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Test Bed Concentrator #1 Calorimetry Results

K. Scott Rawlinson, Vern E. Dudley

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Sandia National Laboratories
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TEST BED CONCENTRATOR #1

CALORIMETRY RESULTS

K. Scott Rawlinson and Vern E. Dudley
Solar Thermal Test Facility Division
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

Calorimetry was performed on Sandia National Laboratories' Test Bed Concentrator #1 (TBC-1) during late July and early August 1989. The purpose of the tests was to determine the total power available from the concentrator and the amount of the total power that can be focused through a 22-cm aperture plate located at the nominal focal point of the dish. The 22-cm aperture corresponds to the diameter of several reflux receivers that are currently under development, fabrication and testing at Sandia. The calorimeter tests will allow the efficiency of the sodium reflux receivers to be calculated. The total power (normalized to 1000 W/m^2) available from TBC-1 is 66.4 kW into the 22-cm aperture plate. Within error limits, this power level is the same with or without the aperture plate. The power levels stated are for this time (July 1989) and will probably change as the mirrors further degrade. Since the last calorimetry tests were performed, the mirror facets have degraded significantly, and the results presented here support this effect. Finally, three of the 220 facets were missing.

Foreword: Solar Thermal Technology

The research and development described in this document were conducted within the U.S. Department of Energy's Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar radiation by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 meters in diameter track the sun in two axes and use mirrors to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100°C in low-temperature troughs to over 1500°C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of the Department of Energy and its network of national laboratories, who work with private industry. Together they have established a comprehensive, goal-directed program to improve performance and provide technically proven options for eventual incorporation into the nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to ensure a successful program.

Introduction

The Test Bed Concentrators (TBCs) were transferred from the Jet Propulsion Laboratory (JPL) to Sandia National Laboratories (SNL) in Albuquerque, New Mexico in 1983. The TBCs are rigid structures that track the sun in azimuth and elevation. Each TBC has 220 mirror facets mounted on a parabolic structure. The facets are made from foam glass with a spherical silvered glass surface. The nominal radius of curvature of the facets varies slightly. The "A" mirrors, which comprise the inner 64 facets, have a nominal radius of curvature of 13.21 m. The "B" and "C" mirrors have nominal radii of curvature of 15.80 m and 16.13 m, respectively. The average slope error of the mirrors (a measure of the actual surface contour to a perfect spherical contour) is 1.2 mrad. Each facet can be individually aimed. With all of the facets aimed at the nominal focal point, the peak flux is over 14,000 suns contained in a 15-cm diameter flux distribution.

Calorimetry tests on Test Bed Concentrator #1 (TBC-1) were last performed in August of 1985. Since that time, many of the mirror facets have degraded. In addition to the normal decrease in reflectivity, many of the mirror facets are "speckled"--most likely due to outgassing from the foam glass diffusing through the copper substrate and corroding the silver.

Figure 1 is a photo of the cold-water cavity calorimeter that was used to absorb and measure the incident power. The photo in Figure 2 shows the TBC during a full-power calorimetry test. For partial-power tests, some of the incident power is eliminated by placing mirror covers over individual facets. Figure 3 is a close-up of calorimeter aperture while on-sun.

Test Preparation

TBC-1 was last aligned in October 1987. Extreme care was taken in this alignment. The bipods, which support the receiver ring, were aligned relative to the parabolic structure so that the center of the receiver ring was on an axis perpendicular to the elevation axis. This procedure defined the correct optical axis of the dish. Also, the distance from the vertex of the dish to the mounting plane was accurately measured using a theodolite. A target, consisting of 220 return images corresponding to each facet, was mounted 61.7 cm (24.3 in) behind the "B" and "C" aim point. The target was constructed so that the "A" mirrors were aimed along the optical axis 641.7 cm (252.625 in) from the vertex, while the "B" and "C" mirrors (the remaining outer facets) were aimed at a distance of 638.5 cm (251.75 in) from the dish vertex. The alignment was performed in the following manner--a laser was mounted on the optical axis of the concentrator, defined by placing the laser in-line with two sets of crosshairs--one set located at the vertex of the dish and another set located inside the receiver ring. The laser beam was aimed at a distant light source located in the mesa north of the TBC. Then the facets were aligned by adjusting the return images of the illuminated mirrors to match the images plotted on the target board. Figure 4 is a photo of the target board following the alignment procedure.

The alignment was checked using the same equipment as described above just before the calorimetry tests. Only six facets needed minor adjustments.

A 22-cm aperture plate, machined from Fiberfrax 3000 insulating board, was mounted to the front surface of the calorimeter. The aperture plate was used to determine the amount of power that could be delivered through a 22-cm diameter aperture, the aperture size established for reflux receivers that will be tested on the TBCs, under identical conditions. Based on the calorimeter measurements, the power available to a receiver, and therefore the receiver efficiency, can be determined.

After the calorimeter was mounted, plumbed, and instrumented, three mirror facets were destroyed during a wind storm with gusts up to 82 mph. Replacing the mirrors would have required personnel to tear down the calorimeter, mount the new mirrors and target board, and align the mirrors at night with a distant light source. Due to manpower and time constraints, the three facets were not replaced. The important aspect of the test was to maintain consistency between the calorimeter tests and the receiver tests.

The aperture plate on the calorimeter was mounted 638.5 cm from the dish vertex (69.7 cm from the receiver ring mounting plane). This location corresponds to the aim point for the "B" and "C" mirrors, the nominal focal point.

Other equipment used in the test includes the water-cooled aperture plate and shutter plate, along with back-up systems for cooling and driving the dish off-sun during an emergency. This equipment is discussed below.

The water-cooled aperture plate and shutter plate are used to protect the equipment mounted on the receiver ring when coming on-sun and going off-sun (see Figure 3). The cooling plates are made from aluminum plates with 1/2-in water jackets between the plates. Water at 57 l/min (15 gpm) is pumped through the system with a portable pump and radiator system. The position of the shutter is controlled from a panel in the control room and is driven with compressed air.

Water for the calorimeter is provided by a hose bib located near the base of the TBC. An automatic flow controller maintains a steady flowrate of 76 l/min (20 gpm) regardless of supply pressure fluctuations.

In the event of a power failure, there are several back-up systems to allow the TBC to be brought off-sun without damage to the equipment. When the power is interrupted, an emergency generator is automatically started. This generator provides power to dc power supplies that are paralleled to the motor control unit for the azimuth and elevation drive motors. The TBCs can then be controlled from a panel in the control room. The panel is powered by an uninterruptable power supply (UPS) system. In addition, an air drive motor on the azimuth drive can be driven with compressed air that is contained in the air compressor tank. If the compressed air is exhausted, a bank of nitrogen bottles is automatically valved into the system, allowing the azimuth rotation to continue.

Instrumentation and Calibration

The important parameters that were needed to calculate the input power accurately were the solar energy input, the calorimeter water flowrate, the inlet temperature, and the delta-temperature through the calorimeter. The inlet and outlet pressures were also measured. Each of the transducers used to make these measurements are discussed below.

Weather Data

Solar energy input to the TBC dish collector was measured with an Eppley normal incidence pyrheliometer. The pyrheliometer was calibrated against a Kendall radiometer at the Sandia Flux Gage Calibration Station; accuracy of the instrument is +/- 0.7%, including uncorrected temperature effects. Wind speed, wind direction, and ambient air temperature were measured by Weathermeasure instruments, located 10 meters above the surface, just north of the TBC dish site.

Fluid Flow

Cold water through the calorimeter was provided from the site's domestic water supply, which maintains a nearly constant water temperature of about 25°C. Water flowrate was controlled by a Griswold automatic flow controller, which minimized any flow fluctuations due to changes in local water pressure. Volumetric flowrate of the water was measured with a Flow Technology turbine flowmeter and associated pulse rate converter. The flowmeter and pulse rate converter were calibrated immediately before the test to an accuracy of better than 1%. During the tests, the mass flowrate of water through the system was periodically checked by dumping the output water into a 55-gallon drum for a closely timed interval, while noting the weight change of the water drum on a balance scale. In all cases, the measured mass flowrate was consistent with that calculated using the turbine flowmeter measurement.

Temperature

Since an accurate measurement of the temperature rise across the calorimeter is critical to the success of the experiment, a differential temperature transducer manufactured by the Delta-T Co. was installed in the calorimeter water flow. This transducer contains a 20-junction thermopile constructed from identical type-T thermocouples (TCs), and provides an output signal of about 0.401 millivolts per degree C temperature differential, with a stated accuracy of 0.04°C. This accuracy was verified by the SNL Standards Lab.

Calculation of differential temperature from the voltage output signal of the Delta-T device requires that the input temperature be known. Input water temperatures were measured with a type-T reference thermocouple internal to the Delta-T transducer. Input and output temperatures were also measured with a separately installed pair of type-T thermocouples, so that an independent calculation of temperature rise (of lower accuracy) could be made to detect any gross failure of the differential temperature device.

The input temperature measurement did not have to be highly accurate, since the iterative calculation of temperature differential from the transducer voltage output was not very sensitive to input temperature. A 5-degree error in input temperature would result in a temperature differential error of only 0.1°C. [See Wald (1), available from the Delta-T Company].

Other thermocouples include water-cooled aperture plate and shutter plate temperatures and the TC isothermal plane reference temperatures. The water-cooled aperture and shutter plate signals are taken for safety shutdown considerations. Finally, all isothermal plane reference junction temperatures are needed to calculate the actual temperature at the TC measuring point. All of these temperatures are recorded with the calorimeter data.

Fluid Pressure

Input water pressure and pressure drop across the calorimeter were measured with Rosemount pressure transducers. These transducers have a stated accuracy of 0.25% of calibrated span. Stability is 0.25% of upper range limit for six months, and the temperature effect is 0.2% of range plus 0.2% of span per 20°C. The transducers were calibrated immediately before the test to an accuracy of 1%.

Data Acquisition System

The data acquisition system was controlled by a Hewlett Packard (HP) 9845B desktop computer. Data channels were sequentially scanned with an HP3497A data acquisition unit, and the resulting analog signals were then measured with an HP3456A digital voltmeter. The voltmeter was calibrated by the SNL Measurement Standards Lab to a stated accuracy better than 0.01%. Data were recorded on the computer's hard disk, and later transferred to floppy disk for archival storage. Data were normally recorded at 10-second intervals during active testing; slower data rates were sometimes used while waiting for weather improvements.

Software Calculations

The absorbed power was calculated by multiplying the mass flowrate by the change in enthalpy of the water as it flowed through the calorimeter. The calculation is valid if the following assumptions are made when performing an energy balance:

(1) Measurement is made at steady state.
(2) No heat loss from the calorimeter occurs.
(3) Changes in potential and kinetic energy are negligible.

The published numbers were taken at steady-state conditions. Heat losses are negligible since the device is a "cold-water" calorimeter, i.e., the convective and radiation losses from the surfaces are small. Assumption #3 is absolutely true for the construction of this particular calorimeter.

The mass flowrate of water was calculated in software by multiplying the volumetric flowrate by the density (based on temperature). The inlet and outlet enthalpies were also calculated in software as a function of temperature and pressure. The polynomials used to calculate these properties produce results that agree within 0.2% of the steam tables found in Keenan and Keyes (2).

Test Procedure

After the water flows were established and the emergency systems were checked, the TBC was brought on-sun with the shutter closed. The shutter was then opened. The calorimeter was allowed to reach steady state, which takes about 15 minutes. The power levels presented later are given for a period of time after steady state has been reached and the isolation level is constant. During the test, test personnel verified that all the temperatures were stable and reasonable. Also, since the flowrate is critical to the power measurement, the mass flowrate is measured by dumping the water into a 55-gallon drum for 1 minute, and weighing the drum with a balance scale. The "bucket and scale" mass flowrate was consistent with the turbine flowmeter measurement. After a satisfactory data point was obtained, the TBC was driven off-sun so that the next test condition could be set.

Observations During Testing

The calorimeter testing was completed without any major problems. However, there were several items worth noting. First, with the 22-cm aperture plate mounted on the calorimeter, there was some amount of spill of solar flux to the left of the aperture. That spot was probably an "A" mirror near the video camera that was knocked loose during another wind gust. Also, when the dish was tracked using "suntrack," the feedback loop using the sun sensors, the TBC oscillated enough to move the beam up and down about 5-cm (2 inches). The gains for the feedback system were adjusted with minor success. These tuning parameters will be fine tuned in the near future. Finally, the offsets for "memtrack," in which the controller sends the TBC to a point based on the solar time and the day of the year, had be modified slightly from day to day. The adjustments were small (about 0.1-0.2 degrees), but noticeable. At this point, it is not known whether the encoder wheel slipped slightly or not. The TBC itself is quite rigid. No changes in power measurements were noted during these adjustments.

Test Results

The test results are summarized in Table I. Multiple data points exist for some of the mirror patterns and mirror cleanliness. These data points represent different segments (approximately 5 minutes containing 30 data scans) during the test when conditions were stable. A sample of the data plots and the data summaries can be found in Appendix I.

Table I

Test Results

Date	Mirrors	Note	Inlet Temp C	Delta-T Temp C	Flow Rate L/min	Solar Flux W/m^2	Meas. Power kW	Norm Power kW	Est Err kW
07/13/89	100%	1	26.5	11.3	75.7	923.4	59.2	64.1	.82
07/13/89	100%	1	26.9	16.8	51.0	929.9	59.6	64.2	.80
07/14/89	100%	2	25.5	11.4	76.2	911.3	60.5	66.4	.84
07/14/89	100%	2	25.6	11.4	76.2	911.2	60.4	66.3	.84
07/14/89	100%	2	25.8	11.4	76.4	909.6	60.6	66.6	.85
07/17/89	75%	3	26.3	8.8	76.3	962.8	46.6	48.4	.63
07/18/89	50%	4	25.7	5.9	76.2	951.9	31.3	32.9	.46
07/20/89	100%	4	25.7	11.5	76.3	941.0	60.8	64.6	.82
07/27/89	100%	5	24.2	10.8	76.3	879.8	57.5	65.3	.83
08/03/89	100%	6	24.2	11.9	74.1	940.0	61.2	65.1	.83
08/03/89	100%	7	24.6	12.4	73.0	963.3	63.0	65.4	.83
Typical Sigma:			0.2	0.05	0.2	5.0	0.3	0.4	

Notes:

1) Mirrors dirty, uncleaned for several months.
2) Mirrors freshly washed with de-ionized water.
3) Mirrors not cleaned for several days, some light dust.
4) Light rain caused mirrors to appear fairly dirty.
5) Mirrors rain-washed (heavy rain).
6) Mirrors washed with de-ionized water previous day, some light dust.
7) Aperture removed from calorimeter.

Prior to cleaning the mirrors, one test was performed with dirty mirrors to obtain the lower power limit that could be expected from the TBC. The mirrors had not been cleaned for several months and appeared very dirty visually. However, the difference between extremely dirty mirrors and freshly washed mirrors was only 2.5 kW maximum. Also, as indicated by the power levels with and without the 22-cm aperture, nearly all the power is contained in a 22-cm beam. Note that the power level for the full power test after the first cleaning (7/14/89) is slightly higher than the power level after the next cleaning (8/03/89). This may be explained by the fact that the first test was performed immediately following the cleaning, while the later test (8/03/89) was performed one day following the washing, allowing dust to settle for a few hours. Another possibility for the discrepancy is that the mirrors may have been initially scrubbed more vigorously initially to remove the heavy residue than the mirrors on the next washing. Also note that a rain-wash cleans the mirrors about as well as spraying the facets with de-ionized water.

The estimated error is based on the root-sum-square error analysis accounting for measurement errors and accuracy specifications with respect to the NIP reading, flowrate, reference temperature, and delta-temperature. The derivation of the equation used can be found in Appendix II.

Comparison With Past Tests

As indicated above, calorimetry had not been performed on TBC-1 since August 1985. At that time, the normalized power (without an aperture plate) was 78 kW. The temperature rise was recorded with RTDs, with thermocouples used as a check. The calibration accuracy of the instrumentation used during that experiment is not known. During the recent test, it was noted that the thermocouples indicated a temperature rise at least 1°C higher than the delta-T device, which would have resulted in an almost 10% increase in power. Also, the mirrors were much less corroded back in 1985. The 12-kW loss in power during the past four years is probably because of a combination of mirror degradation and measurement accuracy, but the breakdown of the difference is not known.

Conclusions

The calorimetry tests were performed with careful attention to calibrations and therefore accuracy. The accuracy of the power measurements is within 0.85 kW (1.3% at maximum power), based on the combination of all measurement errors and calibration accuracies.

The original advertised power of the TBCs was nearly 80 kW. TBC-1 will be used as a solar furnace in the near future. The losses from the attenuater shadowing (7.6%) and from the additional reflectance from the heliostat (10%) bring the full power level from 66 kW to 55 kW. Also, the Stirling Thermal Motors (STM) Stirling cycle engine (25 kW output) to be tested on one of the TBCs will require 69-kW input based on a 90% receiver efficiency and a 40% engine efficiency. Therefore, it is recommended that the mirror facets be replaced to maintain the effectiveness of these two concentrators. Without a doubt, the TBCs have easily been the most reliable, accurate, and rigid concentrators that have been tested at the Solar Thermal Test Facility to this date.

References

1. D. Wald, "Differential Temperature Transducer. An Iterative Method of Evaluating the Signal," Delta-T Company, Santa Clara, CA, n.d.

2. J.H. Keenan, F.G. Keyes, P.G. Hill, J.G. Moore, Steam Tables, Wiley-Interscience, New York, 1978.

3. E.O. Doebelin, Measurement Systems; Application and Design, McGraw-Hill, Inc., New York, 1983, pp. 58-67.

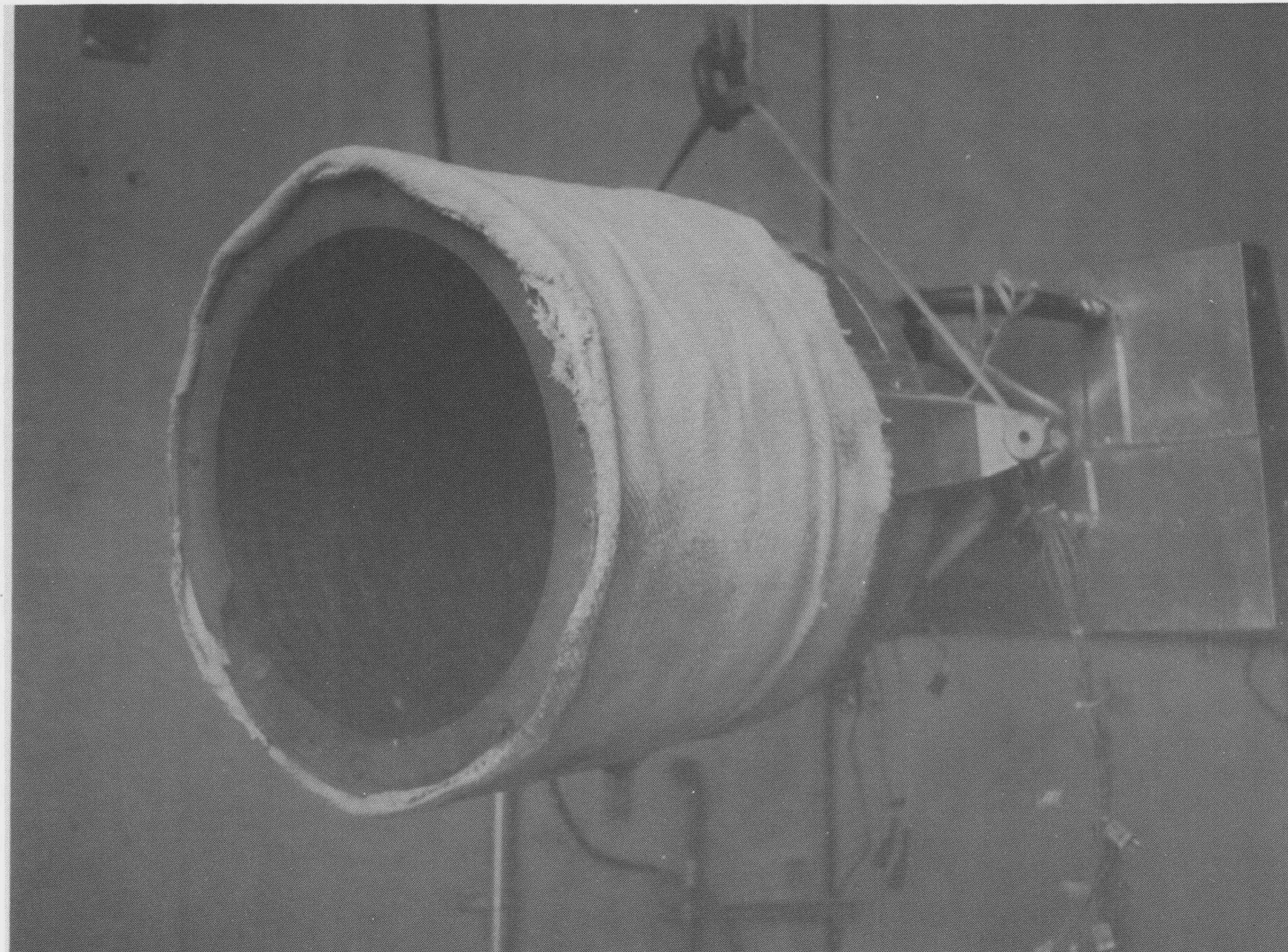


Figure 1. Cold-Water Cavity Calorimeter

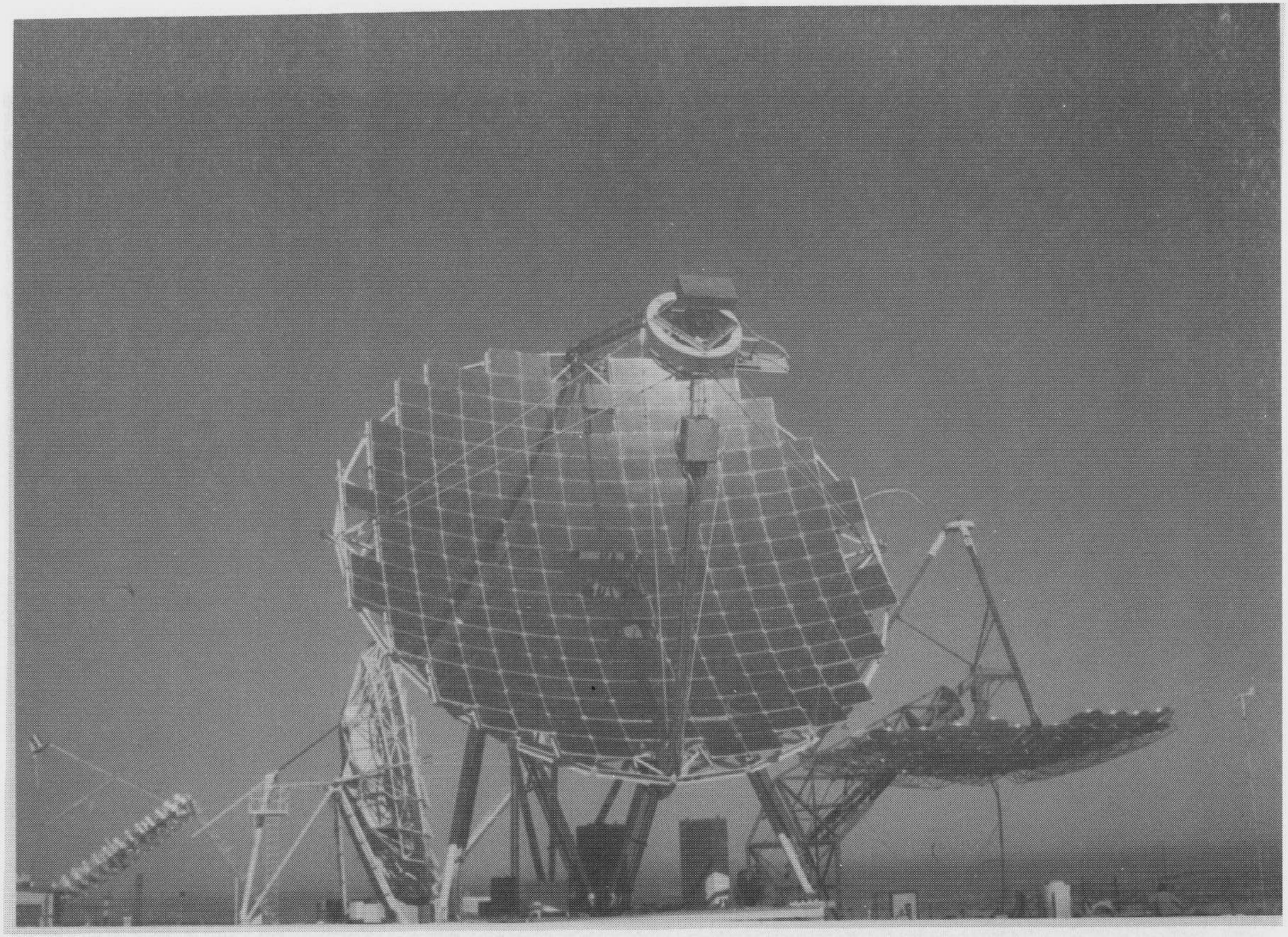


Figure 2. TBC-1 Full-Power Calorimeter Test

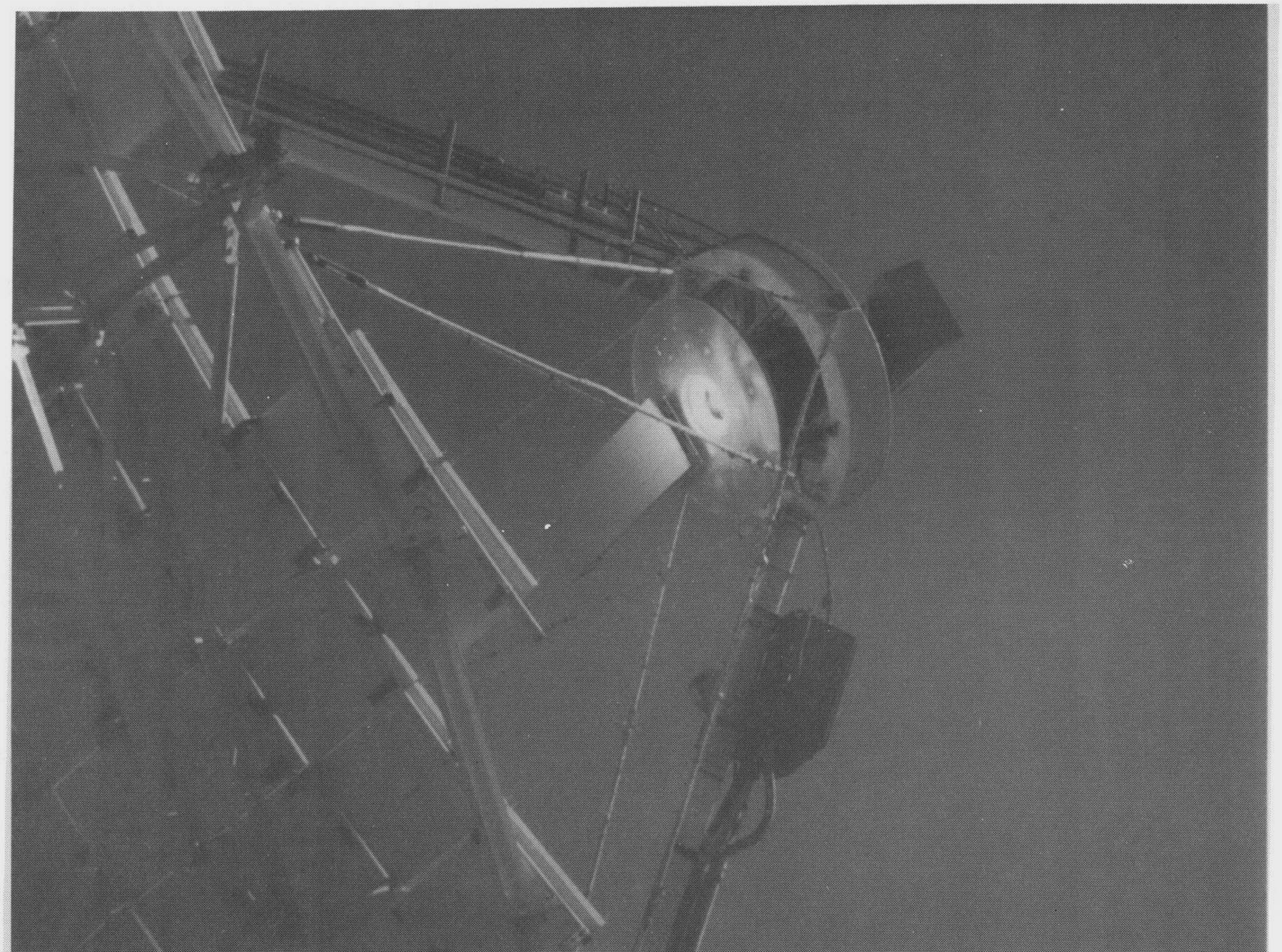


Figure 3. Close-Up of Focal Point Area While On Sun

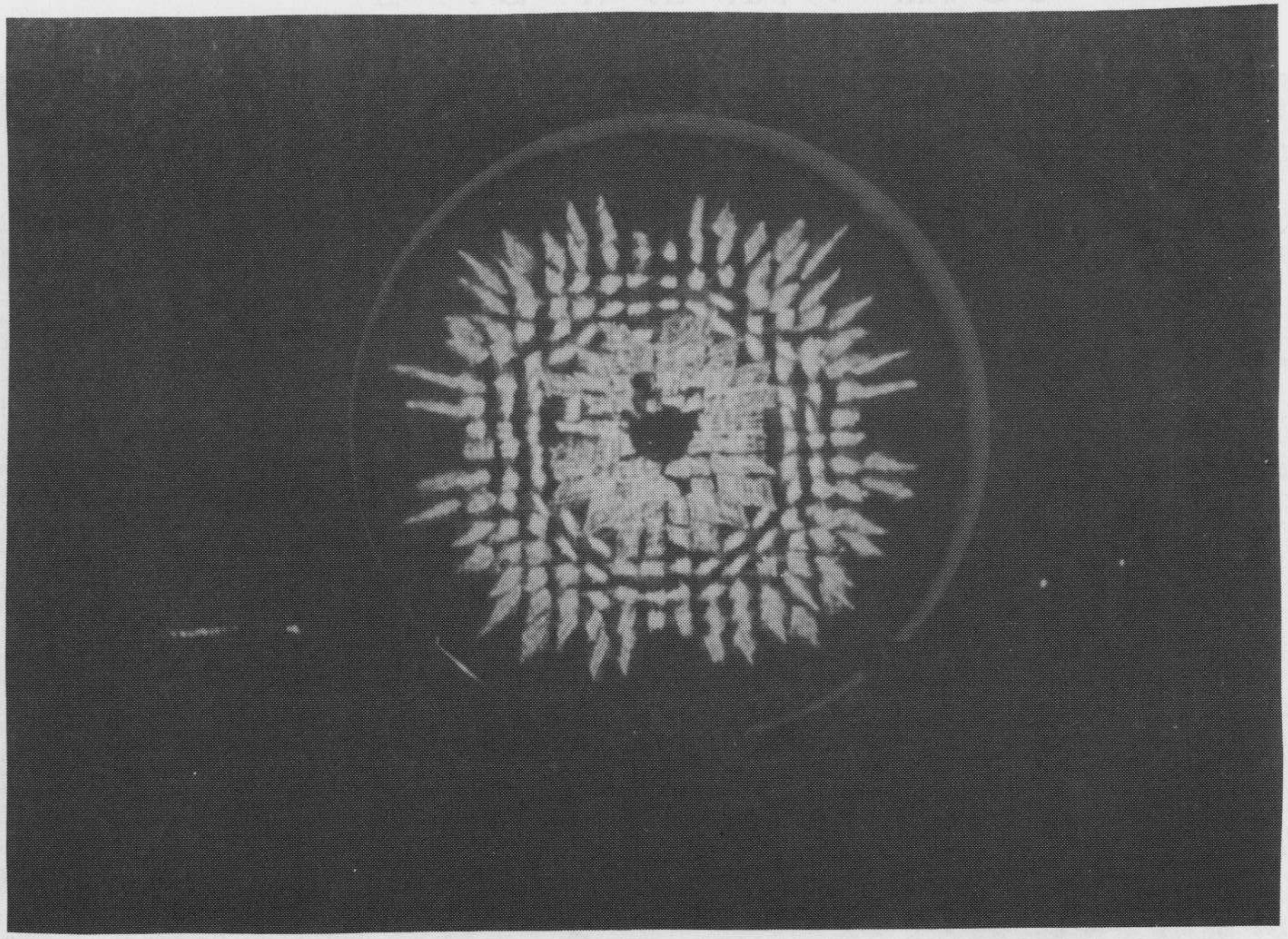


Figure 4. Target Board Following Mirror Facet Alignment Procedure

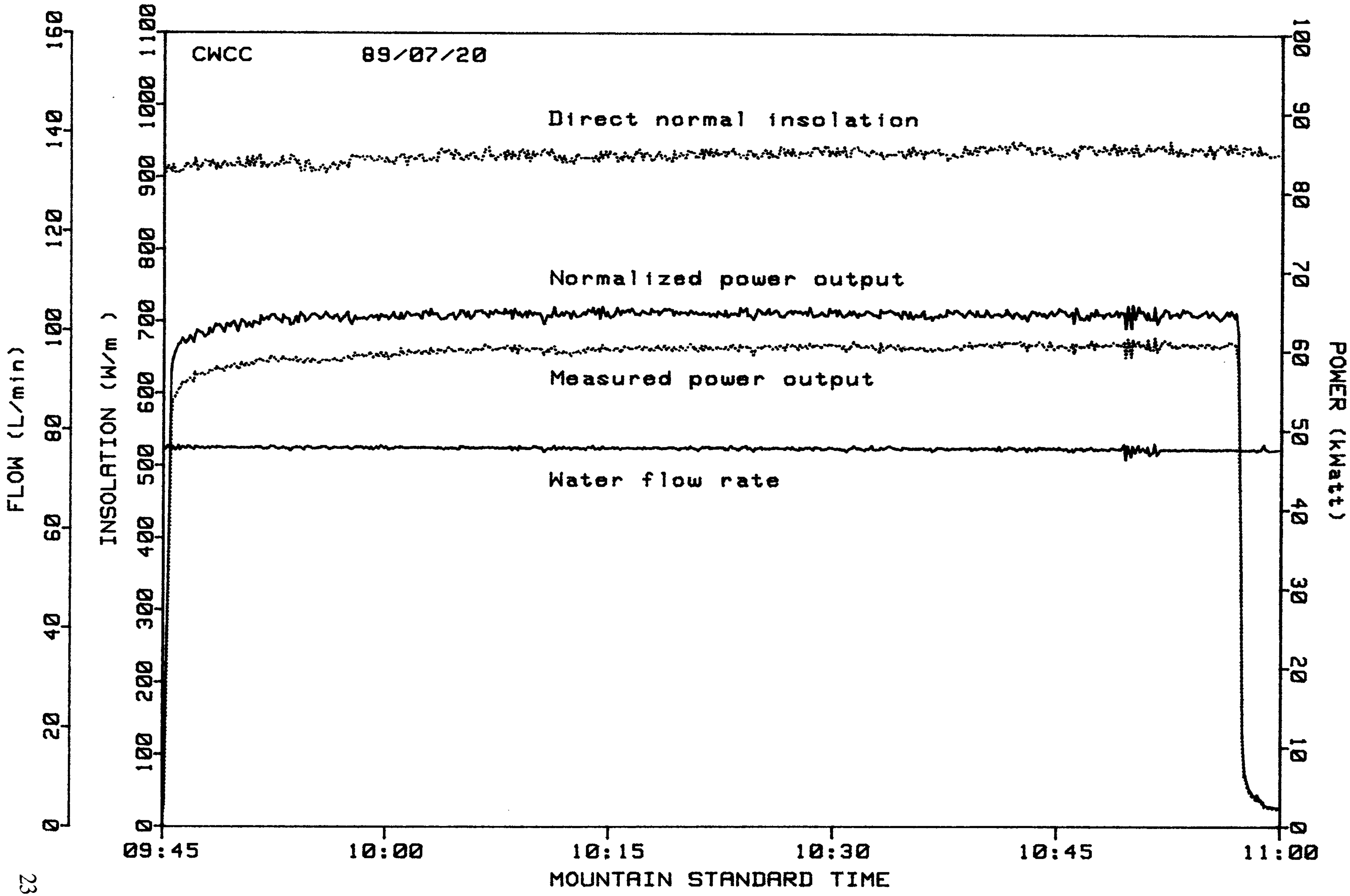
Appendix I - Sample Data Plot and Data Summary

CWCC 89/07/20 Increment of 1 records METRIC UNITS

#3 Mountain Standard Time HH:MM:SS	#10 NIP41 Solar Flux W/m^2	#23 FT738 CWCC Flow L/min	#18 TC021 CWCC in Temp Deg C	#22 DT100 CWCC Delta T Deg C	#38 CWCC Heat gain kW	#39 CWCC Norm Heat gain kW
10:40:00	944.24	76.37	25.57	11.47	60.83	64.42
10:40:06	942.77	76.20	25.54	11.48	60.71	64.40
10:40:16	935.43	76.47	25.50	11.48	60.94	65.14
10:40:31	942.77	76.17	25.60	11.48	60.68	64.36
10:40:37	939.84	76.22	25.52	11.43	60.47	64.35
10:40:46	941.30	76.32	25.55	11.48	60.82	64.61
10:40:59	939.84	75.97	25.58	11.52	60.77	64.66
10:41:06	945.71	76.70	25.53	11.48	61.11	64.62
10:41:16	941.30	75.87	25.55	11.50	60.58	64.36
10:41:29	944.24	76.30	25.58	11.52	61.04	64.64
10:41:36	935.43	76.25	25.57	11.53	61.01	65.22
10:41:46	944.24	76.61	25.56	11.48	61.04	64.65
10:42:00	950.12	76.38	25.63	11.50	60.97	64.17
10:42:06	942.77	76.37	25.54	11.50	60.97	64.68
10:42:15	941.30	75.97	25.51	11.57	61.03	64.84
10:42:29	950.12	76.36	25.58	11.55	61.21	64.42
10:42:35	947.18	76.23	25.54	11.48	60.73	64.12
10:42:45	945.71	76.58	25.56	11.48	61.01	64.51
10:42:58	941.30	75.76	25.55	11.43	60.10	63.84
10:43:05	942.77	76.51	25.58	11.45	60.83	64.52
10:43:15	933.96	76.05	25.54	11.50	60.72	65.02
10:43:30	935.43	76.34	25.59	11.45	60.69	64.88
10:43:35	942.77	76.01	25.49	11.53	60.82	64.51
10:43:44	942.77	76.61	25.50	11.50	61.17	64.89
10:43:58	944.24	76.27	25.60	11.50	60.89	64.49
10:44:04	935.43	76.51	25.54	11.41	60.58	64.76
10:44:14	936.90	76.22	25.51	11.38	60.23	64.28
10:44:27	942.77	76.43	25.55	11.52	61.14	64.85
10:44:34	932.49	76.29	25.52	11.45	60.66	65.05
10:44:44	933.96	76.42	25.52	11.36	60.26	64.52
10:44:59	932.49	76.15	25.60	11.45	60.54	64.92

Statistics for 31 data values.

Largest data value	950.115	76.696	25.634	11.573	61.207	65.218
Smallest data value	932.493	75.758	25.492	11.358	60.097	63.844
Range of data	17.622	.939	.142	.215	1.110	1.373
Arithmetic mean	941.020	76.287	25.552	11.479	60.792	64.603
Population Standard Deviation (Sigma)	4.832	.224	.035	.046	.278	.310
3-Sigma	14.497	.673	.104	.139	.833	.931
Population Variance	23.350	.050	.001	.002	.077	.096



CWCC
89/07/20
Direct normal insolation
Normalized power output
Measured power output
Water flow rate
FLOW (L/min)
INSOLATION (W/m)
POWER (kWatt)
MOUNTAIN STANDARD TIME
09:45
10:00
10:15
10:30
10:45
11:00
0
20
40
60
80
100
120
140
160
100
200
300
400
500
600
700
800
900
1000
1100
10
30
50
70
90

Appendix II - Error Analysis

Calorimeter Error Analysis

The errors stated in this report were calculated using the root-sum-square method, i.e., the 3-sigma limit on the normalized power measurements. The root-sum-square error is defined as [Doebelin (3)]:

$$E_{rss} = \sqrt{\left(\Delta u_1 \frac{\partial \varepsilon}{\partial u_1}\right)^2 + \left(\Delta u_2 \frac{\partial \varepsilon}{\partial u_2}\right)^2 + \cdots + \left(\Delta u_n \frac{\partial \varepsilon}{\partial u_n}\right)^2} \qquad (1)$$

where u_i = measured quantity

Δu_i = error in measured quantity

$\frac{\partial \varepsilon}{\partial u_i}$ = partial derivative of the calculated function with respect to the measured quantity.

By performing an energy balance, the normalized power assuming steady-state conditions, no changes in kinetic or potential energy, can be derived as

$$\dot{Q} = \frac{I_o}{I} \dot{m} (h_2 - h_1) = \frac{I_o}{I} \rho \dot{V} (h_2 - h_1) \qquad (2)$$

where $\dot{Q}$ = normalized power

I_o = direct normal insolation for standard conditions (1000 $\frac{W}{m^2}$)

I = measured direct normal insolation

$\dot{m}$ = mass flowrate of cooling water

ρ = density of water

$\dot{V}$ = volumetric flowrate of water

h_2 = outlet enthalpy

h_1 = inlet enthalpy.

Using the equations that duplicate the tables found in Keenan and Keyes (2), density is a function of the reference temperature; the inlet enthalpy is a function of pressure and the reference temperature; and the outlet enthalpy is a function of pressure, the reference temperature and the delta temperature through the calorimeter. Equation (2) becomes

$$\dot{Q} = \frac{I_o}{I} \rho\,(T_{ref})\,\dot{V}\left[h_2(P,T_{ref},dT) - h_1(P,T_{ref})\right] . \tag{3}$$

However, enthalpy is a very weak function of pressure at near atmospheric conditions and can be ignored without affecting the enthalpies to four decimal places. Therefore

$$\dot{Q} = \frac{I_o}{I} \rho\,(T_{ref})\,\dot{V}\left[h_2(T_{ref}, dT) - h_1(T_{ref})\right] . \tag{4}$$

For this particular analysis, Equation 1 becomes:

$$E_{rss} = \sqrt{\left[\Delta I \frac{\partial \dot{Q}}{\partial I}\right]^2 + \left[\Delta T_{ref} \frac{\partial \dot{Q}}{\partial T_{ref}}\right]^2 + \left[\Delta\, dT \frac{\partial \dot{Q}}{\partial dT}\right]^2 + \left[\Delta \dot{V} \frac{\partial \dot{Q}}{\partial \dot{V}}\right]^2} \tag{5}$$

where

$$\frac{\partial \dot{Q}}{\partial I} = \frac{-I_o}{I^2} \rho\,(T_{ref})\,\dot{V}\left[h_2\,(T_{ref},dT) - h_1(T_{ref})\right] \tag{6}$$

$$\frac{\partial \dot{Q}}{\partial T_{ref}} = \rho\,(T_{ref})\,\frac{I_o}{I}\,\dot{V}\,\frac{\partial h_2(T_{ref,}\,dT)}{\partial T_{ref}} + \frac{I_o}{I}\,\dot{V}\,h_2\,(T_{ref,}\,dT)\,\frac{\partial_\rho(T_{ref})}{\partial T_{ref}}$$

$$- \rho\,(T_{ref})\,\frac{I_o}{I}\,\dot{V}\,\frac{\partial h_1(T_{ref})}{\partial T_{ref}} - \frac{I_o}{I}\,\dot{V}\,h_1\,(T_{ref})\,\frac{\partial_\rho(T_{ref})}{\partial T_{ref}} \tag{7}$$

$$\frac{\partial \dot{Q}}{\partial dT} = \rho\,(T_{ref})\,\frac{I_o}{I}\,\dot{V}\,\frac{\partial h_2(T_{ref,}\,dT)}{\partial dT} \simeq \rho\,(T_{ref})\,\frac{I_o}{I}\,\dot{V}\,\frac{\partial h_2(T_{ref,}\,dT)}{\partial T_{ref}} \tag{8}$$

$$\frac{\partial \dot{Q}}{\partial V} = \rho\left(T_{ref}\right) \frac{I_o}{I} \left[h_2\left(T_{ref} + dT\right) - h_1\left(T_{ref}\right)\right] . \tag{9}$$

The polynomial for the density of water is

$$\rho = 10^3 \left(a + b\,T_{ref} + c\,T_{ref}^2\right)^{-1} . \tag{10}$$

Therefore,

$$\frac{\partial \rho}{\partial T_{ref}} = -10^3 \left[\frac{b + 2\,cT_{ref}}{\left(a + b\,T_{ref} + c\,T_{ref}^2\right)^2}\right] \tag{11}$$

where $a = .9999$

$b = 2.209 \times 10^{-7}$

$c = 4.863 \times 10^{-6}$.

The polynomial for the enthalpy of water is given as

$$h = a + b\,T_{ref} + cT_{ref}^2 . \tag{12}$$

Therefore,

$$\frac{\partial h}{\partial T_{ref}} = b + 2cT_{ref} \tag{13}$$

where $a = -9.590 \times 10^{-3}$

$b = 4.203$

$c = -3.070 \times 10^{-4}$.

The inlet enthalpy and slope, h_1 and $\frac{\partial h_1}{\partial T_{ref}}$, are evaluated at T_{ref}, while the outlet enthalpy and slope, h_2 and $\frac{\partial h_2}{\partial T_{ref}}$, are evaluated at $T_{ref} + dT$.

Example:

T_{ref}	=	25°C
dT	=	10°C
$\dot{V}$	=	76.5 l/min = 1.275×10^{-3} m^3/sec
I	=	950 W/m^2
ΔI	=	6.6 W/m^2 (0.7% of I)
ΔT_{ref}	=	0.8°C (Type T TC)
ΔdT	=	0.04°C (Manufacturer's specification)
$\Delta \dot{V}$	=	$.01275 \times 10^{-3}$ m^3/sec (1% of $\dot{V}$).

Using these values in the above equations yields

$$\rho = 997 \ \ kg/m^3$$

$$\frac{\partial \rho}{\partial T_{ref}} = -.242 \ \frac{kg}{m^3 - C}$$

$$h_1 = h\ (T_{ref}) = 104.9 \ \ kJ/kg$$

$$h_2 = h \left(T_{ref} + dT\right) = 146.7 \ kJ/kg$$

$$\frac{\partial h_1\ (T_{ref})}{\partial T_{ref}} = \frac{\partial h}{\partial T_{ref}}\ (T_{ref}) = 4.188 \ \frac{kJ}{kg\text{-}C}$$

$$\frac{\partial h_2 (T_{ref,} dT)}{\partial T_{ref}} = \frac{\partial h}{\partial T_{ref}} (T_{ref} + dT) = 4.182 \frac{kJ}{kg\text{-}C}$$

Substituting these values into Equations (6) through (9) yields

$$\frac{\partial \dot{Q}}{\partial I} = -.059 \frac{kW - m^2}{W}$$

$$\frac{\partial \dot{Q}}{\partial T_{ref}} = -.022 \text{ kW/°C}$$

$$\frac{\partial \dot{Q}}{\partial dT} = 5.596 \text{ kW/°C}$$

$$\frac{\partial \dot{Q}}{\partial \dot{V}} = 43{,}868 \text{ kJ/m}^3$$

Substituting into Equation (1), the root-sum-square error becomes

$$E_{rss} = \sqrt{.152 + 3.098 \times 10^{-4} + .050 + .313} \quad kW \qquad (14)$$

$$E_{rss} = .72 \text{ kW.}$$

By noting the relative size of the terms in Equation (14), the largest errors come from the calibration accuracies of the pyrheliometer and the flowmeter.

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