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INDOOR TEST FOR THERMAL PERFORMANCE EVALUATION ON THE NORTHROP CONCENTRATING SOLAR COLLECTOR

Prepared by

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George C. Marshall Space Flight Center, Alabama 35812

For the U. S. Department of Energy

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Solar Energy

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16. ABSTRACT <p>This report describes the test procedure used and the results obtained from an evaluation test program conducted to obtain thermal performance data on a Northrup concentrating solar collector under simulated conditions. These tests were made using the Marshall Space Flight Center's solar simulator. A time constant test and incident angle modifier test were also conducted to determine the transient effect and the incident angle effect on the collector.</p> <p>The Northrup concentrating solar collector is a water/glycol/working fluid type, dipped galvanized steel housing, transparent acrylic Fresnel lens cover, copper absorber tube, fiber glass insulation and weighs approximately 98 pounds. The gross collector area is about 29.4 ft² per collector. A collector assembly includes four collector units within a tracking mount array.</p>			
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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 program. The test program was conducted to obtain the following data and information on the solar collector:

- Thermal performance data.
- Effects of long-term exposure to natural weathering elements.

All testing activities were conducted at the MSFC Breadboard Test Facility, and the thermal performance evaluations were made under natural outside conditions. The test was conducted, and the data evaluated, using the methods provided in Reference 2.1 as applicable to outdoor testing of concentrating collectors with solar tracking mount. The effects of long-term exposure to natural weathering will be conducted and reported at a later date.

2.0

REFERENCE

2.1

ASHRAE 93-77

Methods of Testing to Determine the Thermal Performance of Solar Collectors

3.0

COLLECTOR ARRAY ASSEMBLY DESCRIPTION

Manufacturer:	Northrup
Manufacturer's Address:	302 Nichols Drive Hutchins, Texas 75141
Model Number:	8/4 MSF-NSC-P
Type:	Concentrating, solar tracking
Working Fluid:	Water/Glycol, 50% by volume
Gross Collector Area, ft ² :	29.375 for a single collector unit

3.1

Collector Configuration

The collector assembly includes 4 collector units within a tracking mount array. For purposes of this test, one collector unit in the array was used for thermal evaluations. The total area for the four unit array was 117.5 ft². This yields a gross collector area of 29.375 ft² per collector, which was used for the efficiency determination according to ASHRAE standards. The actual

3.0 COLLECTOR ARRAY ASSEMBLY DESCRIPTION (Continued)3.1 Collector Configuration (Continued)

tracking area of each collector was 22.83 ft² (See Figure 2). The aperture area was 9.72 ft² per collector. Figure 4 includes a plot of efficiency based on the aperture area for comparison purposes. (A)

Collector Housing Material: 20 Gauge Hot Dipped
Galvanized Steel

Collector Top Cover: Aperture: 9.72 ft²
Material: Transparent Acrylic
Plastic Fresnel Lens
Transmissivity: 0.92

Absorber Tube: Copper

Pressure: Operating, 50 PSIG;
Test, 80 PSIG
Flow Rate: 0.40 gpm/collector unit
Water Pressure Drop: 0.6 ft. of H₂O
with 0.4 GPM
through tube
Selective Coating: 0.95 Absorptivity
and 0.12 emissivity

Insulation: Fiberglas, 1.1 lb/ft³, 1000° max. temp.
K = .3 @ 150°F Mean Temperature

Sun Tracker: 110 VAC, 0.39 Amps
1 Required per 24 Collectors
Accuracy of Tracker ± 0.2 degrees
Tracking Drive Speed: 2.59°/minute,
or 10.36 times sun speed (A)

Weight: Collector - 95 Lbs. dry, 98 Lbs. filled with
water

Total Weights of Systems -

Assembly: 8/4 MSF-NSC-P Model,
24" Collector Spacing, 4 collectors,
dry, 590 pounds total; 380 lbs. col-
lectors, 210 lbs. frame

Unit Temperature Limitation: 600°F

4.0

SUMMARY

Thermal performance tests have been conducted on a Northrup Concentrating Solar Collector, prior to weather exposure evaluations. (Weather exposure evaluations are to be performed as part of this test program, and the results will be reported separately at their conclusion.) The collector efficiency, thermal response time and incident angle modifier test results are presented in Section 6. Graphical presentations of the thermal response time, collector efficiency and incident angle modifier comprise Figures 2 through 4, respectively.

Measurements of stagnation temperatures were not performed because maximum temperatures encountered were above the range of available sensors.

The structural load evaluations were not performed, since the concentrating collector is not subject to large frontal area snow loads.

A view of the Northrup collector under test is shown in Photograph 1. Short term results of weathering in an area of high relative humidity are shown in Photograph 2.

(A)

5.0 TEST CONDITIONS AND TEST EQUIPMENT

5.1 Ambient Conditions

Unless otherwise specified herein, all tests were performed at ambient conditions existing at Test Bed #2 of the MSFC Solar Test Facility 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. Instrumentation locations on the test loop and the concentrating collector are depicted in Figure 1. A listing of the equipment used in the test follows:

<u>Apparatus</u>	<u>Manufacturer/Model</u>	<u>Range/Accuracy</u>
Platinum Resistance Thermometer	Supplied by Collector Manufacturer	N/A
Pyranometer	Eppley - PSP	0-800 BTU/Ft ² .Hr $\pm$ 3%
Pyroheliometer	Eppley	0-800 BTU/Ft ² .Hr (Class 1)
Liquid Loop	MSFC Supplied	.1 - 1.2 GPM
Flowmeter	Foxboro/1/202 81T3C1	.1 - .91 $\pm$ 1% GPM
Strip Chart Recorder	Mosley 680	5-500mv $\pm$ 2%
Differential Pressure Sensor	Statham	0-10 PSID $\pm$ 1%
Platinum Resistance Thermometer	Hy-Cal	-50 - 500°F $\pm$ 1°F
Wind Direction Sensor	Teledyne Geotech/M1567	0 - 360 $\pm$ 1%
Wind Velocity Sensor	Teledyne Geotech/M1567	0.75 - 60 mph $\pm$ 1/2%

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 and the pyroheliometer were calibrated by the manufacturer. The stated accuracy is through the data acquisition system.

5.3

Data Acquisition Systems

Test data obtained during performance tests was transmitted from the test site through the primary data acquisition system #1 to the real time data link and the DDP-224 computer located in MSFC Building 4646. A separate data link from Building 4646 provided for printout of real time data at the test site.

The end-to-end accuracy of data derived from performance testing was 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 was not done, confidence in printout accuracy was 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 indicated that the data presented is suitable for the purpose intended.

6.0 TEST REQUIREMENTS AND PROCEDURES

6.1 Collector Time Constant Test

Tested By B. Henderson

Started 5/26/78

Completed 5/26/78

6.1.1 Requirements

The collector shall be mounted and insulated in a manner consistent with the manufacturer's recommended installation methods. The collector sun-tracking mechanism shall be operational during this test. The proposed mounting is shown in Figure 2. The total solar flux shall be established to be continuously greater than 250 BTU/Ft²·Hr and data taken only during a "quasi-steady state" condition. The collector time constant shall be determined by abruptly reducing the solar flux to zero through shading. This will be done with the inlet temperature adjusted to within 2°F of ambient while the liquid is circulating at 200 lbm/hr. The differential temperature across the collector shall be monitored to determine the time (t) required to reach the condition of

$$\frac{\Delta T(t)}{\Delta T_0} \leq 0.30$$

where $\Delta T(t)$ is the fluid differential temperature across the collector as a function of time after shading and ΔT_0 is the differential temperature existing at initiation of shading.

The following data will be recorded for the test:

- Solar flux.
- Ambient temperature.
- Inlet liquid temperature.
- Collector differential temperature.
- Collector flowrate.

6.1.2 Test Procedure

1. Mount the concentrating collector and its associated equipment on Test Bed #2. The sun-tracking mechanism shall be operational during this test.
2. Assure the data acquisition system is operational.
3. Adjust the liquid flow rate to 200 lbm/hr.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1 Collector Time Constant Test (Continued)

6.1.2 Test Procedure (Continued)

4. Adjust the liquid inlet temperature to within $\pm 2^\circ\text{F}$ of ambient.
5. Assure the solar flux level is at least $250 \text{ BTU/Ft}^2\cdot\text{Hr}$ and is not fluctuating.
6. Monitor the differential temperature across the collector.
7. Allow the system to stabilize at above conditions for at least 5 minutes.
8. Reduce the solar flux to zero by abruptly shading the collector from the sun. If care is taken to avoid shading the sun-tracking control unit, the collector will remain in proper alignment with the sun. Mark on strip chart the moment when the collector is shaded.
9. Monitor and record the differential temperature across the collector until the ratio of $\frac{T_e - T_i}{T_{e,ini} - T_i}$ is less than 0.30.
10. Inform the data control group that the testing has been terminated.

6.1.3 Test Results

The differential temperature across the collector was recorded on a strip chart. The chart speed on the recorder was adjusted such that the time-scale was approximately 10 inches in length. The inlet and outlet fluid temperatures, flowrates, and solar insolation rates were recorded at one-minute intervals through the test. Results of the test are shown in Figure 3. The standard ASHRAE formula of $\frac{T_{e,\tau} - T_i}{T_{e,ini} - T_i} = 0.368$ yields a time constant of two minutes and three seconds. Data analysis methods are presented in Section 7.1.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Collector Thermal Efficiency Test

Tested by B. Henderson
Started 3/22/78
Completed 4/28/78

6.2.1 Performance Criteria Requirements

The collector to be tested shall be pre-conditioned prior to initiation of the test. Pre-conditioning shall consist of stagnation heat in a non-operational mode for three cumulative days in which the incident solar radiation measured in the plane of the collector shall be a mean of 1500 BTU/Ft²/day (406 Langleys). 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 stand for the duration of the test. In addition, the test stand shall be located so that no shadow will be cast onto the collector by any obstruction at any time during the test period. The test shall be conducted at times having weather conditions such that the integrated average insolation measured in the plane of the collector used for the computation of instantaneous efficiency values shall not be less than 200 BTU/Ft²·Hr. The concentrating collector assembly sun-tracking mechanism shall be activated to insure that the incident angle remains consistent throughout the course of the test. The air velocity across the collector surface shall be measured and recorded as part of the test data.

Thermal performance evaluation data shall be obtained at inlet temperatures of 0, 25, 50, and 100°F above the ambient temperature at the liquid flow rate of 200 lbm/hr.

At least four "data points" shall be taken for each value of inlet temperature at the specified flowrate. The efficiency curve shall be established by "data points" that represent efficiency values determined by integrating the data over a time period equal to the time constant or 5 minutes, whichever is larger. The integrated value of incident solar energy will be divided into the integrated value of energy obtained from the collector to obtain the instantaneous efficiency.

The following data shall be recorded during the test at each operational condition.

1. Ambient temperature.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Collector Thermal Efficiency Test (Continued)

6.2.1 Performance Criteria Requirements (Continued)

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

6.2.2 Test Procedure

1. Mount the concentrating collector and its associated equipment on Test Bed #2. The sun-tracking mechanism shall be operational during this test. The tilt angle shall be adjusted such that the solar incident angle is 0 degrees in the north-south plane at solar noon.
2. Assure that the data acquisition system is operational.
3. Establish the proper flowrate and inlet temperature for each test designation 1 through 4 specified below.

<u>Test No.</u>	<u>Inlet Liquid Temperature Differential above Exist- ing Ambient Temp. °F</u>	<u>Liquid Flowrate lbm/hr</u>
1	0	200
2	25	200
3	50	200
4	100	200

4. Continuously adjust the inlet temperature and flow rate to maintain the desired "data point" characteristics. Monitor the test parameters by using the teletype at the test site.
5. The sun-tracking mechanism shall allow testing at any time throughout the day when the insolation level is steady and at least 200 BTU/Ft²·Hr.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Collector Thermal Efficiency Test (Continued)

6.2.2 Test Procedure (Continued)

6. Inform the data control group that the testing has been terminated. Label and save the printout from teletype as a record.

6.2.3 Test Results

The results of the thermal efficiency tests are presented in Figure 4. Table I contains the supporting data obtained during the tests. Data analysis methods are presented in Section 7.2.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)6.3 Collector Elevation Angle Modifier Test

Tested By	<u>B. Henderson</u>
Started	<u>5/19/78</u>
Completed	<u>5/19/78</u>

6.3.1 Test Requirement

The incidence angle modifier test specified by ASHRAE standards is not applicable to tracking collectors. (A)
 The modifier for non-perpendicular elevation angles, however, is significant for this type of collector. The collector elevation angle modifier test shall be conducted at north-south solar incident angles of 0, 20, 30 and 40 degrees. The liquid flow rate shall be 200 lb/hr with the inlet temperature controlled to approach the ambient air temperature. Since these tests are being performed at outdoor conditions, the inlet liquid temperature should be maintained as close as practical to ambient. The tests shall be conducted with a continuous direct solar flux rate greater than 240 BTU/Hr·Ft², when the wind speed is less than approximately 2 mph. The following data shall be recorded during the test.

1. Solar insolation angle along north-south axis of collector.
2. Ambient air temperature.
3. Collector inlet temperature.
4. Collector outlet temperature.
5. Collector differential temperature.
6. Liquid flow rate.
7. Direct and diffuse solar flux.
8. Tilt angle relative to solar vector.
9. Wind speed.

6.3.2 Test Procedure

1. Adjust the collector elevation angle such that the incident solar angle on the collector north-south axis is 0°. (A)
 This procedure is applicable for testing at solar noon ± 1 hour. (See Figure 2.)
2. Adjust the flowrate to 0.4 gpm.
3. Adjust the inlet temperature to equal the ambient air temperature as closely as possible.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)6.3 Collector Elevation Angle Modifier Test (Continued)6.3.2 Test Procedure (Continued)

4. Measure and record the direct and diffuse solar insolation.
5. Measure and record the angle between the collector normal and the solar vector (elevation angle). (A)
6. Record data at one-minute intervals for five minutes after steady conditions are established.
7. Repeat the above steps for elevation angles in the north-south axis of 20, 30, and 40 degrees. (A)
8. Upon completion, power down liquid loop and inform data control group that the tests have been completed.

6.3.3 Test Results

The following data was recorded during the elevation angle modifier test. Graphical results are shown in Figure 5.

Collector Tilt Angle, Degrees	0	20	30	38	46
Average Direct Solar Insolation Rate, BTU/Hr·Ft ²	295.0	269.0	237.0	242.0	212.0
Ambient Air Temperature, °F	78.6	79.5	72.6	76.1	69.5
Collector Inlet Temperature, °F	80.1	81.8	73.0	80.2	72.4
Collector Outlet Temperature, °F	89.5	89.9	79.9	83.5	74.4
Collector Differential Temp., °F	9.4	8.1	6.9	3.3	2.0
Flow Rate Through Collector lbm/hr	200.0	200.0	200.0	200.0	200.0
Incident Angle Modifier, $K_{\alpha\tau}$	1.0	1.0	1.0	.54	.43

7.0

ANALYSIS

7.1

Time Constant Test

The time constant test was performed according to ASHRAE 93-77 by shading the collector. According to the definition of time constant given in ASHRAE 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:

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

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

where:

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

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

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

From Figure 3 the time constant was determined to be 2 minutes and 3 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:

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

where:

q_u = Rate of useful energy extracted from the solar collector (BTU/Hr)

A = Gross collector area (Ft²)

I = Total solar energy incident upon the plane of the solar collector per unit time per unit area (BTU/Hr·Ft²)

$\dot{m}$ = Mass flow rate of the transfer liquid through the collector per unit area of the collector (Lbm/Ft²·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.

For concentrating collectors, only the direct flux is used for efficiency calculations.

7.0 ANALYSIS (Continued)

7.2 Thermal Performance Test (Continued)

Substitution in Equation (2) results in:

$$\eta = \frac{P_{abs}}{P_{inc}} \quad (3)$$

where:

P_{abs} = Total collected power

P_{inc} = Total incident power

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

$$\text{Collector Efficiency} = \frac{P_{abs}}{P_{inc}} \times 100 \quad (4)$$

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

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

Each term in Equation (5) was measured and recorded independently during the test. 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

$$((t_i - t_a)/I)$$

where:

t_i = Liquid inlet temperature ($^{\circ}\text{F}$)

t_a = Ambient temperature ($^{\circ}\text{F}$)

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

The abscissa term $((t_i - t_a)/I)$ 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, as well as calculated efficiency data, is shown in Figure 4. The second order polynomial to best describe the test results is:

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

7.0 ANALYSIS (Continued)

7.2 Thermal Performance Test (Continued)

where:

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

Due to the unusually large difference in gross collector area and aperture area for the concentrating collector, efficiency values were determined for both areas. The curve fit coefficients for the gross area and aperture area, respectively, are:

$$a_0 = 0.18; a_1 = -0.1547; \text{ and } a_2 = -0.0126$$

$$a_0 = 0.5524; a_1 = -0.4674; \text{ and } a_2 = -0.0380.$$

7.0 ANALYSIS (Continued)7.3 Elevation Angle Modifier Test

Two methods are proposed by ASHRAE 93-77 for incident angle modifier tests. The outdoor procedure using a movable test rack was used for this test. The collector was adjusted so that the incident radiation angles were 0°, 20°, 30°, 38°, and 46° to the normal of the collector surface in the north-south direction (See Figure 2). (A)

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

$$K_{d\tau} = \frac{\eta}{F_R (\tau_a) n} \quad (1)$$

where η = efficiency at tilted angle

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

For equation (1) to be applicable, the inlet liquid temperature must be controlled to within $\pm 2^\circ\text{F}$ of the ambient air temperature. This same procedure was applied to the elevation angle modifier test. (A)

The results of this computation are shown in Section 6.4.3 and are plotted against elevation angle of incidence in Figure 5.

TABLE I
NORTHROP CONCENTRATING COLLECTOR THERMAL PERFORMANCE TEST DATA

																(A)
Ambient Air Temperature (T_a), °F	64.7	65.2	66.9	68.1	71.1	72.4	74.7	75.2	77.3	75.9	67.0	69.4	67.6	69.0	86.9	79.8
Fluid Inlet Temperature (T_i), °F	65.7	85.2	116.0	149.0	180.1	71.1	100.2	127.8	153.0	182.3	67.3	97.0	126.4	147.5	186.0	82.3
Fluid Outlet Temperature (T_e), °F	75.0	94.2	124.4	156.0	185.3	80.5	109.0	135.7	159.7	185.7	75.6	104.8	133.0	154.1	190.5	91.2
Differential Fluid Temperature (ΔT), °F	9.3	9.0	8.4	7.0	5.2	9.4	8.8	7.9	6.7	3.4	8.3	7.8	6.6	6.6	4.5	8.9
Direct Solar Flux (I_D), BTU/Hr·Ft ²	315	312	313	310	276	302	302	295	291	201	280	294	278	280	243	290.2
Flow Rate, Lb/Hr	205	205	205	205	205	205	205	205	205	205	205	205	205	205	205	205
Efficiency (η), %	17.4	17.3	16.1	13.7	11.5	18.4	17.5	16.1	14.0	10.3	17.8	15.9	14.3	14.3	11.3	18.4
$(T_i - T_a)/I_D$ °F·Hr·Ft ² /BTU	.003	.064	.157	.250	.394	.016	.084	.178	.260	.529	.000	.093	.211	.280	.407	.005
Total Solar Flux (I_T), BTU/Hr·Ft ²	344	343	341	339	312	337	341	337	339	278	316	335	336	332	293	329.5

- — Platinum Resistance Thermometer (PRT)
- — Thermocouple
- — Flow Meter
- ⊗ — Solar Flux, Total
- △ — Differential Pressure
- ⊠ — Differential PRT
- ✕ — Wind Velocity
- ⊕ — Pyranometer, Direct

Figure 1. Instrumentation Locations for Northrup (Liquid) Collector Test

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Figure 3. Time Constant Test of the Northrup Concentrating Solar Collector

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η - Collector Efficiency in Percent

Figure 4. Northrup Concentrating Collector Performance for Outdoor Test at 0.41 GPM

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Figure 5. Northrup Concentrating Solar Collector Performance for Elevation Angle Modification

Photograph 1. Northrup Concentrating
Solar Collector

Photograph 2. Effects of Weathering
on Northrup Concentrating Solar Collector