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DOE/NASA CONTRACTOR REPORT

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COMPARISON OF INDOOR-OUTDOOR THERMAL PERFORMANCE FOR THE SUNPAK EVACUATED TUBE LIQUID COLLECTOR

Prepared by

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National Aeronautics and Space Administration
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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 test procedures used and the test results obtained during an evaluation test program. The test program was conducted to obtain thermal performance data for the current production configuration Owens-Illinois Sunpak evacuated tube liquid collector. Reference 2.6 reported the data for early demonstration hardware. All testing took place at the Marshall Space Flight Center Solar Testing Facility, either at the Solar Simulator or at the outdoor test bed area. The test was conducted and the data evaluated using the methods provided in Reference 2.1 as applicable to both indoor and outdoor testing of solar collectors. Tests utilizing the MSFC Solar Simulator were conducted in accordance with procedures contained in Reference 2.2.

2.0 REFERENCES

2.1	ASHRAE 93-77	Methods 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
2.3	I.S.O.M. Feb. 1978, plus Addendum Nov. 1978	Owens-Illinois Sunpak™ Installation and Operation Manual
2.4	RD&D Test Report E8021	Florida Solar Energy Center Solar Collector Test Report, Model: Sunpak™
2.5	DSET No. 19780S and DSET No. 18962S	DSET Laboratories, Inc., Solar Collector Reports, Collector Model Sunpak™
2.6	DOE/NASA CR-161189	Results of Thermal Performance Evaluation of the Owens-Illinois Sunpak Liquid Solar Collector at Indoor Conditions

3.0 COLLECTOR DESCRIPTION

Manufacturer:	Owens-Illinois
Manufacturer's Address:	P. O. Box 1035, Toledo, Ohio 43666
Type:	Sunpak - Evacuated Tube
Working Fluid:	Water or Water/Glycol (33% by Volume for outdoor tests)
Gross Collector Area, Ft^2:	32.0
Overall External Dimensions:	Width, Feet: 4.0 Length, Feet: 8.0 Aperture Area, Ft^2: 27.4
Normal Tube Dimensions:	Two-inch diameter x 44 in. long standard 8mm O.D. glass feeder tubes inside evacuated tubes

3.0 COLLECTOR DESCRIPTION (Continued)

Collector Glazing:	Concentric glass tubes with an evacuated space between cylinders. Cover tube transmittance factor, .92. Absorber tube absorptivity factor, .86. Absorber tube emmissivity factor, .07.
Module Weight, Lbs:	Empty: 110.0
	Water Filled: (Approximately 9 gallons) 185.0
Liquid Flow Path:	Liquid flows in a serpentine series flow pattern through the collector manifold* and the 24 evacuated tubes.
**Shaped Specular Reflector:	Interlocking treated lightweight aluminum, 40" long x 4" wide x .025" thick.
Diffuse Reflector:	PPG Interior Latex, Color No. 37875, Reflectance 0.70

* A thermal performance test report (Reference 2.6) from data at the MSFC Solar Simulator was issued prior to this report for the Sunpak™ solar collector model used in early demonstration projects. The current Sunpak™ collector model tested for this report has a redesigned and modified manifold. The flow pattern through the collector has remained essentially the same in both collector models.

** Late in the test program, Owens-Illinois informed MSFC that the shaped specular reflector used at MSFC in testing the current model Sunpak™ collector was a development reflector rather than a production item. The current Sunpak™ collector was therefore retested at the Solar Simulator with the production item shaped specular reflector.

4.0 SUMMARY

Thermal performance tests were conducted on the updated model Sunpak evacuated tube liquid collector at the Marshall Space Flight Center Solar Test Facilities. The collector was tested indoors utilizing the MSFC Solar Simulator and outdoors while mounted on a table capable of sun tracking. Data was obtained at both indoor and outdoor conditions for a diffuse reflecting surface, a plywood sheet painted flat white (PPG Interior Latex, Color No. 37875), and for the shaped specular reflector (SSR), supplied by Owens-Illinois, fastened in place. A schematic of the collector is shown in Figure 1 with the SSR attached. Photograph 1 shows the Sunpak collector with the SSR in place, while Photograph 2 shows the Sunpak collector with only the diffuse reflecting surface. A typical flux map taken during testing at the Solar Simulator is depicted graphically in Figure 2. Results of the time constant test are presented in Figure 3. The test conditions and the data obtained during the test program are listed in Tables I through IV for the thermal performance tests and in Tables V through IX for the incident angle modifier tests. In addition, graphic presentation of data obtained from thermal performance tests is shown in Figure 4 for the Sunpak collector with the SSR and in Figure 5 for the Sunpak collector with a diffuse reflector. The transient effects of solar incidence angle on the Sunpak collector are shown in Figure 6 for the collector with the SSR and in Figure 7 for the collector with a diffuse reflector. Figure 8 compares results from an altitude angle-incident angle modifier test performed at the Solar Simulator with the SSR and the diffuse reflector. Figure 9 shows thermal efficiency of the Sunpak collector with SSR as a function of inlet temperature. Figure 10 depicts thermal efficiency of the Sunpak collector with a diffuse reflector as a function of inlet temperature. For comparison purposes, data from References 2.4, 2.5, and 2.6 are shown where appropriate.

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 Sunpak liquid collector 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 X for the Sunpak collector with shaped specular reflector (current production SSR) and in Table XI for the collector with the diffuse reflector.

5.0 TEST CONDITIONS AND TEST EQUIPMENT

5.1 Ambient Conditions

Unless otherwise specified herein, all tests were performed at ambient conditions immediately surrounding the collector at the particular MSFC solar testing site at the time of the test.

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. Testing took place at two locations, indoors at the MSFC Solar Simulator and outdoors at the MSFC Solar Test Bed Facility. A listing of equipment used for indoor and outdoor testing follows:

Indoor Testing

Apparatus	Manufacturer/Model	Range/Accuracy
Pyranometer	Eppley - PSP	0-800 $BTU/Ft^2 \cdot Hr$ Class 1
Liquid Loop	MSFC Supplied	.1 - 1.2 GPM
Anemometer	Supplied by AMC	0 - 60 MPH
Flowmeter	Foxboro/1/2-2 81T3C1	.1 - .91 $\pm$ 1% GPM
Platinum Resistance Thermometers	Hy-Cal	0 - 500^oF $\pm$ 0.5^oF
Digital Printer	Doric Digitrend 220	0 - 500 mv $\pm$ 2%
Fans	MSFC Supplied	N/A
Solar Simulator	MSFC Supplied	See Reference 2.2

Outdoor Testing

Apparatus	Manufacturer/Model	Range/Accuracy
Pyranometer	Eppley PSP	0-800 $BTU/Ft^2 \cdot Hr$ Class 1
Liquid Loop	MSFC Supplied	.1 - 1.2 GPM
Flowmeter	Fischer & Porter Co./ Rotameter	.1 - 1.12 $\pm$ 1% GPM

5.0 TEST CONDITIONS AND TEST EQUIPMENT (Continued)

5.2 Instrumentation and Equipment (Continued)

Apparatus	Manufacturer/Model	Range/Accuracy
Type T Thermocouples	MSFC Supplied	0 - 500 ^{o}F $\pm$ .5^{o}F
Data Logger	Model 2240A, John Fluke Company	1 - 30 mv $\pm$ .01%

The PSP pyranometers were calibrated by the manufacturer.

6.0 TEST REQUIREMENTS AND PROCEDURES

6.1 Collector Thermal Efficiency Test

6.1.1 Test Requirements - Indoors

Thermal performance data from the Sunpak evacuated tube liquid collector with shaped specular reflector and with only a diffuse reflector shall be obtained at the MSFC indoor test facility. 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. Utilizing the MSFC Solar Simulator and the portable liquid loop, parametric performance evaluation data shall be recorded of the following test variables and conditions.

Variable/Condition	Requirement
(1) Collector inlet liquid temperature differential above existing ambient temperature level	$0^{\circ}F$, $25^{\circ}F$, $75^{\circ}F$, and $100^{\circ}F$
(2) Collector outlet liquid temperature	Measured data
(3) Incident solar flux level	260, 300 $BTU/Hr\text{-}Ft^2\ ^{\circ}F$
(4) Liquid flow rate through collector	2.65 lbm/min (0.318 GPM)
(5) Wind speed	7.5 mph
(6) Ambient air temperature	Existing room condition

6.1.2 Procedure - Indoors

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 2.2, 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 front 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.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1 Collector Thermal Efficiency Test (Continued)

6.1.2 Procedure - Indoors (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 each minute for a minimum of one hour until stabilized conditions occur.
13. Repeat Steps 9 through 12 as necessary for the Sunpak collector, with the shaped specular reflector attached and also with only a diffuse reflector, 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/Min.	Wind Speed, MPH
1	0	260	2.65	7.5
2	0	300	2.65	7.5
3	25	260	2.65	7.5
4	25	300	2.65	7.5
5	75	260	2.65	7.5
6	75	300	2.65	7.5
7	100	260	2.65	7.5
8	100	300	2.65	7.5

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

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1 Collector Thermal Efficiency Test (Continued)

6.1.3 Test Requirements - Outdoors

Thermal performance data from the Sunpak evacuated tube liquid collector, with shaped specular reflector and with a diffuse reflector, shall be obtained at the MSFC outdoor test bed facility. Because of low outside temperature conditions, a 33% ethylene glycol/water mixture transfer fluid will circulate through the collector loop. Variation in flow rate and specific heat of heat transfer fluids have been shown to produce negligible effects on the thermal performance of evacuated tube solar collectors. Therefore, comparisons of the collector performance with variations in these parameters should be valid. The collector shall be mounted on the sun tracking test table. The collector at all times should be positioned perpendicular to incoming solar radiation. In addition, the test shall be conducted at times having clear weather conditions such that the integrated average insolation measured in the plane of the collector and used for the computation of collector efficiency values shall not be less than 200 BTU/Ft^2·Hr. The collector shall be mounted in a location such that there will be no significant energy reflected or reradiated onto the collector from surrounding buildings or any other surfaces in the vicinity of the test for the duration of the test. Wind speed across the collector at test times should not exceed 7.5 MPH. The following data shall be recorded of test variables and conditions:

1. Collector inlet liquid temperature.
2. Collector outlet liquid temperature.
3. Total insolation from pyranometer.
4. Liquid flow rate through the collector.
5. Collector differential temperature.
6. Ambient air temperature.

Thermal performance evaluation data shall be obtained at inlet temperatures of approximately 0, 25, 50, and 100°F above the ambient temperature at a flow rate of 3.0 lbm/min (.36 GPM), to compensate for the lower specific heat of the glycol mixture.

6.1.4 Procedure - Outdoors

1. Mount the collector on the sun tracking table. Position the table such that the collector plane is perpendicular to solar radiation at all times.
2. Initiate operation of the data acquisition system to record data at one minute intervals and check to verify that all necessary channels are operational.
3. Perform sensor accuracy verification tests.
4. Establish the proper flow rate and monitor inlet temperature for each test day.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1 Collector Thermal Efficiency Test (Continued)

6.1.4 Procedure - Outdoors (Continued)

5. Record all data continuously at one minute intervals at quasi-steady state conditions over the clear test days.

6. Repeat the test procedure as necessary for the Sunpak collectors on separate test days with shaped specular reflector attached and also with only a diffuse reflector.

7. Upon completion of testing, save the printout as a record.

6.1.5 Test Results

The results obtained during these tests are contained in Table I for the Sunpak collector with shaped specular reflector and in Table II for the Sunpak collector with a diffuse reflector, both at indoor conditions. Table III contains thermal performance test data for the Sunpak collector with shaped specular reflector at outside conditions while Table IV shows thermal performance data with only a diffuse reflector at outside conditions. Figure 4 shows Sunpak thermal efficiency with the shaped specular reflector at indoor vs. outdoor conditions. Similarly, Figure 5 shows thermal efficiency with only a diffuse reflector at indoor vs. outdoor conditions. Figure 9 represents thermal efficiency of the Sunpak collector with SSR as a function of inlet temperature. Figure 10 depicts thermal efficiency of the Sunpak collector with a diffuse reflector as a function of inlet temperature.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Incident Angle Modifier Test

6.2.1 Test Requirements - Indoors

The collector incident angle modifier shall be determined by tilting the collector at 10°, 20°, 30°, 40°, 50°, and 60° with respect to the solar simulator surface. The liquid flow rate shall be 2.65 lbm/min. ± 0.10, with the inlet temperature controlled to within ± 2°F of ambient. The insolation rate shall be 300 $BTU/Ft^2 \cdot Hr$. 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) Incident solar flux level.

(7) Liquid flow rate through the collector.

6.2.2 Procedure - Indoors

1. Set up collector at required tilt angle.
2. Establish required flowrate.
3. Establish required inlet temperature.
4. Establish solar simulator flux level at 300 $BTU/Ft^2 \cdot Hr$. and measure the flux levels at 72 locations on the collector surface and record on data sheet.
5. Record data each minute for at least one hour until stabilized conditions occur.
6. Repeat above steps as necessary for the Sunpak collector with the shaped specular reflector attached and also with only a diffuse reflector to obtain required data for each tilt angle.

6.2.3 Test Requirements - Outdoors

With the collector positioned at a fixed 45° slope facing due south, the incident angle modifier shall be determined from collector efficiency data when the direction of incident solar radiation is approximately 10, 30, 45, and 55 degrees with respect to 0° at solar noon. Since these tests are being conducted outdoors, the inlet liquid temperature should be controlled as close to ± 2°F of ambient air temperature as is practical. Because of low outside temperature conditions, a 33% by volume ethylene glycol/water mixture transfer fluid will circulate through the collector loop. The test should be conducted on a clear day with a wind speed not exceeding 7.5 MPH. The following data shall be recorded during the tests:

1. Ambient air temperature.
2. Collector inlet liquid temperature.
3. Collector outlet liquid temperature.
4. Collector differential temperature.
5. Incident solar flux level..
6. Liquid flow rate through the collector.

6.2.4 Procedure - Outdoors

1. Mount the collector in a fixed position on the outdoor test table at a 45° slope facing due south.
2. Initiate operation of the data acquisition system to record all data at one minute intervals and check to verify that all necessary channels are operational.
3. Perform sensor accuracy verification tests.
4. Establish a flow rate of 3 lbm/min (.36 GPM) with an inlet liquid temperature equal to ambient air temperature (± 2.0°F).
5. Monitor the test parameters by using the data logger printout at the test site.
6. Record data continously at one minute intervals over the clear test day.
7. Repeat the test procedure as necessary for the Sunpak collector on separate test days with the shaped specular reflector attached and also with only a diffuse reflector.
8. Upon completion of testing, save the printout as a record.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Incident Angle Modifier Test (Continued)

6.2.5 Requirements and Procedure - Indoors (Altitude Angle Incident Angle Modifier)

The collector altitude angle incident angle modifier shall be determined by tilting the collector at an altitude angle of 25° and 35° with respect to the solar simulator surface. The liquid flow rate shall be 2.5 lbm/min $\pm$ .10, with the inlet temperature controlled to within $\pm$ 2°F of ambient. The insolation rate shall be 300 BTU/Hr-Ft^2. The tests shall be performed using water as the heat transfer medium. The following data shall be recorded during the tests:

1. Collector tilt angle.
2. Ambient air temperature.
3. Collector inlet liquid temperature.
4. Collector outlet liquid temperature.
5. Collector differential temperature.
6. Incident solar flux level.
7. Liquid flow rate through the collector.

Test procedure steps are as follows:

1. Set up collector at required tilt angle.
2. Establish required flow rate.
3. Establish required inlet temperature.
4. Establish solar simulator flux level at 300 BTU/Ft^2·Hr and measure the flux level at 72 locations on the collector surface and record on data sheet.
5. Record data each minute at least one hour until stabilized conditions occur.
6. Repeat above steps as necessary for the Sunpak collector with the shaped specular reflector to obtain required data for each tilt angle.

6.2.6 Test Results

Incident angle modifier test data for the Sunpak collector with shaped specular reflector at indoor conditions is listed in Table V.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Incident Angle Modifier Test (Continued)

6.2.6 Test Results (Continued)

Table VI lists incident angle modifier data for the Sunpak collector with a diffuse reflector at indoor conditions. Altitude angle - incident angle modifier data at indoor conditions with the SSR and the diffuse reflector are contained in Table VII. Further incident angle modifier data for outdoor conditions is contained in Table VIII with the shaped specular reflector in place and in Table IX with only a diffuse reflector. Figure 6 shows a comparison of incident angle modifier data for indoor and outdoor conditions with the shaped specular reflector fastened on while Figure 7 shows a comparison of incident angle modifier data for indoor and outdoor conditions with only the diffuse reflector. Figure 8 is a graphic representation of altitude angle - incident angle modifier data for the Sunpak collector with shaped specular reflector at indoor conditions as compared with diffuse reflector data.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.3 Collector Time Constant Test

6.3.1 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 $\pm$ 2°F of ambient while the liquid is flowing at 2.50 lbm/min.

The differential temperature across the collector shall be monitored to determine the time required to reach the condition of:

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

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.

6.3.2 Procedure

1. Adjust the liquid (water) flow rate to 2.50 lbm/min.

2. Adjust the inlet temperature to ambient $\pm$ 2°F.

3. Power up the solar simulator and establish a solar flux level of 300 BTU/Ft²·Hr.

4. Establish wind speed of 7.5 mph.

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

6. Power down solar simulator.

7. Record the change of ΔT across the collector.

6.3.3 Results

The results of the time constant test are shown in Figure 3.

7.0 YS S

7.1 Thermal Performance Test

The analysis of data contained in this report is consistent with the procedures of References 2.1 and 2.2. The thermal efficiency of the Sunpak liquid collector with shaped specular reflector attached determined from test data contained in Table I and Table III is given by the following equation:

$$\eta = 0.526 - 0.135 \left(\frac{Ti-Ta}{I}\right) \text{ based on gross area.}$$

The thermal efficiency of the Sunpak liquid collector with only a flat white diffuse reflecting surface determined from test data contained in Table II and Table IV is given by the following equation:

$$\eta = 0.375 - 0.138 \left(\frac{Ti-Ta}{I}\right) \text{ based on gross area.}$$

The procedure for calculating thermal efficiency as outlined in ASHRAE 93-77 is adequate for indoor testing of the Sunpak collector due to the fact that true "steady state" conditions can be achieved. However, when testing outdoors, true steady state seldom occurs even when utilizing an altazimuth table. In the case of collectors with large fluid capacity and long time constants, the residence time of the fluid may be 50% greater than the time constant. In this case, instantaneous data must be taken at an interval equal to the residence time to allow for the effects on the inlet fluid to show up on the outlet at a residence time later. ASHRAE 93-77 states that an integrated value of solar radiation and energy output over a period equal to the time constant or five minutes, whichever is greater, is sufficient, but this does not compensate for conditions of a drift in inlet temperature which does not show up in the outlet temperature until a residence time later. Therefore, the calculated values of efficiency were determined by a method taking into account the "residence time" of the collector. To quote the Owens-Illinois Sunpak^{TM} installation and operation manual, "Performance of the Sunpak ^{TM} collector can be monitored by comparing the useful energy being gained by the collector to the insolation entering the plane of the collector. Consideration must be given to the residence time of the collector when determining heat gained. For example, a module operating with a 0.3 gpm flow rate will have a thirty minute residence time. To calculate the heat being gained, one would determine a ΔT by subtracting an inlet temperature from the outlet temperature which occurs thirty minutes later. This residence time would, of course, be different for other flow rates. Residence time can be estimated assuming plug flow and a 9 gallon/module fluid capacity."

Taking into account the calculated "residence time" of the collector for the flow rate at the time of testing, an averaged inlet temperature condition at a given time was subtracted from an averaged outlet collector temperature at the calculated later time to determine the heat gain for the collector. The quasi-steady state solar flux

7.0 **ANALYSIS** (Continued)

7.1 Thermal Performance Test (Continued)

level was averaged over that calculated time period for use in efficiency calculations. Flux levels at the solar simulator, of course, remained constant over each test condition, while outside flux averages are for clear day data with a small percentage of diffuse insolation. Due to the excellent insulative properties of the evacuated tube and considerable data scatter, the best curve fit is a first order polynomial of the form:

$$\eta = a_0 + a_1 \tau$$

where $\tau = (Ti - Ta)/I$.

The coefficients were determined to be:

$a_0 = 0.526$, $a_1 = -0.135$ — Based on gross area with shaped specular reflector

$a_0 = 0.375$, $a_1 = -0.138$ — Based on gross area with a diffuse reflector

7.0 **ANALYSIS** (Continued)

7.2 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 0°, 10°, 20°, 30°, 40°, 50°, and 60° to the normal of the collector surface when testing indoors. For the MSFC Solar Test Bed Facility only method 2 (testing outside using a permanent test rack) is applicable. Efficiency data at outdoor conditions was determined when the direction of incident solar radiation was approximately 10, 30, 45, and 55 degrees with respect to solar noon on clear test days.

According to ASHRAE 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 = 0.526 for the Sunpak collector with shaped specular reflector and 0.375 for the Sunpak collector with only a diffuse reflector.

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.

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

where

$F_R U_L$ is the negative of the slope determined from the thermal efficiency curve, = -0.135 for the Sunpak collector with shaped specular reflector and 0.138 for the Sunpak collector with a diffuse reflector.

Data in the incident angle modifier tables show that the inlet liquid temperatures were not all within ± 2°F of ambient air temperature. Hence, equation (2) was used for evaluation where applicable. Otherwise, equation (1) was used.

The results of these computations are shown in incident angle modifier tables and plotted against incident angle in Figures 6 and 7. An altitude angle - incident angle modifier for the Sunpak collector

7.0 ANALYSIS (Continued)

7.2 Incident Angle Modifier Test (Continued)

with the SSR and with a diffuse reflector for altitude angles of 25° and 35° was determined using appropriate values of $F_R(\alpha\tau)n$ and F_RU_L from above. The altitude angle-incident angle modifier is plotted in Figure 8.

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 Sunpak collector with a shaped specular reflector for a typical solar cooling application is 37.3%. Similarly, at the same conditions, the all day efficiency of the Sunpak collector with only a diffuse reflector is 35.0%. The selected site dependent data in conjunction with test data used in these determinations is shown in Tables X and XI. 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.

7.0 ANALYSIS (Continued)

7.3 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 abruptly reducing the solar flux to zero 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 within $\pm$ 2°F of ambient air temperature, then the following equation must be used.

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

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
Ag	= 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 $\pm$ 2°F of the ambient, hence equation (1) was used for evaluation. From Figure 3 the time constant was determined to be 19.6 minutes.

TABLE I

THERMAL PERFORMANCE TEST DATA FOR THE SUNPAK COLLECTOR
WITH SHAPED SPECULAR REFLECTOR
AT INDOOR CONDITIONS

	Development SSR 305 BTU/Hr·Ft^2							Development SSR 260 BTU/Hr·Ft^2					Current Production SSR 308 BTU/Hr·Ft^2				
Ambient Air Temp. (T_a), °F	68.00	73.00	80.70	76.34	78.10	78.01	75.80	70.15	69.35	77.52	77.39	80.10	72.31	73.22	73.62	74.92	73.47
Fluid Inlet Temp. (T_i), °F	71.13	109.27	149.50	147.52	175.54	184.50	166.84	71.14	108.42	145.99	179.96	175.30	75.90	76.78	100.39	133.83	158.59
Fluid Outlet Temp. (T_e), °F	103.53	140.48	180.15	178.10	206.01	214.90	194.83	98.46	134.82	171.25	205.40	200.60	107.17	107.95	131.38	163.25	187.67
Differential Fluid Temp. (ΔT), °F	32.40	31.21	30.65	30.58	30.47	30.40	27.99	27.32	26.40	25.26	25.44	25.30	31.27	31.17	30.99	29.42	29.08
Total Solar Flux (I), BTU/Hr·Ft^2	305.64	305.64	305.64	305.64	305.64	305.64	304.86	258.70	258.70	258.70	258.70	258.70	308.6	308.6	308.6	308.6	308.6
Flow Rate, Lbm/Min.	[illegible].65	2.65	[illegible].65	2.65	2.60	2.60	2.70	2.65	2.65	2.65	2.60	2.60	2.7	2.7	2.7	2.7	2.7
$(T_i-T_a)/I$ °F·Hr·Ft^2/BTU	.010	.119	.225	.233	.319	.348	.299	.004	.151	.265	.394	.368	.012	.012	.087	.191	.276
Efficiency (η), %	.527	.507	.498	.497	.486	.485	.465	.525	.507	.485	.479	.477	.513	.511	.508	.483	.477

TABLE II

THERMAL PERFORMANCE TEST DATA FOR THE SUNPAK LIQUID COLLECTOR WITH DIFFUSE REFLECTOR AT INDOOR CONDITIONS

Ambient Air Temperature (T_a), °F	67.73	69.77	65.83	69.11
Fluid Inlet Temperature (T_i), °F	67.77	70.07	124.78	156.09
Fluid Outlet Temperature (T_e), °F	89.77	92.19	146.06	176.62
Differential Fluid Temperature (ΔT), °F	22.00	22.12	21.28	20.53
Total Solar Flux (I), BTU/Hr·Ft^2	296.80	298.18	301.75	301.75
Flow Rate, LBM/Min	2.70	2.70	2.65	2.60
$(T_i - T_a)/I$ °F·Hr·Ft^2/BTU	.000	.001	.195	.288
Efficiency (η), %	.375	.376	.350	.332

TABLE III

THERMAL PERFORMANCE TEST DATA FOR THE SUNPAK LIQUID COLLECTOR WITH SHAPED SPECULAR REFLECTOR AT OUTSIDE CONDITIONS

Ambient Air Temperature (T_a), °F	41.5	47.4	38.2	57.0	58.4	5[illegible].6	59.2	59.6	58.5
Fluid Inlet Temperature (T_i), °F	62.19	72.27	72.41	99.39	104.41	105.72	111.62	114.80	160.20
Fluid Outlet Temperature (Te), °F	91.66	103.94	103.28	132.48	135.25	136.72	141.00	142.23	189.90
Differential Fluid Temperature (ΔT), °F	29.47	31.67	30.60	33.09	30.84	31.00	29.38	27.43	29.70
Total Solar Flux (I), BTU/Hr·Ft^2	277.83	306.59	296.12	316.41	314.27	311.71	302.32	277.55	341.10
Flow Rate, Lbm/Min	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Cp BTU/Lbm·°F	.87	.88	.88	.89	.90	.90	.90	.90	1.0
$(T_i - T_a)/I$ °F-Hr-Ft^2/BTU	.074	.081	.115	.133	.146	.151	.177	.202	.298
Efficiency (η), %	.519	.511	.516	.523	.497	.503	.497	.500	.490

TABLE IV

THERMAL PERFORMANCE TEST DATA FOR THE SUNPAK LIQUID COLLECTOR WITH DIFFUSE REFLECTOR AT OUTSIDE CONDITIONS

Ambient Air Temperature (T_a), °F	49.3	52.1	41.2	37.1	48.8
Fluid Inlet Temperature (T_i), °F	74.22	80.80	86.31	98.82	114.34
Fluid Outlet Temperature (T_e), °F	99.42	101.20	109.71	121.10	133.54
Differential Fluid Temperature (ΔT), °F	25.20	20.40	23.40	22.28	19.20
Total Solar Flux (I), BTU/Hr·Ft^2	318.10	277.10	320.25	312.99	296.05
Flow Rate, Lbm/Min	2.85	2.95	3.0	3.0	3.1
$(T_i-T_a)/I$ °F-Hr-Ft^2/BTU	.078	.104	.141	.197	.221
Efficiency (η), %	.373	.358	.362	.356	.339

TABLE V

INCIDENT ANGLE MODIFIER TEST DATA FOR THE SUNPAK LIQUID COLLECTOR WITH SHAPED SPECULAR REFLECTOR AT INDOOR CONDITIONS

Angle, °	10	20	30	40	50	62
Ambient Air Temperature (T_a), °F	82.38	80.32	82.26	70.07	69.88	69.15
Fluid Inlet Temperature (T_i), °F	81.53	81.36	81.24	70.43	70.17	70.04
Fluid Outlet Temperature (T_e), °F	111.95	107.17	103.30	89.33	86.90	84.82
Differential Fluid Temperature (ΔT), °F	30.42	25.81	22.06	18.90	16.73	14.78
Total Solar Flux (I), BTU/Hr·Ft^2	301.7	278.3	250.3	221.0	183.5	138.2
Flow Rate, Lbm/Min	2.70	2.60	2.65	2.70	2.65	2.65
Efficiency (η), %	.510	.452	.438	.433	.453	.531
$K\alpha\tau$ Adjusted Efficiency Ratio	.970	.860	.833	.823	.861	1.01

TABLE VI

**INCIDENT ANGLE MODIFIER TEST DATA
FOR THE SUNPAK COLLECTOR WITH A DIFFUSE REFLECTOR AT INDOOR CONDITIONS**

Angle	20°	40°	50°	60°
Ambient Air Temperature (T_a), °F	73.0	74.0	73.0	74.1
Fluid Inlet Temperature (T_i), °F	68.4	68.4	68.3	68.4
Fluid Outlet Temperature (T_e), °F	90.4	88.5	87.0	85.2
Differential Fluid Temperature (ΔT), °F	22.0	20.1	18.7	16.8
Total Solar Flux (I), $BTU/Hr \cdot Ft^2$	279.0	222.87	185.8	144.4
Flow Rate, Lbm/Min	2.65	2.65	2.65	2.65
Efficiency (η), %	.392	.448	.500	.578
Adjusted Efficiency Ratio $K\alpha\tau$	1.04	1.18	1.32	1.52

TABLE VII

ALTITUDE ANGLE-INCIDENT ANGLE MODIFIER TEST DATA
FOR THE SUNPAK COLLECTOR WITH SHAPED SPECULAR REFLECTOR
AND WITH A DIFFUSE REFLECTOR

	Shaped Specular Reflector		Diffuse Reflector	
Angle	25°	35°	25°	35°
Ambient Air Temperature (T_a), °F	69.5	69.6	65.42	57.38
Fluid Inlet Temperature (T_i), °F	70.68	70.44	65.44	57.07
Fluid Outlet Temperature (T_e), °F	100.60	98.02	85.83	75.69
Differential Fluid Temperature (ΔT), °F	29.92	27.58	20.39	18.62
Total Solar Flux (I), BTU/Hr·Ft^2	293.82	275.36	267.86	246.99
Flow Rate, Lbm/Min	2.5	2.5	2.5	2.5
Efficiency (η), %	.477	.469	.357	.353
Adjusted Efficiency Ratio $K\alpha\tau$	.943	.927	.952	.941

TABLE VIII

INCIDENT ANGLE MODIFIER TEST DATA FOR THE SUNPAK COLLECTOR WITH SHAPED SPECULAR REFLECTOR AT OUTSIDE CONDITIONS

	Morning Data				Afternoon Data			
Angle, Degrees	15	30	45	0	15	30	45	50
Ambient Air Temp. (T_a), ^oF	55.55	50.29	42.94	58.66	60.59	62.25	62.40	62.30
Fluid Inlet Temp. (T_i), ^oF	101.31	83.18	69.62	115.01	123.60	127.47	124.54	122.82
Fluid Outlet Temp. (T_e), ^oF	128.74	105.75	85.60	145.28	150.63	149.06	139.73	136.19
Differential Fluid Temp., (ΔT), ^oF	27.43	22.57	15.98	30.27	27.03	21.59	15.19	13.37
Total Solar Flux (I), $BTU/Hr \cdot Ft^2$	289.93	251.12	186.65	302.77	290.53	251.16	187.15	161.23
Flow Rate, Lbm/Min	2.93	2.95	2.96	2.93	2.92	2.92	2.92	2.93
C_p, BTU/Lbm-^oF	.884	.876	.868	.89	.892	.892	.890	.889
$(T_i-T_a)/I$ ^oF-Hr-Ft^2/BTU	.158	.131	.143	.186	.217	.260	.332	.375
Efficiency (η), %	.459	.435	.412	.489	.454	.420	.396	.404
$K\alpha\tau$ (Adjusted Efficiency Ratio)	.913	.861	.820	.98	.918	.865	.838	.864

TABLE IX

INCIDENT ANGLE MODIFIER TEST DATA FOR THE SUNPAK COLLECTOR WITH DIFFUSE REFLECTOR AT OUTSIDE CONDITIONS

Angle, Degrees	5.5	9.5	24.5	39.5	54.5
Ambient Air Temperature (T_a), °F	40.7	42.4	44.2	45.2	45.4
Fluid Inlet Temperature (T_i), °F	78.64	91.59	101.07	108.42	111.44
Fluid Outlet Temperature (T_e), °F	102.71	114.46	121.68	125.82	123.80
Differential Fluid Temperature (ΔT), °F	24.07	22.87	20.61	17.40	12.36
Total Solar Flux (I), BTU/Hr·Ft^2	320.63	309.87	272.42	213.88	132.67
Flow Rate, Lbm/Min	3.0	3.0	3.0	3.0	3.0
C_p BTU/Lbm·°F	.88	.89	.90	.91	.91
$(T_i-T_a)/I$ °F-Hr-Ft^2/BTU	.118	.159	.209	.296	.498
Efficiency (η), %	.371	.369	.383	.416	.477
$K\alpha\tau$ (Adjusted Efficiency Ratio)	1.03	1.04	1.09	1.21	1.45

TABLE X

SUNPAK LIQUID COLLECTOR WITH SHAPED SPECULAR REFLECTOR CALCULATED ALL DAY EFFICIENCY
(Current Production SSR)

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	197	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	1.85	.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		.276	.410	.444	.458	.467	.469	.463	.457	.442	.410	.283	
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	.70*	.97	.84	.82	.91	.91	.82	.84	.97	.70*	0	
7. Energy output from collector [Line 3 x Line 4 x Line 6]		11.59	52.50	73.47	93.51	119.42	124.62	106.68	95.59	84.46	37.88		799.7
8. Collector thermal efficiency, Line 7/Line 3													37.3

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

*Estimated or extrapolated values

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TABLE XI
SUNPAK LIQUID COLLECTOR WITH DIFFUSE REFLECTOR 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	197	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	1.85	.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	0	.115	.263	.305	.340	.325	.328	.323	.318	.300	.260	.121	
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	1.2*	1.52	1.24	1.10	1.03	1.03	1.10	1.24	1.52	1.2*	0	
7. Energy output from collector [Line 3 x Line 4 x Line 6]		8.3	52.8	74.5	93.1	94.1	98.6	99.8	98.2	89.8	41.2		750.4
8. Collector thermal efficiency, Line 7/Line 3													35.0

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

*Estimated or extrapolated values.

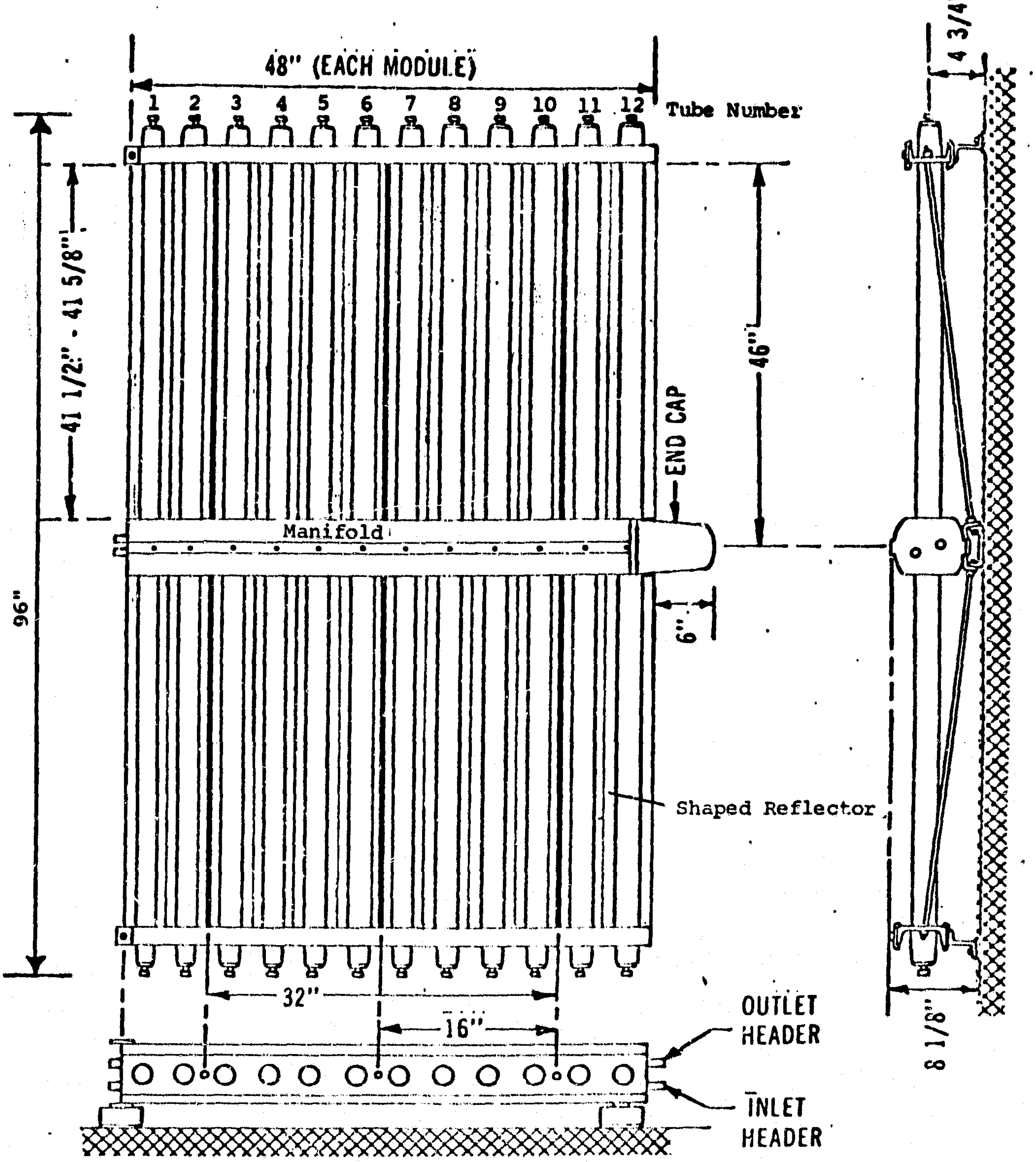

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Figure 1. Sunpak Evacuated Tube Liquid Collector Configuration

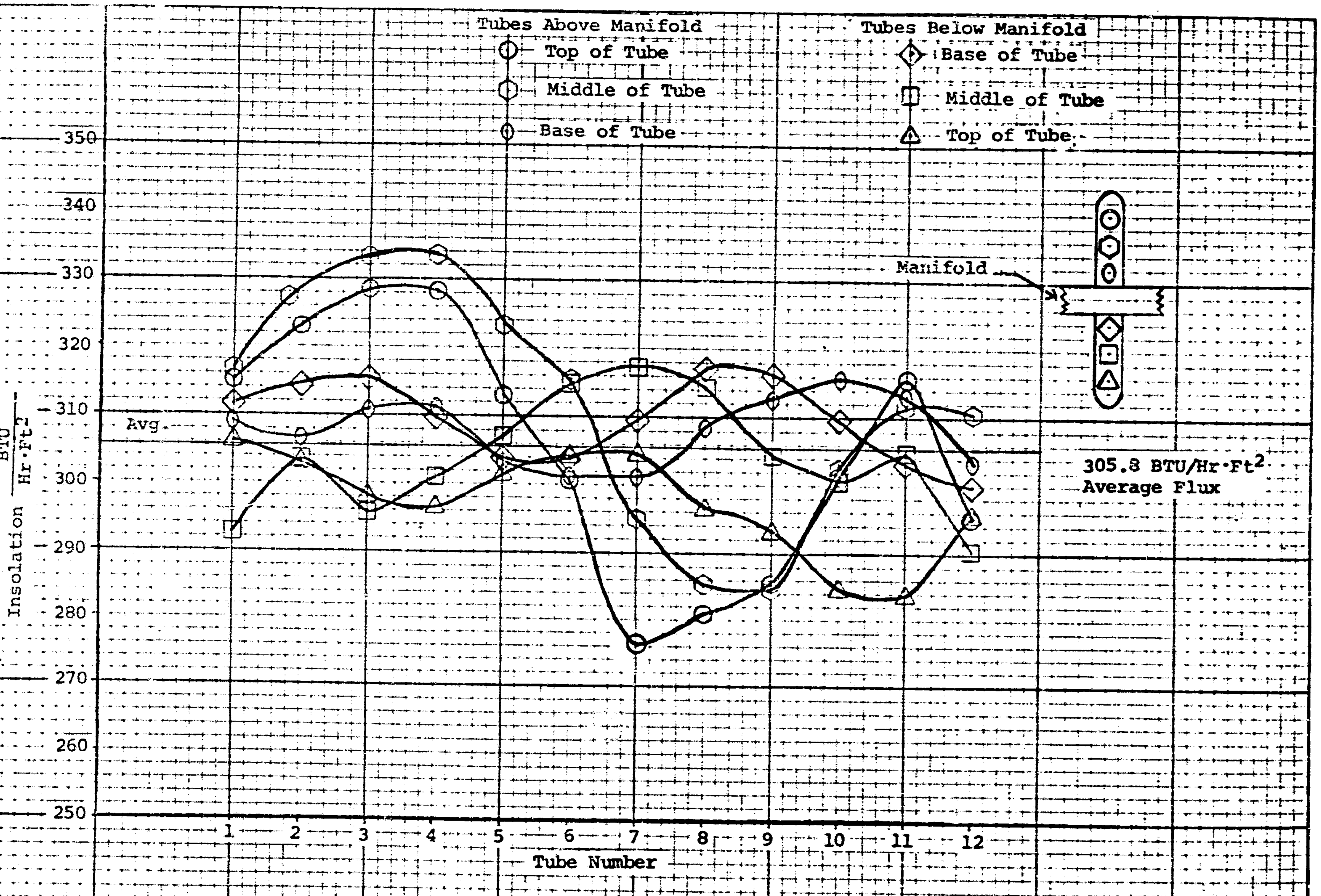


Figure 2. A Typical Flux Map During Sunpak Collector Testing at Indoor Conditions

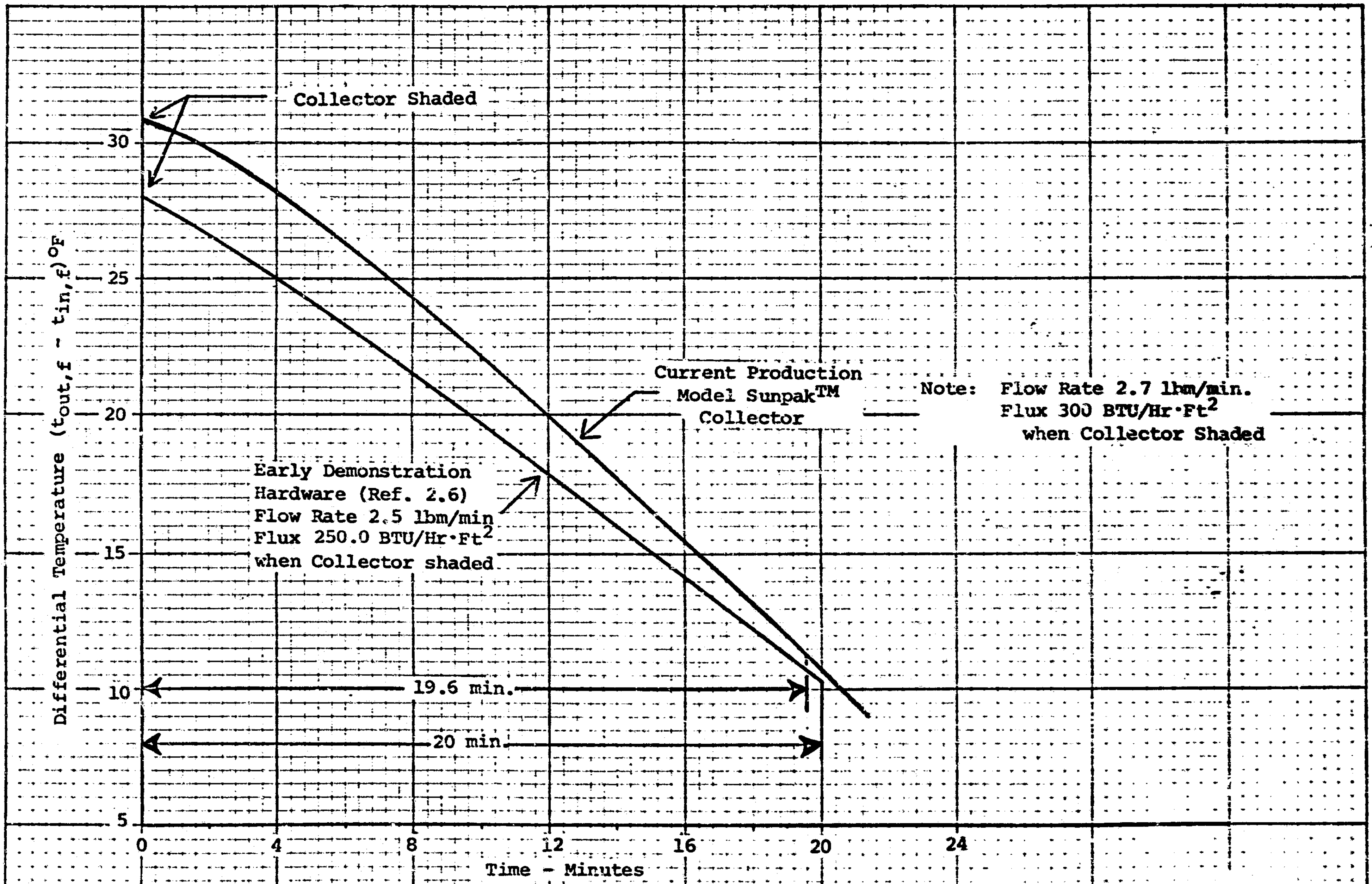


Figure 3. Time Constant Test Results for the Sunpak Liquid Collector with Shaped Specular Reflector at Indoor Conditions

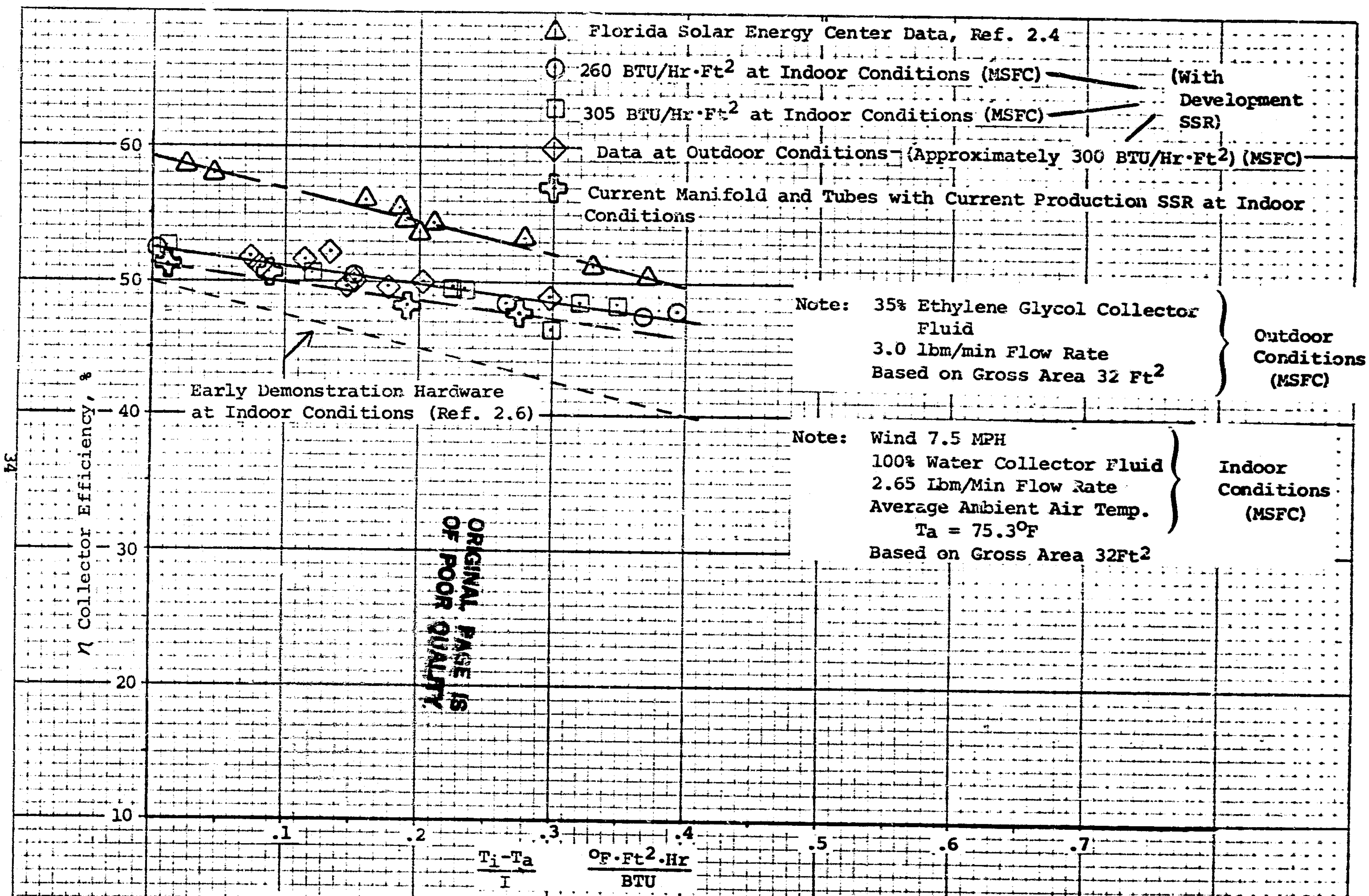


Figure 4. Thermal Efficiency of the Sunpak Liquid Collector with Shaped Specular Reflector at Indoor Conditions Compared with Performance at Outdoor Conditions

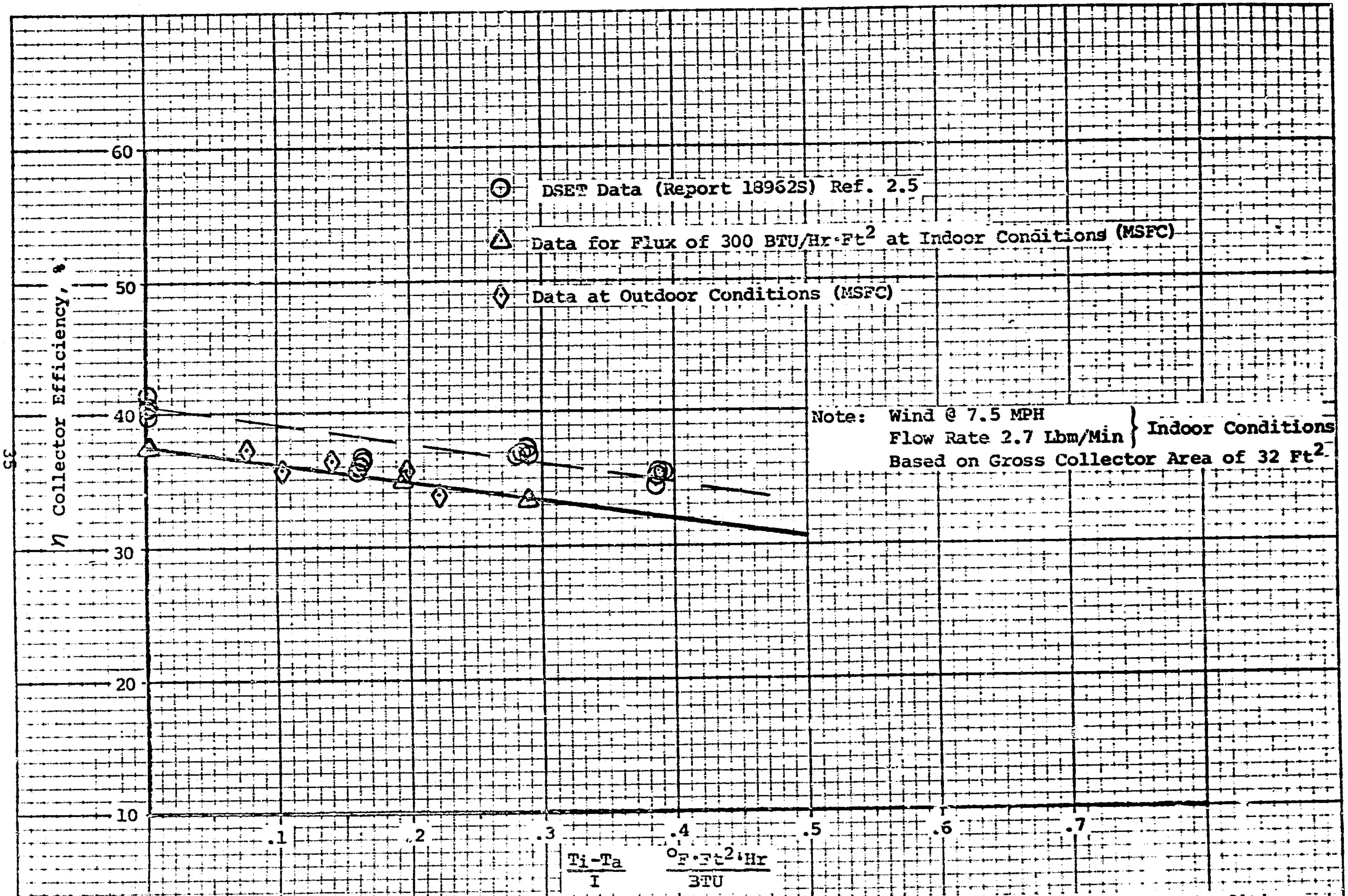


Figure 5. Thermal Efficiency of the Sunpak Liquid Collector with a Diffuse Reflector at Indoor Conditions Compared to Performance at Outdoor Conditions

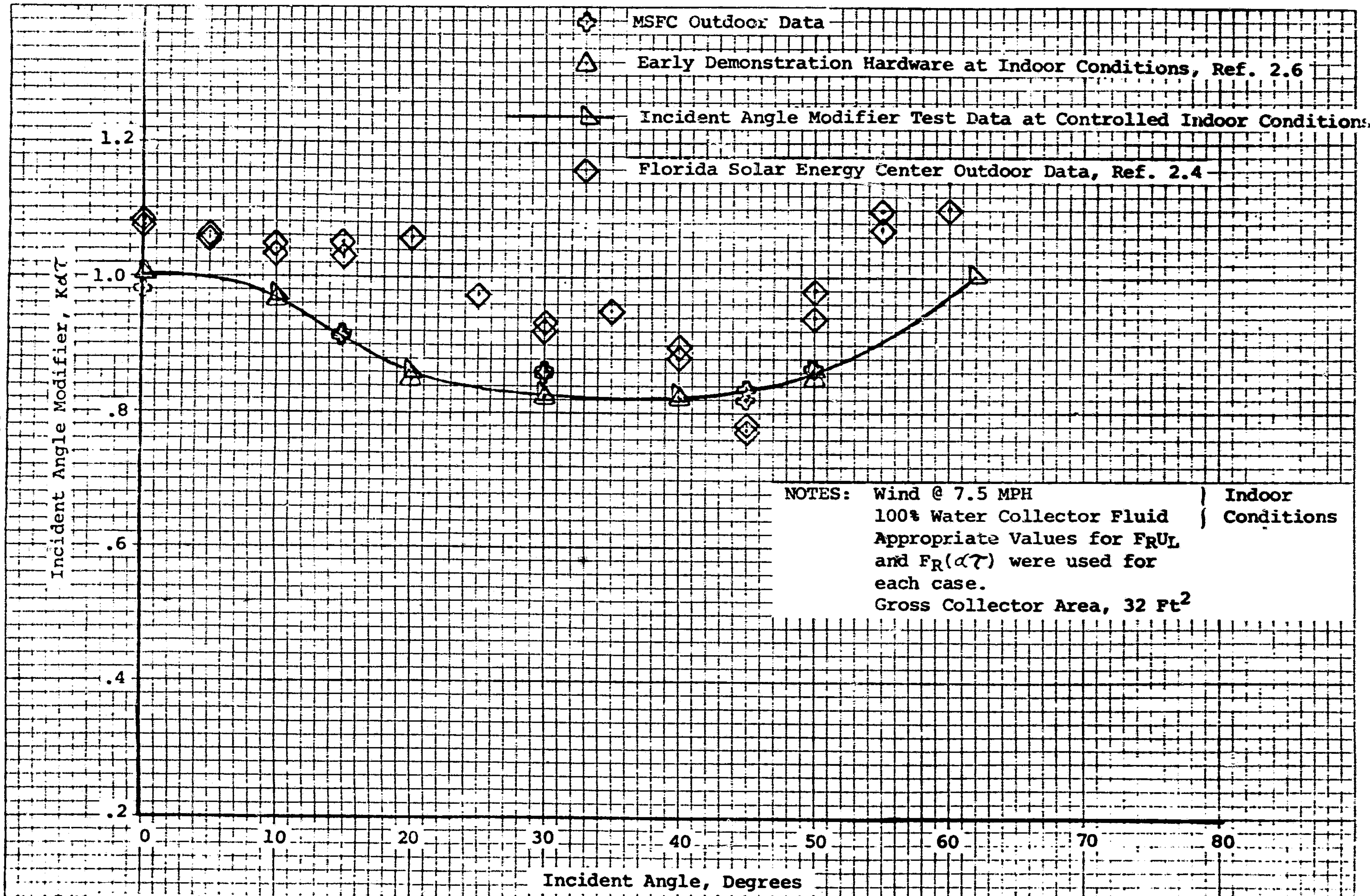


Figure 6. Comparison of Incident Angle Modifier Data for the Sunpak Collector with a Shaped Specular Reflector

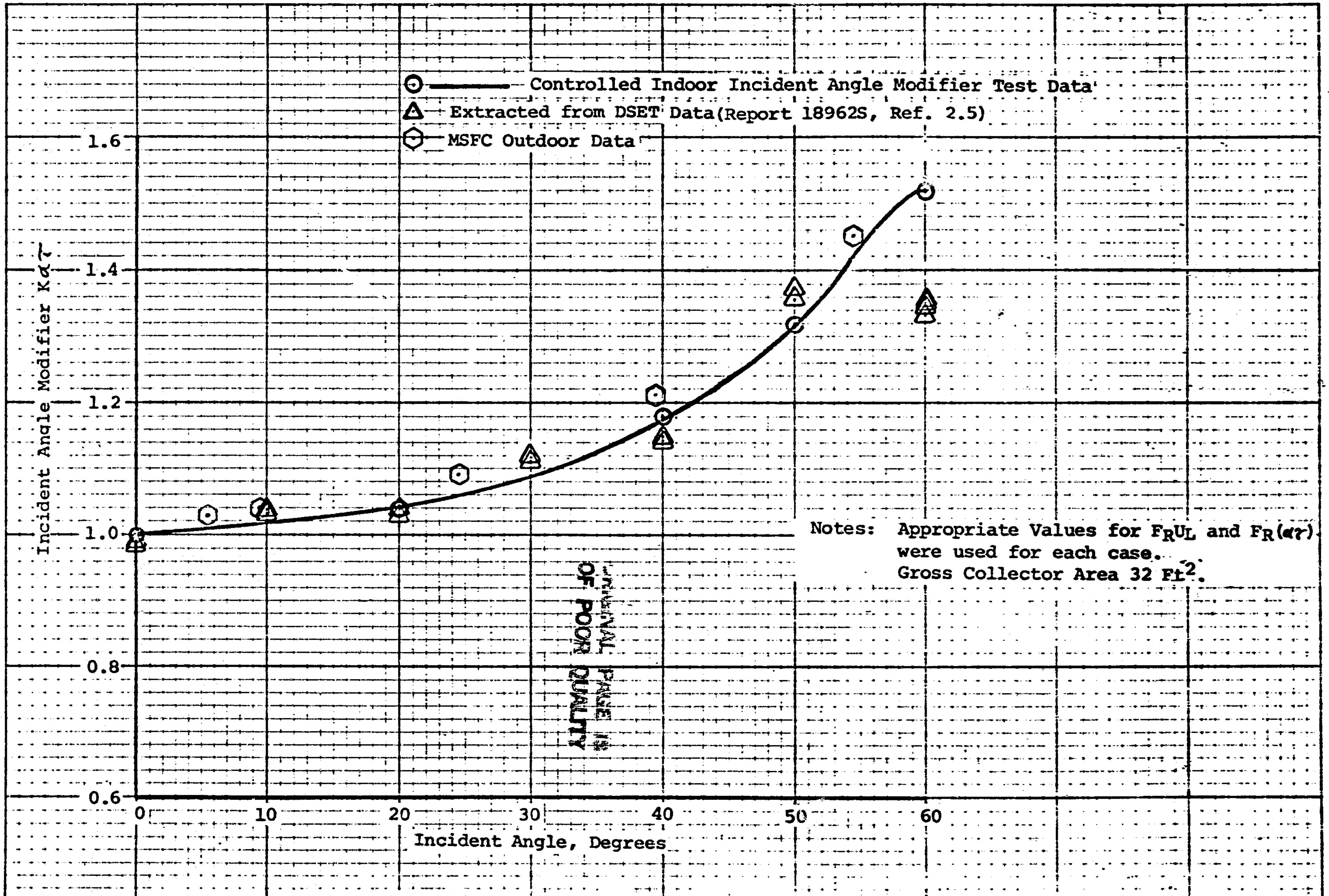


Figure 7. Comparison of Incident Angle Modifier Data for the Sunpak Collector with a Diffuse Reflector.

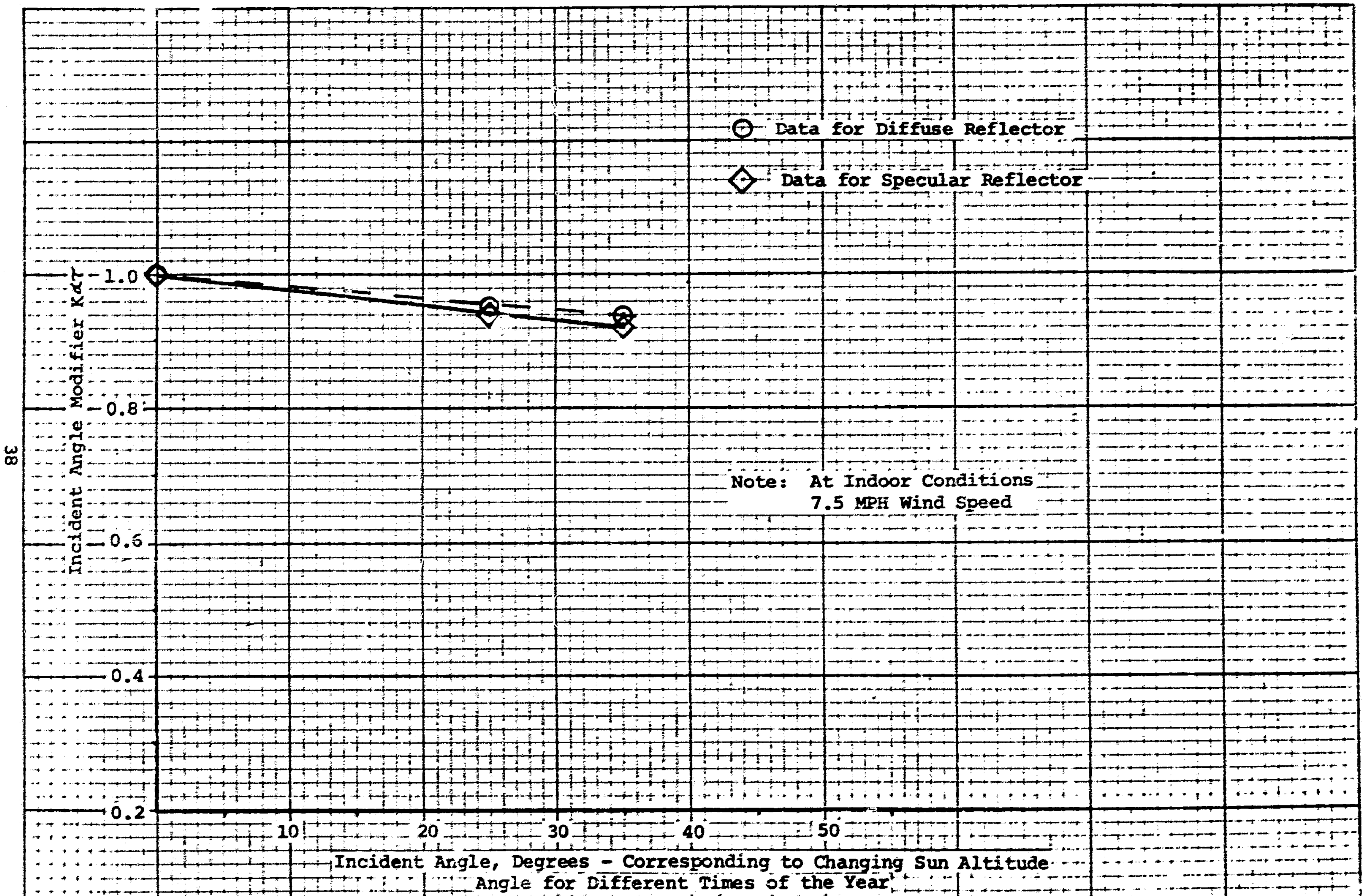


Figure 8. Altitude Angle-Incident Angle Modifier for the Sunpak Collector with Shaped Specular Reflector Compared with the Diffuse Reflector

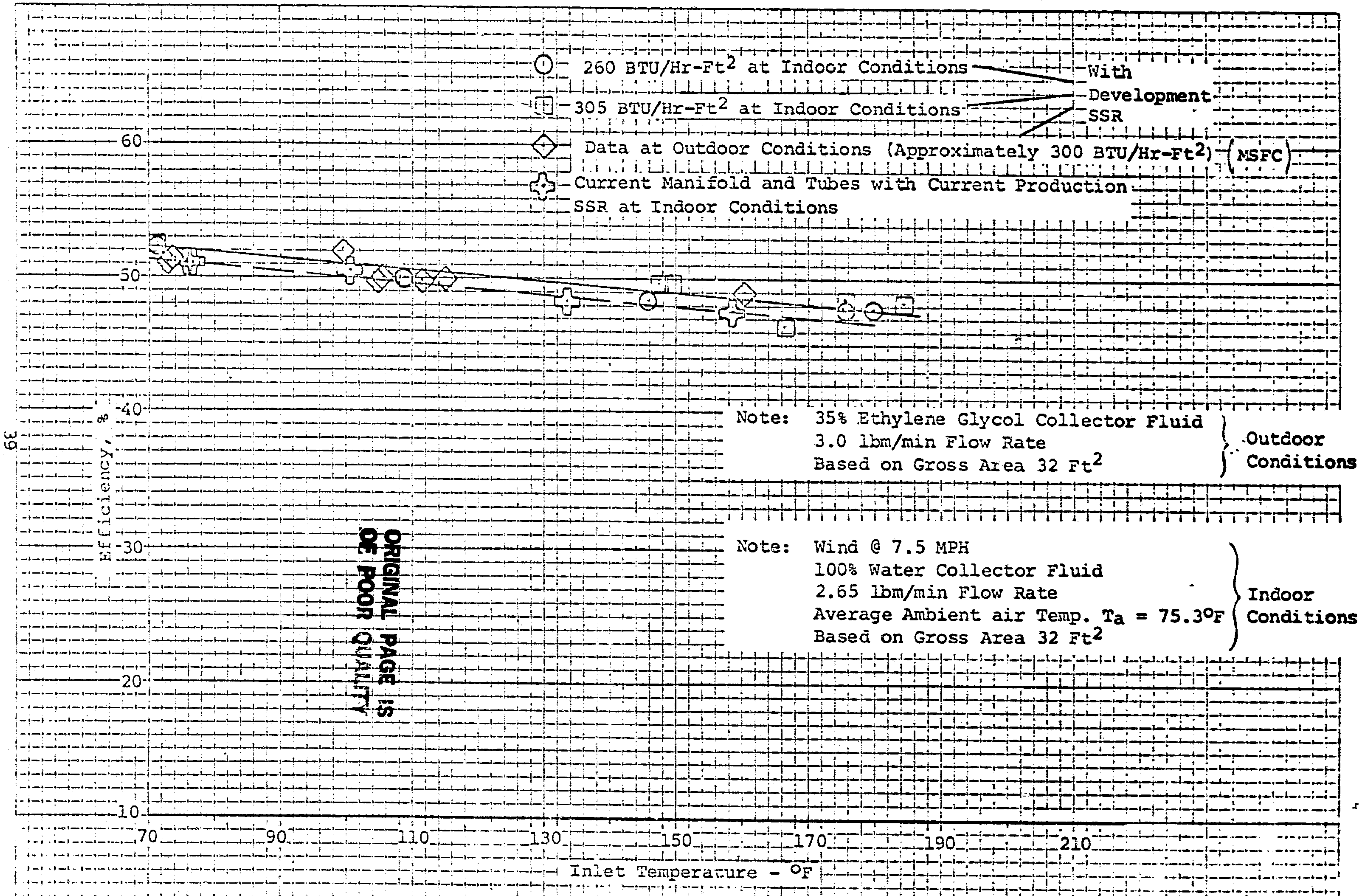


Figure 9. Thermal Efficiency of the Sunpak Collector with a Shaped Specular Reflector As A Function of Inlet Temperature

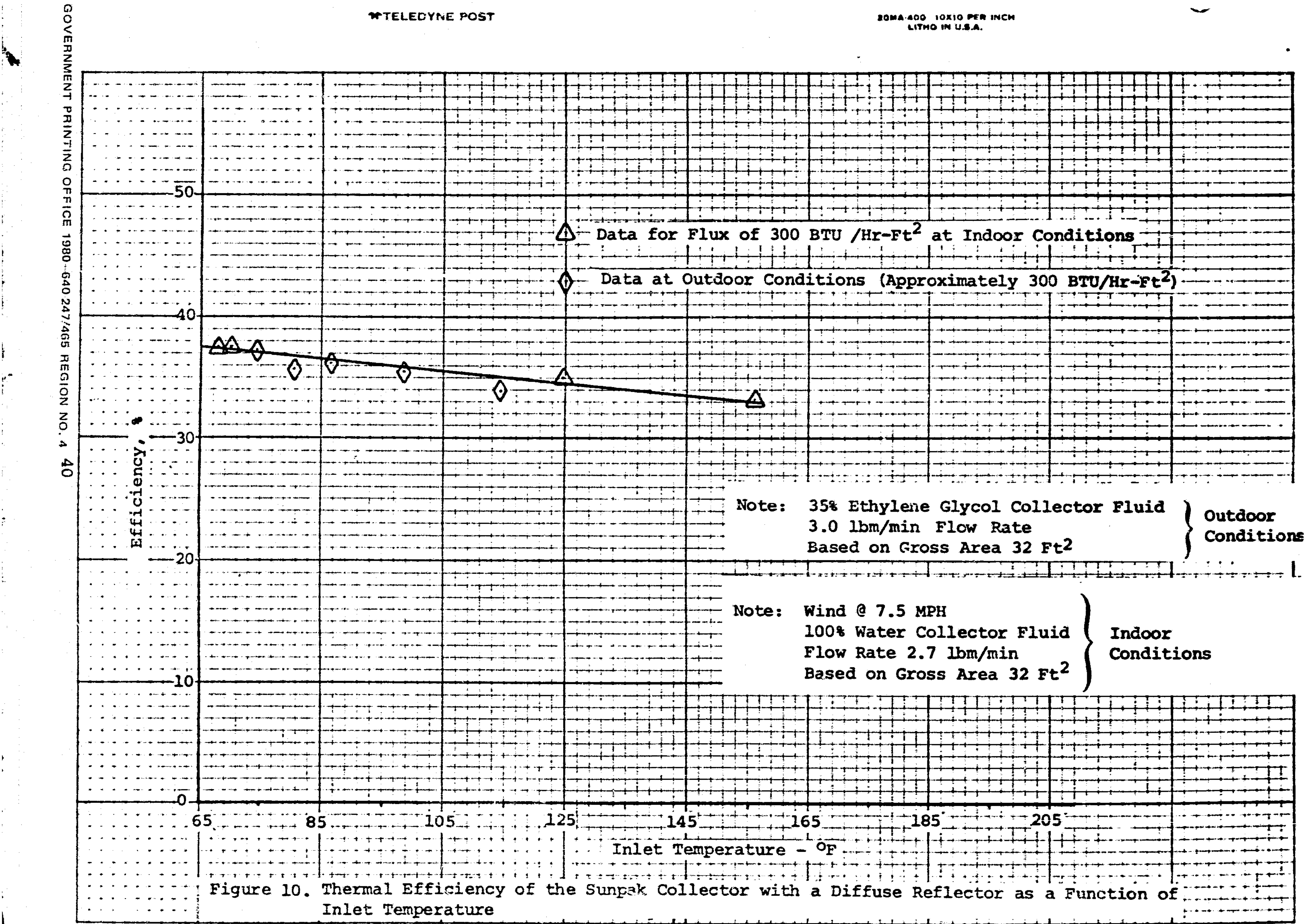
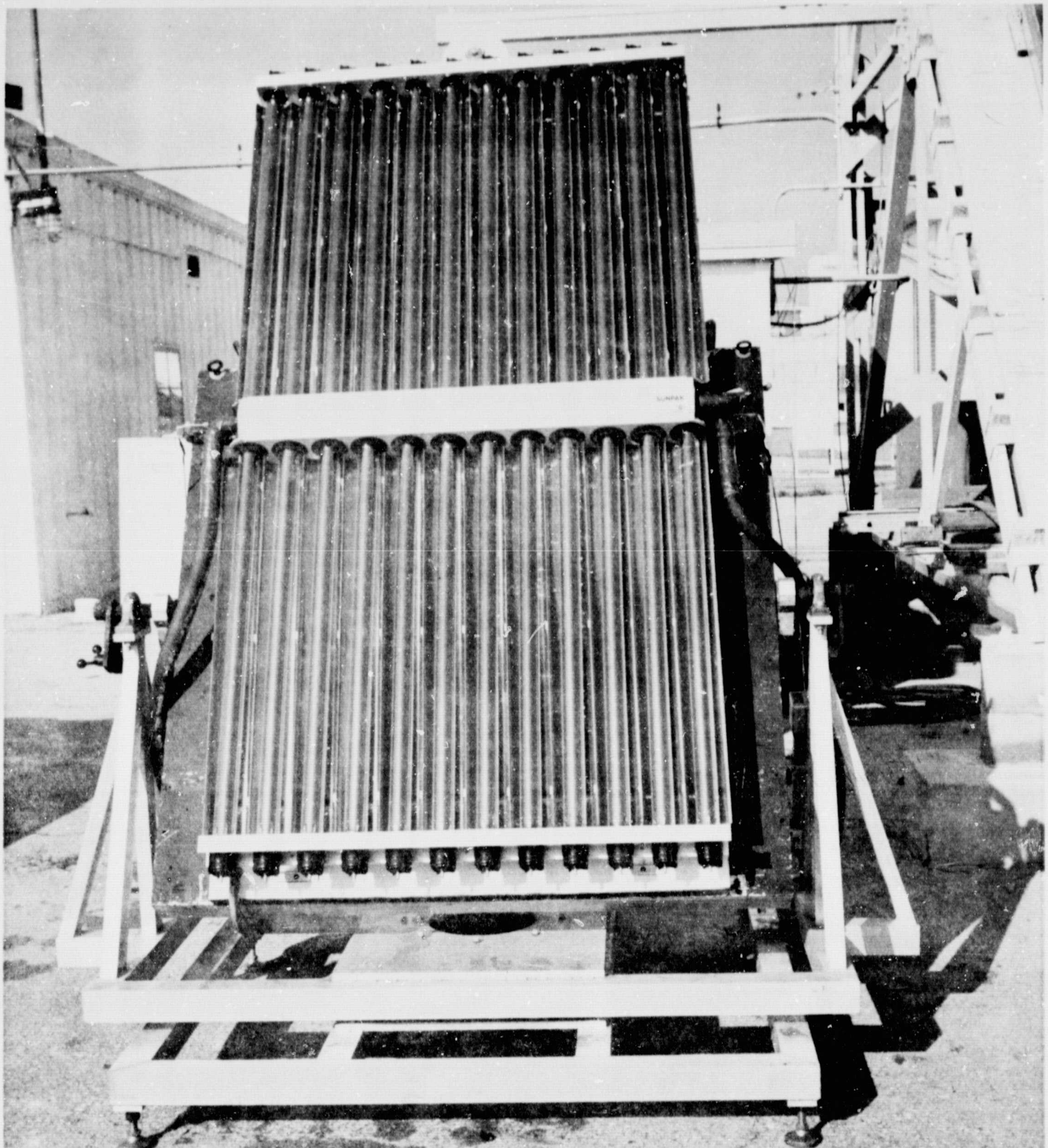
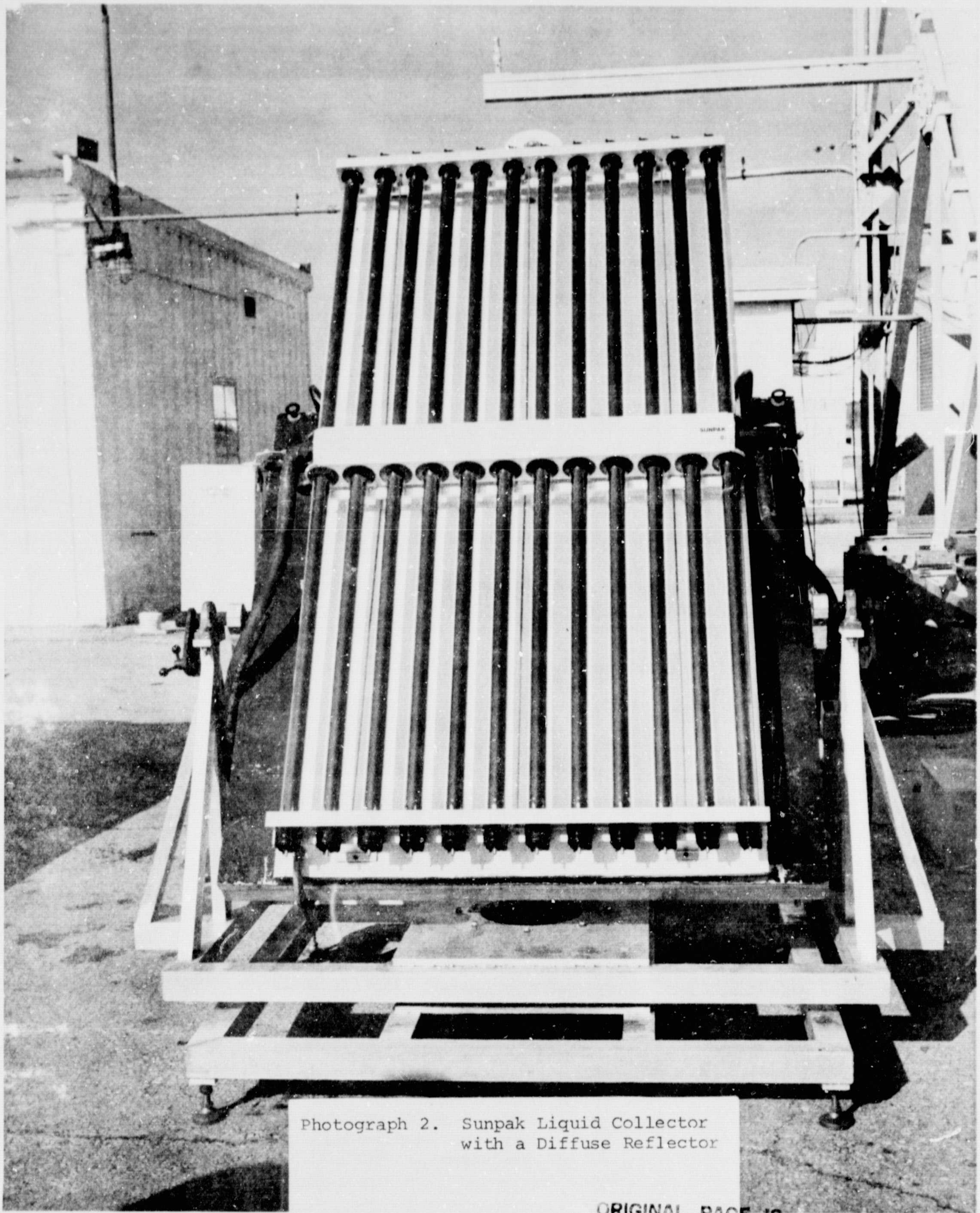


Figure 10. Thermal Efficiency of the Sunpak Collector with a Diffuse Reflector as a Function of Inlet Temperature



Photograph 1. Sunpak Liquid Collector with Shaped Specular Reflector



Photograph 2. Sunpak Liquid Collector with a Diffuse Reflector