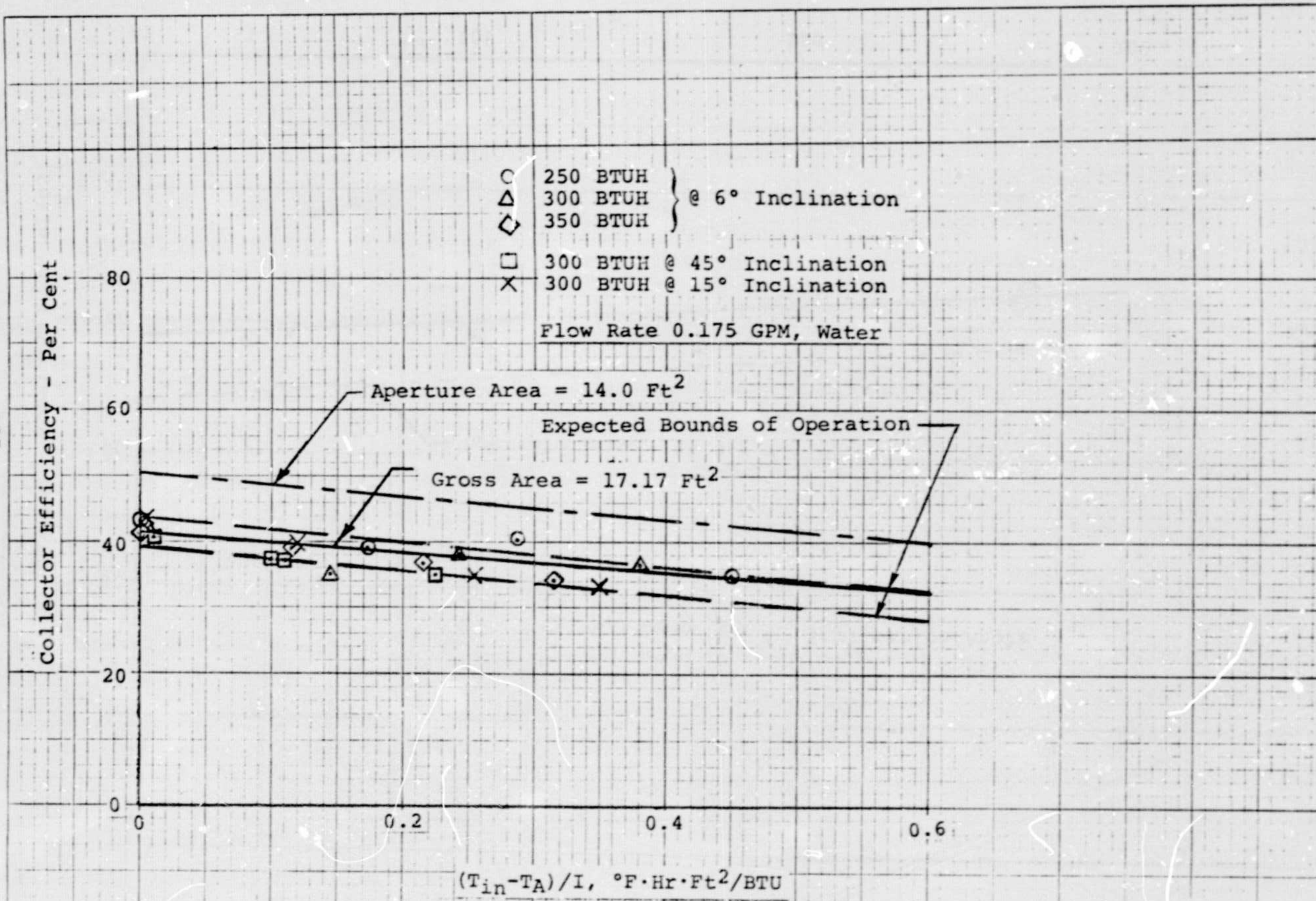

Figure 2. Thermal Efficiency of the DEC-8 Sunmaster Collector

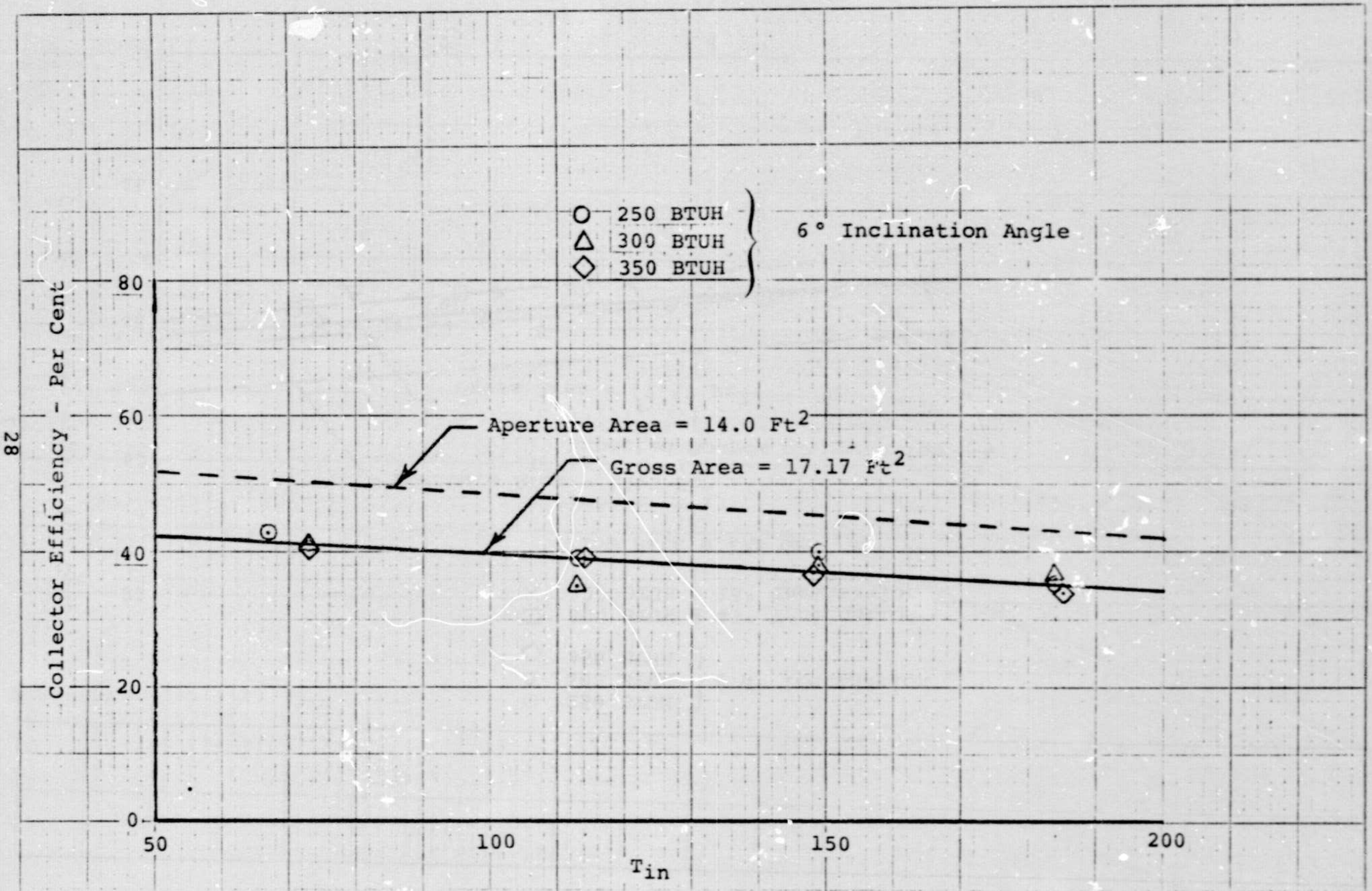

Figure [illegible] Efficiency of the Sunmaster DEC-8 Configuration as a Function of Inlet Temperature for a Water Flow Rate of .175 GPM

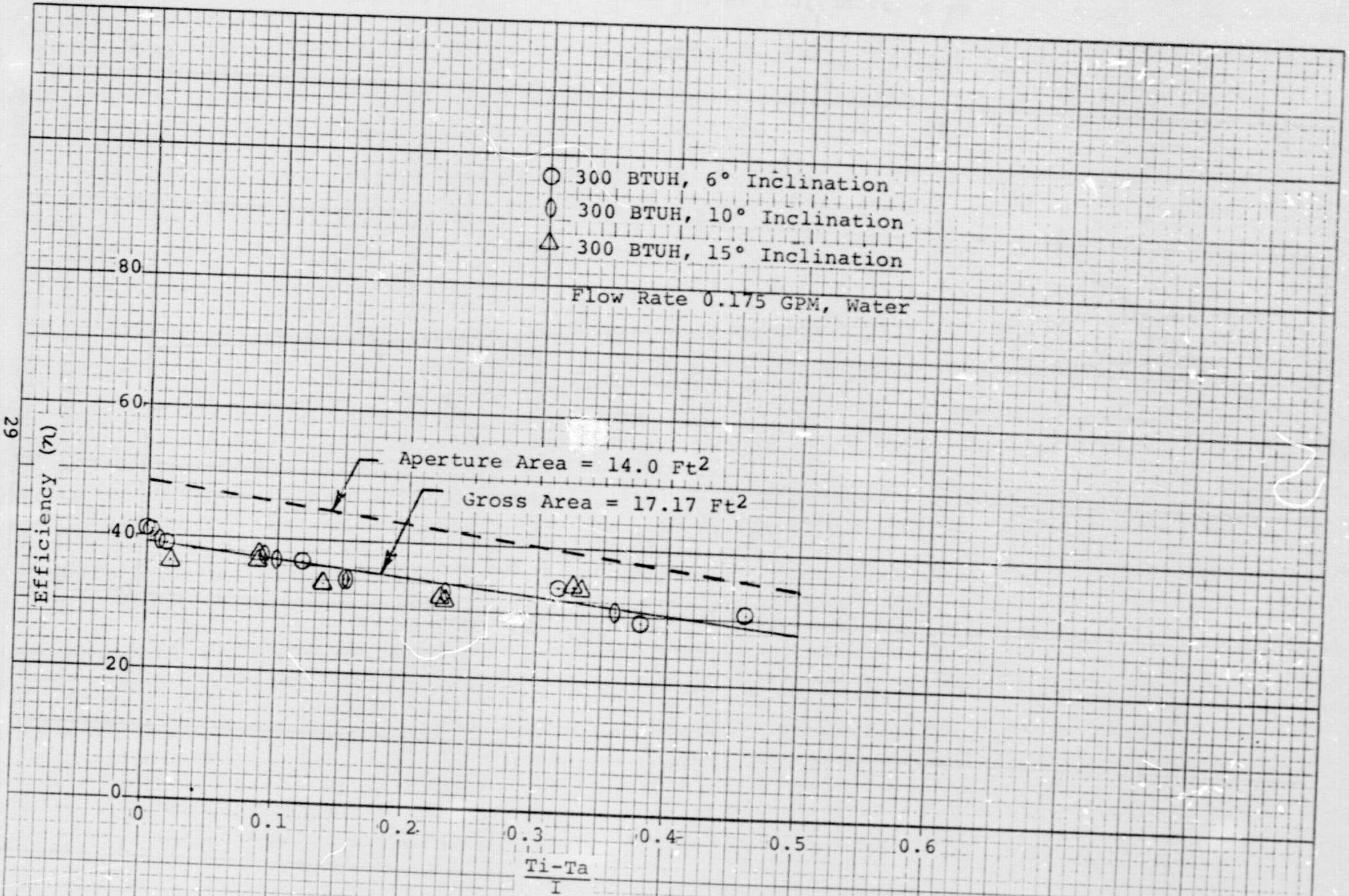

Figure 4. Thermal Efficiency of the DEC-8A Sunmaster Collector

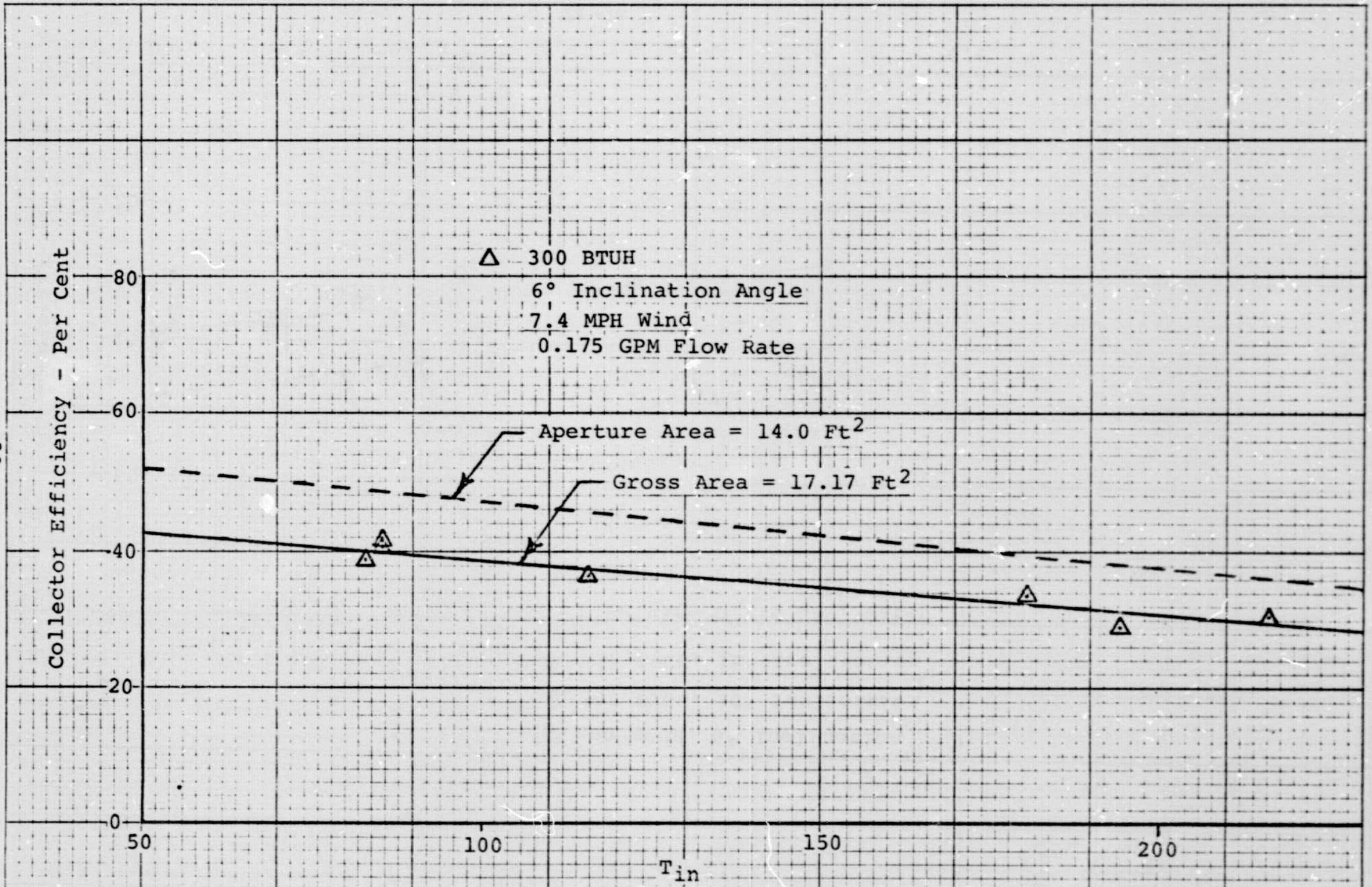

Figure 5. Efficiency of the Sunmaster DEC-8A Configuration as a Function of Inlet Temperature

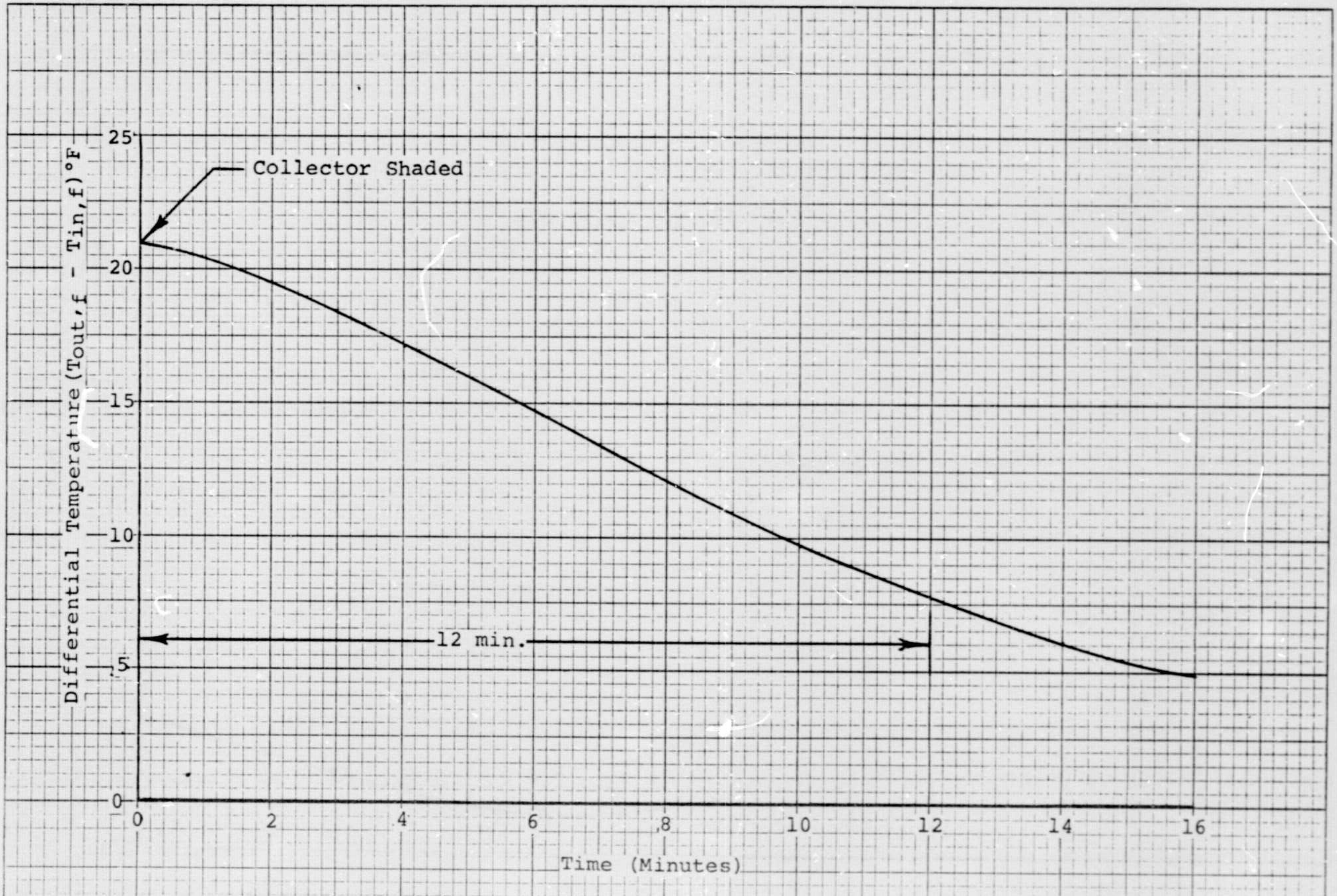

Figure 6. Time Constant Test for the Sunmaster DEC-8A Configuration at 0.175 GPM

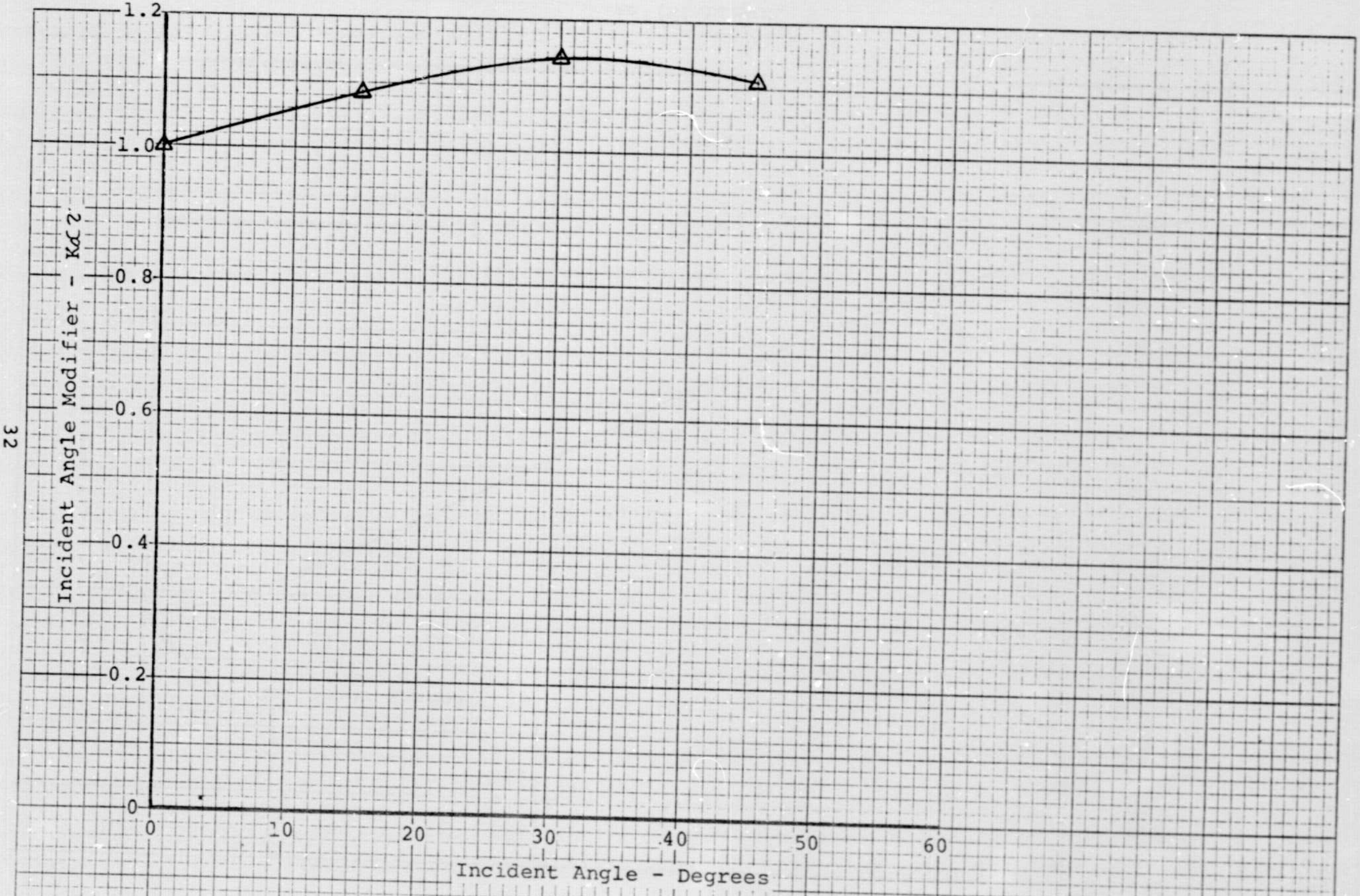

Figure 7. Incident Angle Modifier for the Sunmaster DEC-8A Configuration

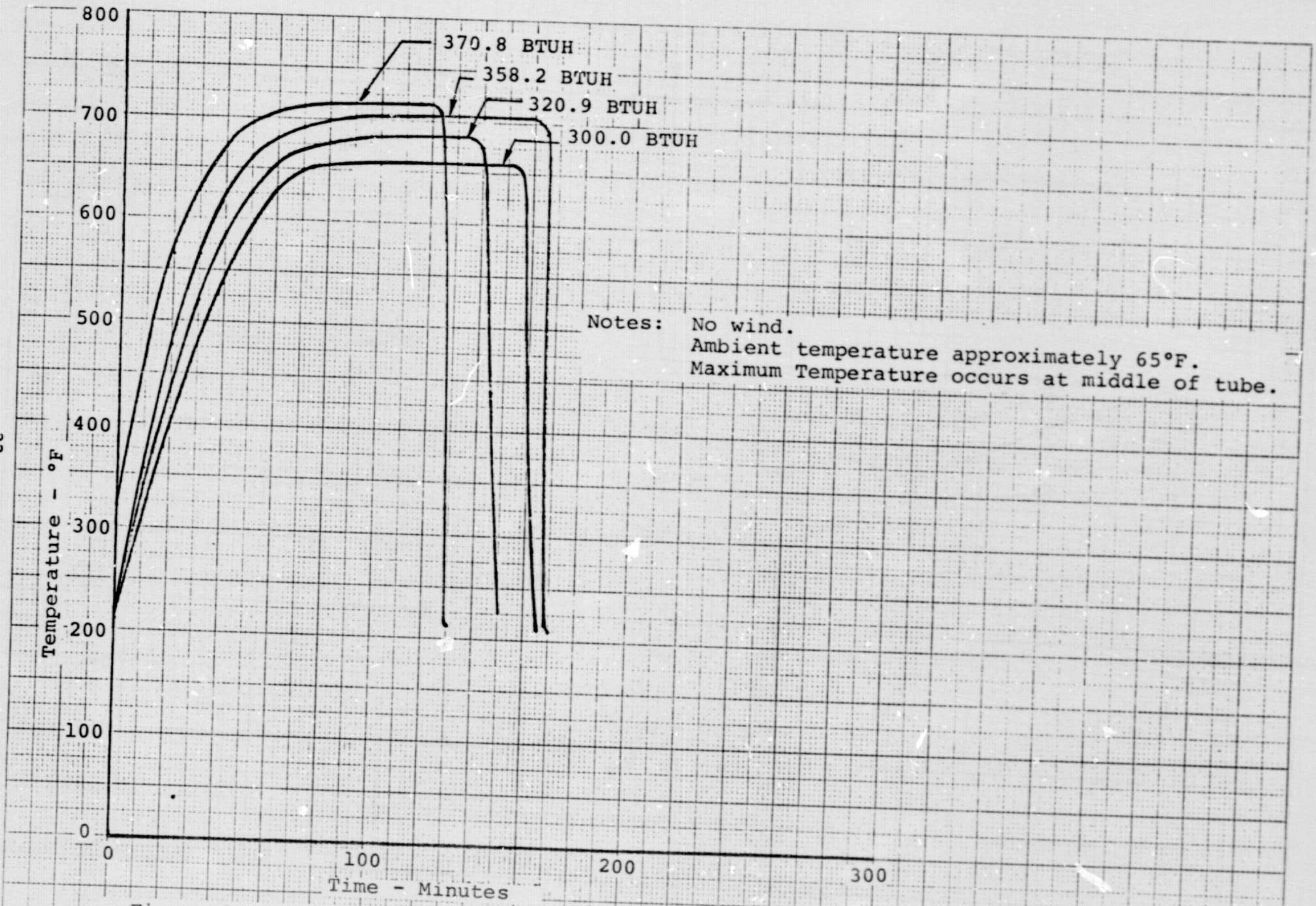

Figure 8. Typical Temperature Response At The Maximum Temperature Location For The Sunmaster DEC-8 Configuration

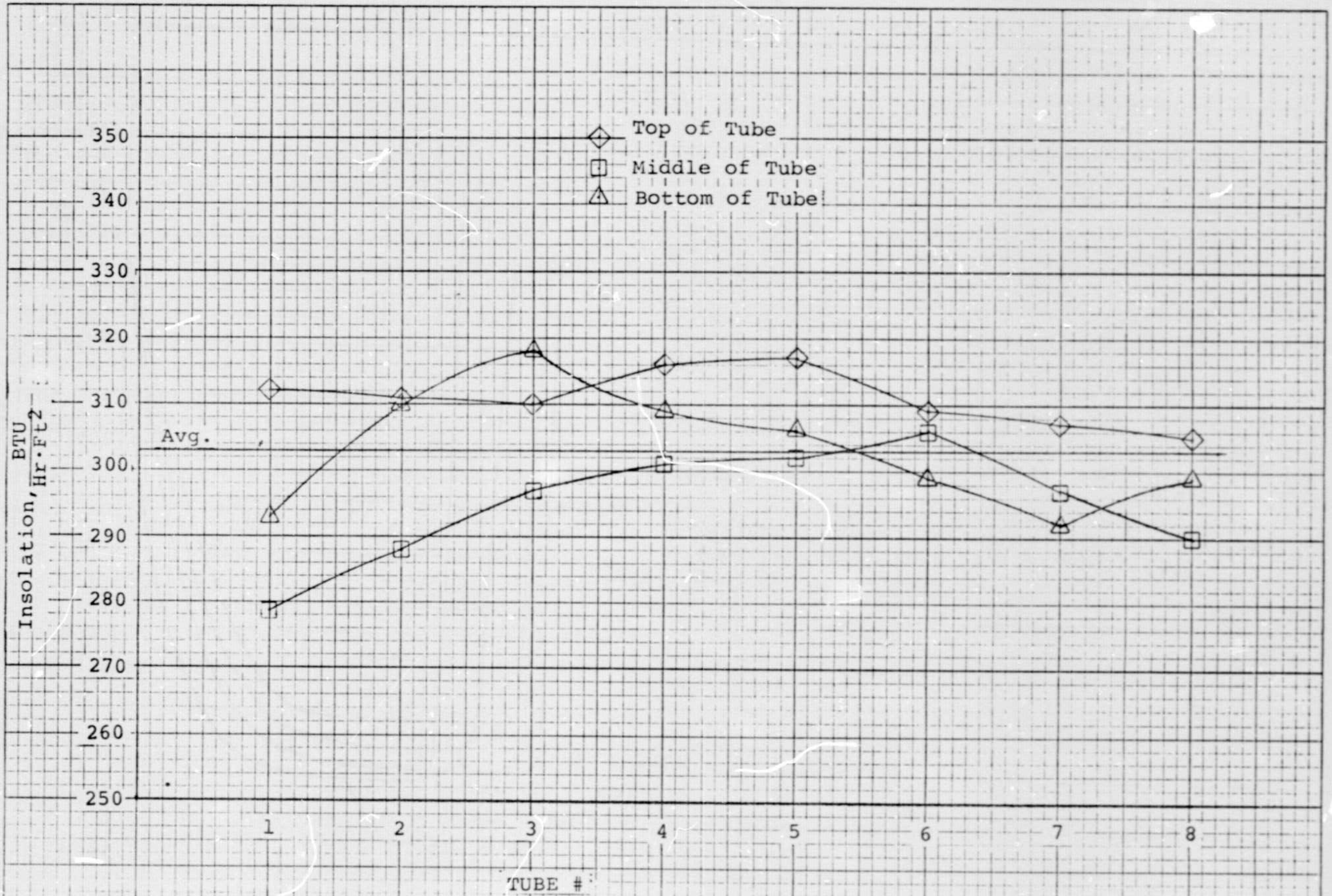

Figure 9. Typical Flux Map During The Sunmaster Testing

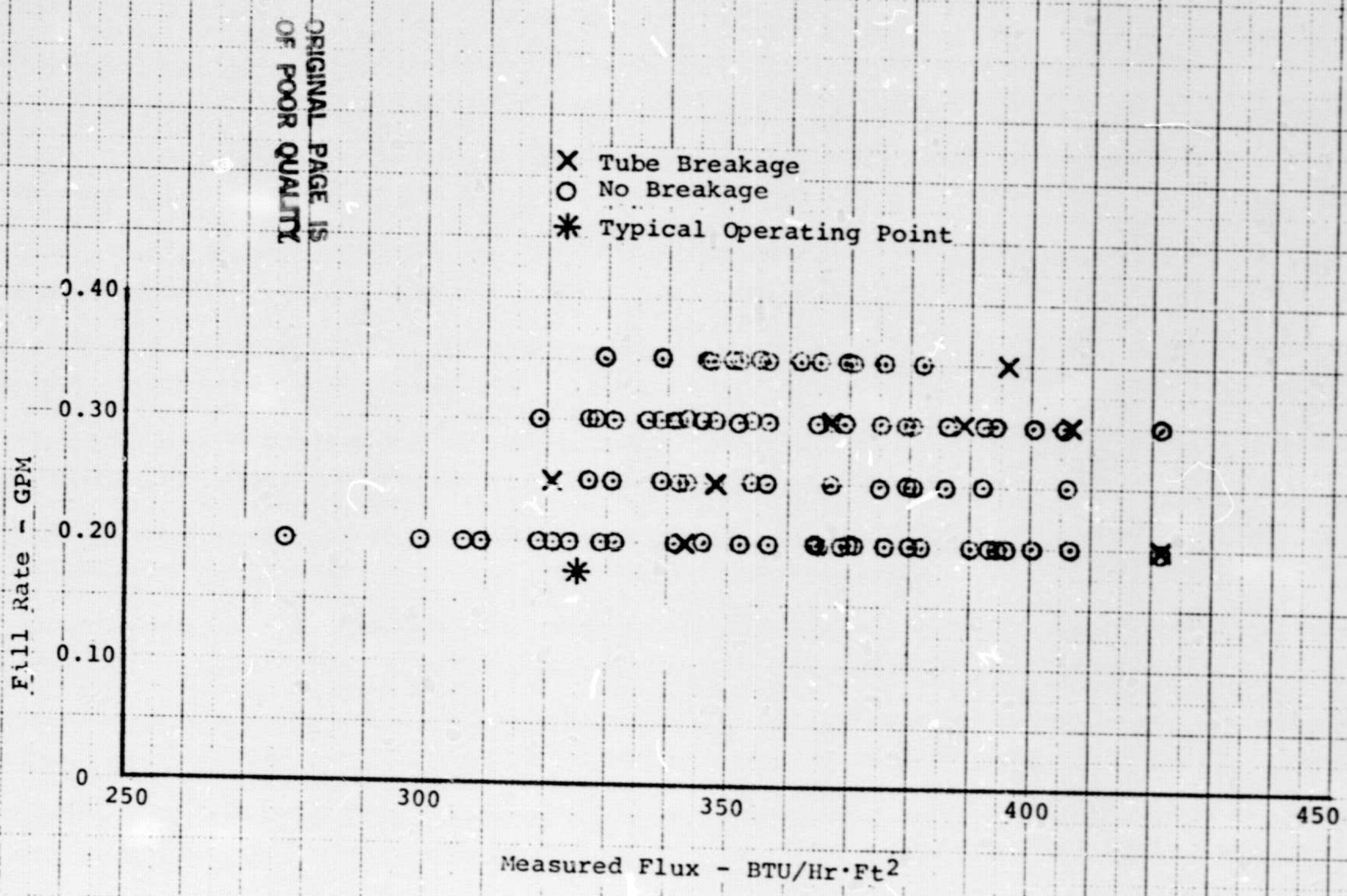

Figure 10. Singular Tube Exposure Versus Fill Rate Noting Tube Breakage for the Hot Fill Test of the Sunmaster Collector