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A SOLAR SIMULATOR USED FOR PRE-FLIGHT THERMAL QUALIFICATION OF THE RAE-A SPACECRAFT

DANNY L. LESTER
ROY McINTOSH

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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Radiometry Section
GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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ABSTRACT

Extensive modifications were performed on the solar simulation facility operated by the Thermophysics Branch of NASA - Goddard Space Flight Center in preparation for testing the RAE-A flight unit. The solar beam diameter was enlarged by almost 50 percent from 48 inches to 70 inches. This was accomplished by redesigning portions of the optical system and increasing the capabilities of other optical and mechanical components. The RAE-A was tested in the facility for 29 hours, and flight data is in close agreement with predictions made from the analytical model verified during the solar simulation test.

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A SOLAR SIMULATOR USED FOR PRE-FLIGHT THERMAL QUALIFICATION OF THE RAE-A SPACECRAFT

INTRODUCTION

During the summer of 1967 the Thermophysics Branch of NASA - Goddard Space Flight Center was assigned the responsibility of providing the thermal vacuum solar simulation test for the RAE-A flight unit. In order to accomplish this, it was necessary to modify extensively the existing facilities—particularly the A1200 Solar Simulator.[1] The existing simulator provided only a four foot diameter light beam while the RAE-A required a beam size at least five and one-half feet in diameter. The RAE-A also required an intensity of one solar constant (135.1 MW cm^{-2}).[2] These requirements necessitated modification or replacement of every major simulator component. The success of this modification and environmental testing program can be judged from the fact that the RAE-A temperatures are behaving as predicted. Table 1 indicates the performance of the system before and after the modifications.

SYSTEM DESCRIPTION

Basically, the Thermal Vacuum Solar Simulator (TVSS) comprises the following components:

1. A Spectrolab A1200 solar simulator

2. A 10 ft. diameter x 15 ft. long horizontally mounted vacuum chamber which houses the collimating element and test volume. The chamber is properly shrouded and baffled; and is evacuated by three oil diffusion pumps having a combined pumping speed of 150,000 liters per second.

The A1200 is a 19 lamp, vertically mounted, solar simulator having an off axis optical system with respect to the vacuum chamber center line.

An optical schematic of the system is shown in Figure 1.

Test volume irradiance is rendered in the following manner. Approximately 50% of the electrical input power to an individual lamp is emitted as radiant energy. A large portion of this energy is captured by the aconic light source collector and directed onto the turning flat. When the source module is properly aligned, the light beam is then folded and smear focused to fall on the center lenticule of the field lens array.

Table 1
Solar Simulator Characteristics

Characteristic	Prior to Modification	Modified System
Beam Size (Minor axis x Maj. axis x Depth)	47 in x 52 in x 96 in	68 in x 70 in x 96 in
Beam Configuration	Ellipse	Ellipse
Uniformity using 1cm x 1cm detector	±5% any plane; ±5% volume	±1.9% one plane; ±10% volume
Collimation (Half angle)	2 degrees	1.5 degrees
Stability (1 sec to 24 hours)	±1%	±1%
Intensity (No spectral filters)	$242 mwcm^{-2}$ max.; $12.7 mwcm^{-2}$ min.	$164 mwcm^{-2}$ max.; $8.6 mwcm^{-2}$ min.
Intensity (Seven spectral filters)	$148 mwcm^{-2}$ max.; $7.8 mwcm^{-2}$ min.	$113 mwcm^{-2}$ max.; $5.9 mwcm^{-2}$ min.
Efficiency (No spectral filters)	6.5%	4.8%
Efficiency (Seven spectral filters)	4.0%	3.3%
f/no. of system (working)	f/1.8	f/1.4
Reflected Energy	≤2% of incident irradiance	≤2% of incident irradiance over 75% of test volume
Size and type of collimator	60 in diameter off-axis parabola	91.5 in diameter spherical
Off-axis angle of collimator	43° 10'	41° 22'
Type of lamp	2500 watt xenon compact arc	4200 watt xenon compact arc
Number of lamps	19	19
Interior dimensions of vacuum chamber (Diameter x Depth)	10 ft x 15 ft	10 ft x 15 ft
Ultimate vacuum obtainable	10^{-9} Torr	10^{-9} Torr
Thermal Shroud Temperature Range	-196°C to 250°C	-196°C to 250°C

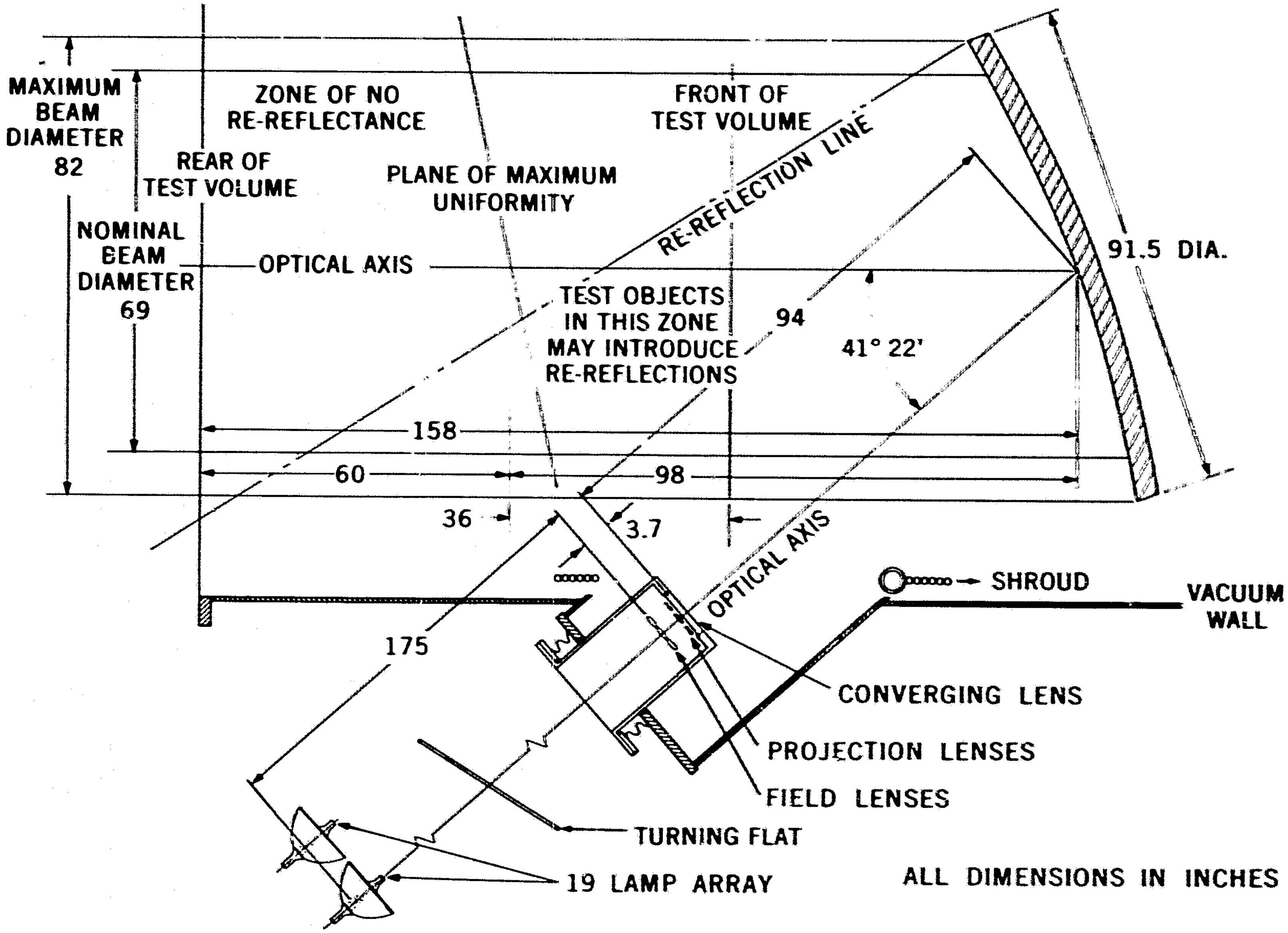


Figure 1. Optical Diagram of Solar Simulator

The uniformity of irradiance at the field lens plane essentially determines planar uniformity in the test volume; therefore, each light source module is "uniformity adjusted" to produce a proper pattern of irradiance at this location. Each field lens is a pseudo source for the corresponding projection lens, which is located near the infinity focus of the collimator. The clear aperture of the field lens acts as the pseudo sun and thus determines the solar beam subtense angle. After minor correction by the converging lens the light beam is then reflected by the spherical collimator into the test volume.

The test beam can be tailored and processed at the lens assembly by using uniformity and/or spectral filters. The best uniformity obtained to date is shown in Figure 2. This x-y plot represents a vertical, horizontal, and two diagonal scans taken at a plane in the test volume referred to as the plane of maximum uniformity. The beneficial result of spectral filtering can be seen by comparing Figure 3A with Figure 3B. Seven spectral filters were used to achieve the spectral distribution illustrated in Figure 3B. The uniformity and spectral filters will be described in detail later.

For discussion of the modifications, the simulator has been divided into four separate subsystems as follows:

1. The lamp housing or silo, which encloses the 19 lamp array (see Figure 4), the plano mirror, and the heat exchanger

2. Transfer optics

3. Collimator

4. Control and monitoring systems, including the source power supplies

In order to accommodate the RAE-A for pre-flight thermal vacuum and solar simulation testing all four subsystems required major modifications.

LAMP HOUSING

The individual light source module consists of a xenon short arc lamp, lamp cage, aluminized electroformed nickel collector, and high voltage lamp starter.

Since the test beam had to be enlarged considerably, it was necessary to replace the existing 2.5 kw lamps with 4.2 kw lamps. The 4.2 kw lamp warranty stipulated that the metal to quartz seals should never exceed 200°C. This condition could not be obtained on the negative seal of the lamp because of its location

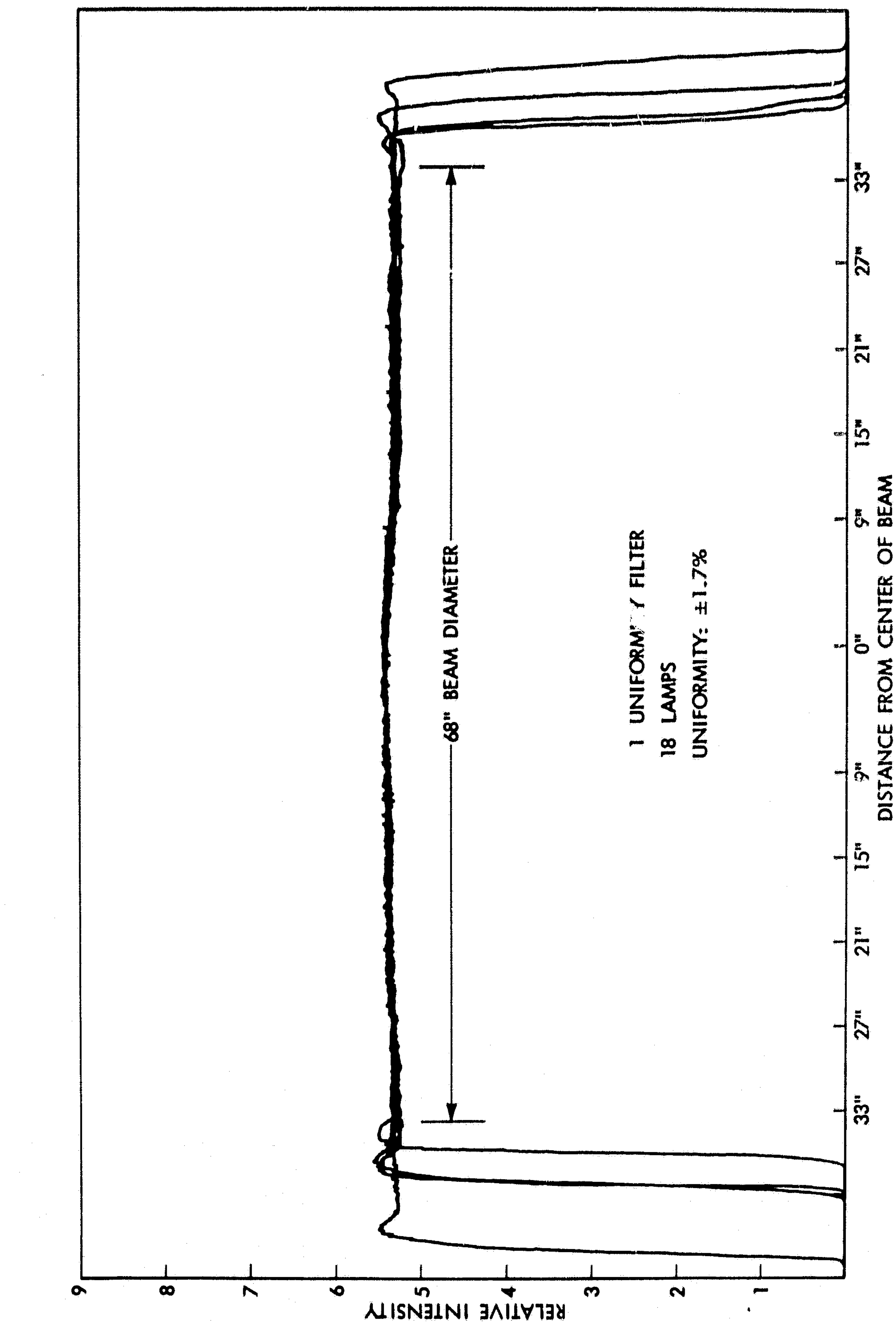


Figure 2. Best Uniformity Obtained

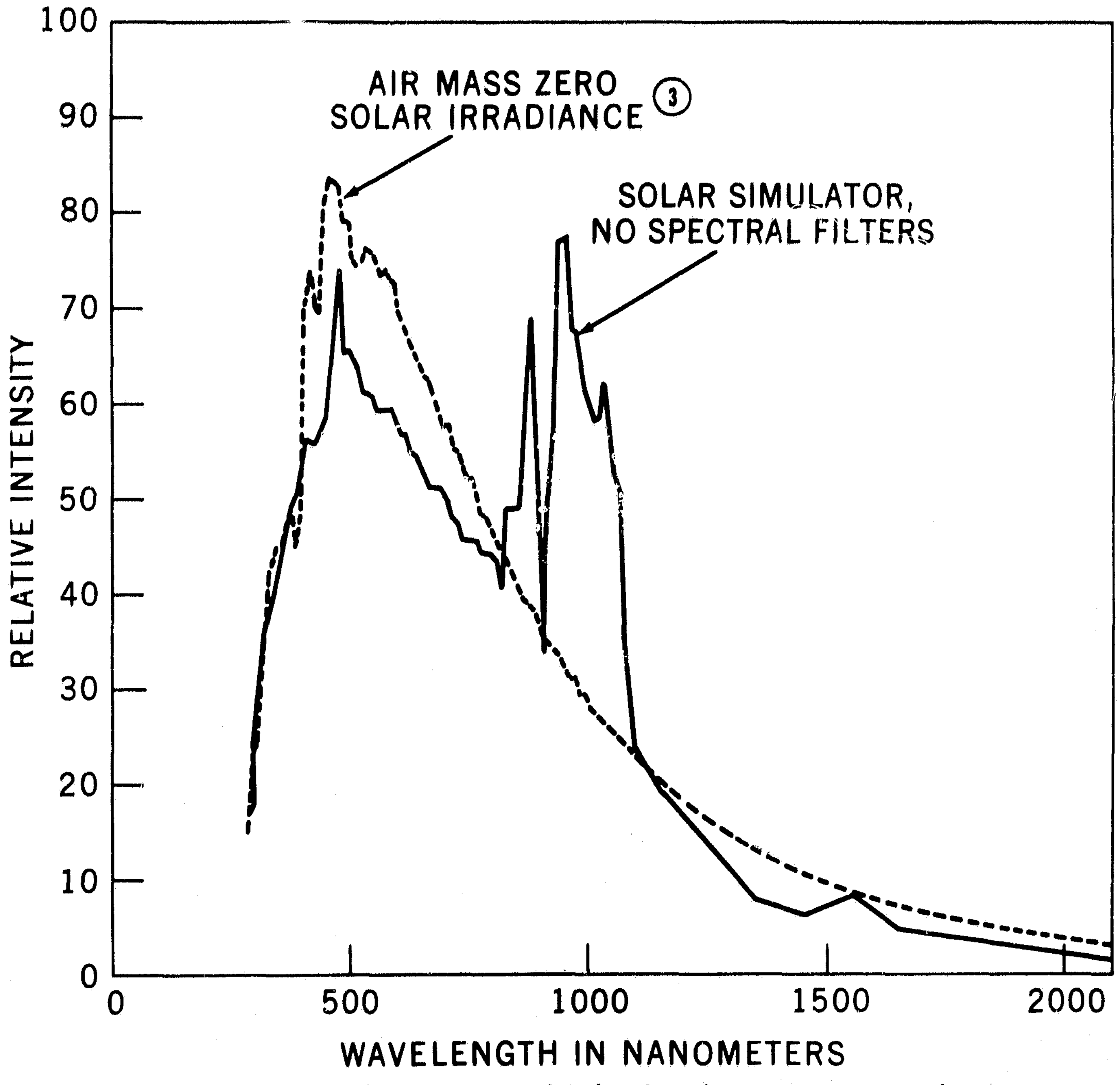


Figure 3A. Spectral Irradiance of Solar Simulator, No Spectral Filters

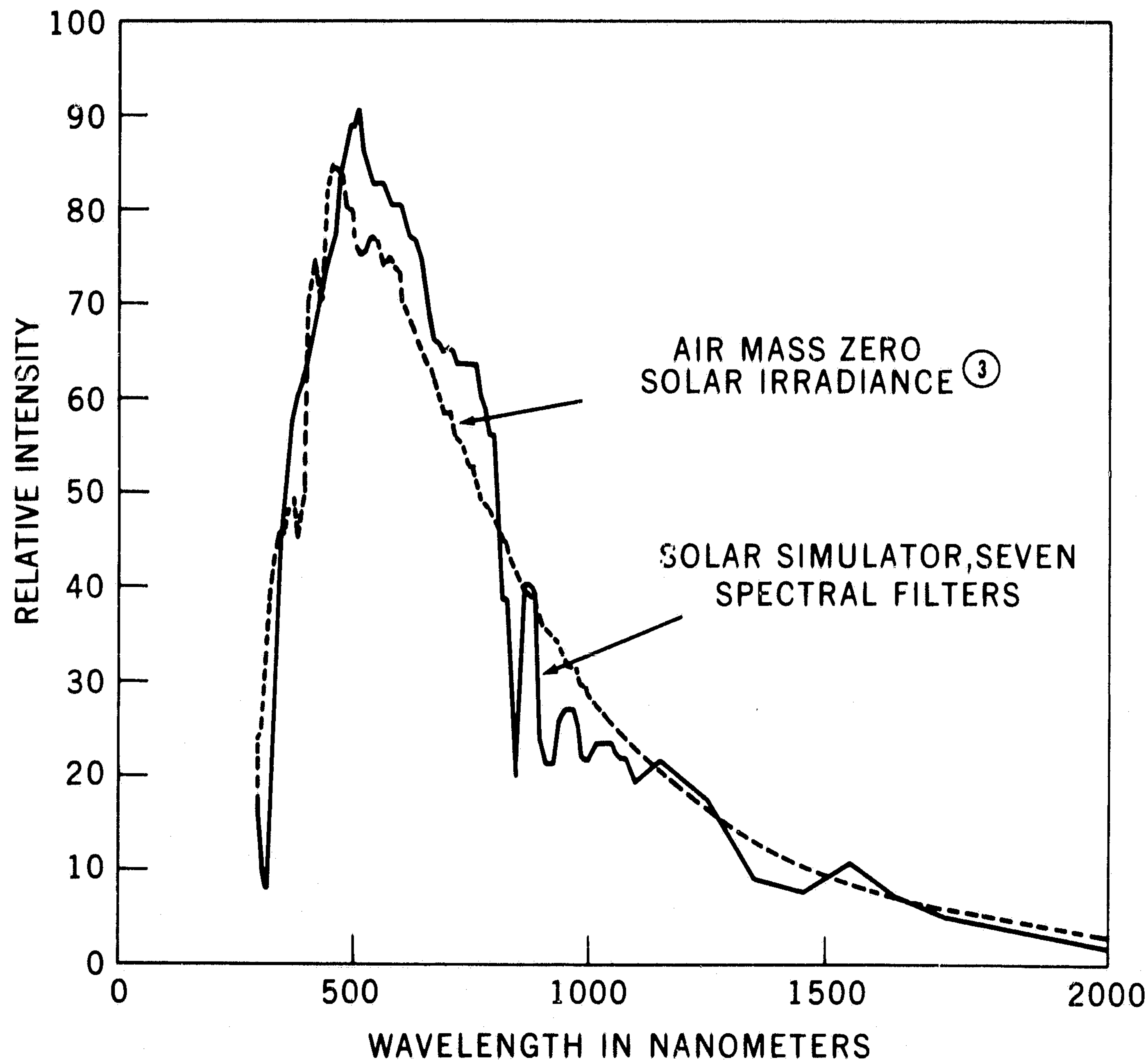


Figure 3B. Spectral Irradiance of Solar Simulator, Seven Spectral Filters

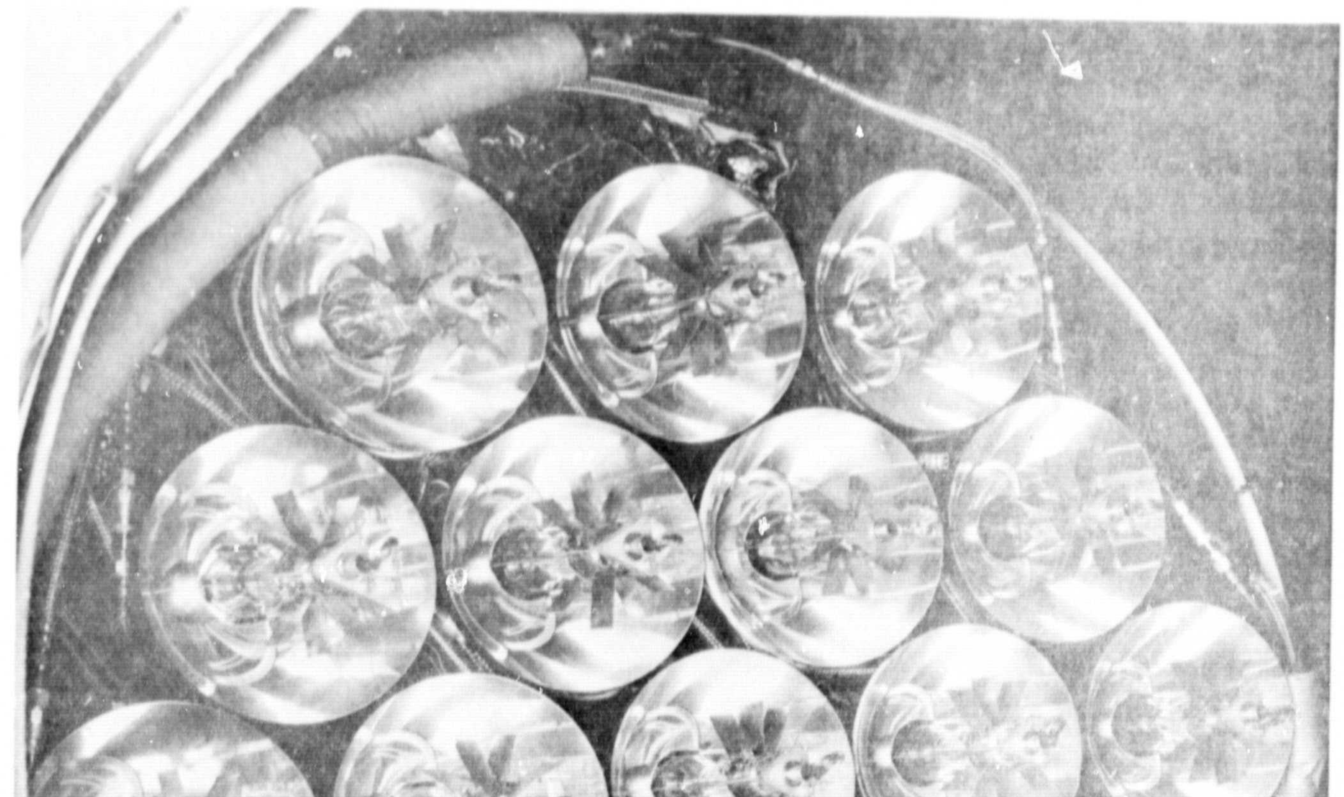


Figure 4. Lamp Array

in the radiation emanating from the source collector. Brass fins were mounted on the negative base of each lamp to provide additional radiating surface and thus maintain its temperature below 200°C. The arrangement of these fins can be seen in Figure 5. There was no detectable decrease in test volume irradiance as a result of using these fins. In addition to the brass fin modification, new lamp cages were purchased because the 4.2 kw lamps were mechanically incompatible with the existing cages.

Water cooling the source collector was a necessity for removing the additional thermal input from the larger lamps. This extra heat load would have caused irreparable damage to the collector. The collectors were modified for water cooling by bonding a pre-formed copper coil to the outside surface with a high temperature epoxy. Solenoid valves were installed to allow water to flow only during lamp operation thus preventing water condensation when the lamps were off.

The lamp starters have a high voltage transformer capable of conducting a maximum of 95 amperes. The nominal operating current of 140 amperes for the 4.2 kw lamps would destroy these transformers; consequently, the starters were equipped with solenoids and copper shorting bars. During lamp operation, current by-passes the transformer by way of the shorting bar thus preventing internal damage to the starter. Figure 5 is a picture of the modified light source module minus the lamp starter.

A larger plane mirror was purchased as required by the new optical design. This mirror is an aluminum disc 36 inches in diameter by 1.375 inches thick. The aluminum disc was machined, Kanigen coated, optically polished, aluminized, and overcoated with silicon oxide, in that order. The mirror is water-cooled by copper tubing affixed to its back surface.

A closed-loop technique is used for forced air cooling inside the lamp housing. Air is cooled by passage through a large water-cooled heat exchanger located adjacent to the lamp silo. A second and smaller water-cooled radiator was installed in the heat exchanger to assist in removing additional heat generated by the 4.2 kw lamps. Furthermore, if future conditions warrant, this radiator can be readily connected to an LN_2 line for increased cooling capacity. A beneficial aspect of this closed-loop cooling method is that the lamp housing is purged with dry nitrogen to reduce ozone produced by the short arc lamps.

TRANSFER OPTICS

The lens assembly (see Figure 6) is a seven element-integrator type system having seven field and seven projection lenses and one converging lens. All

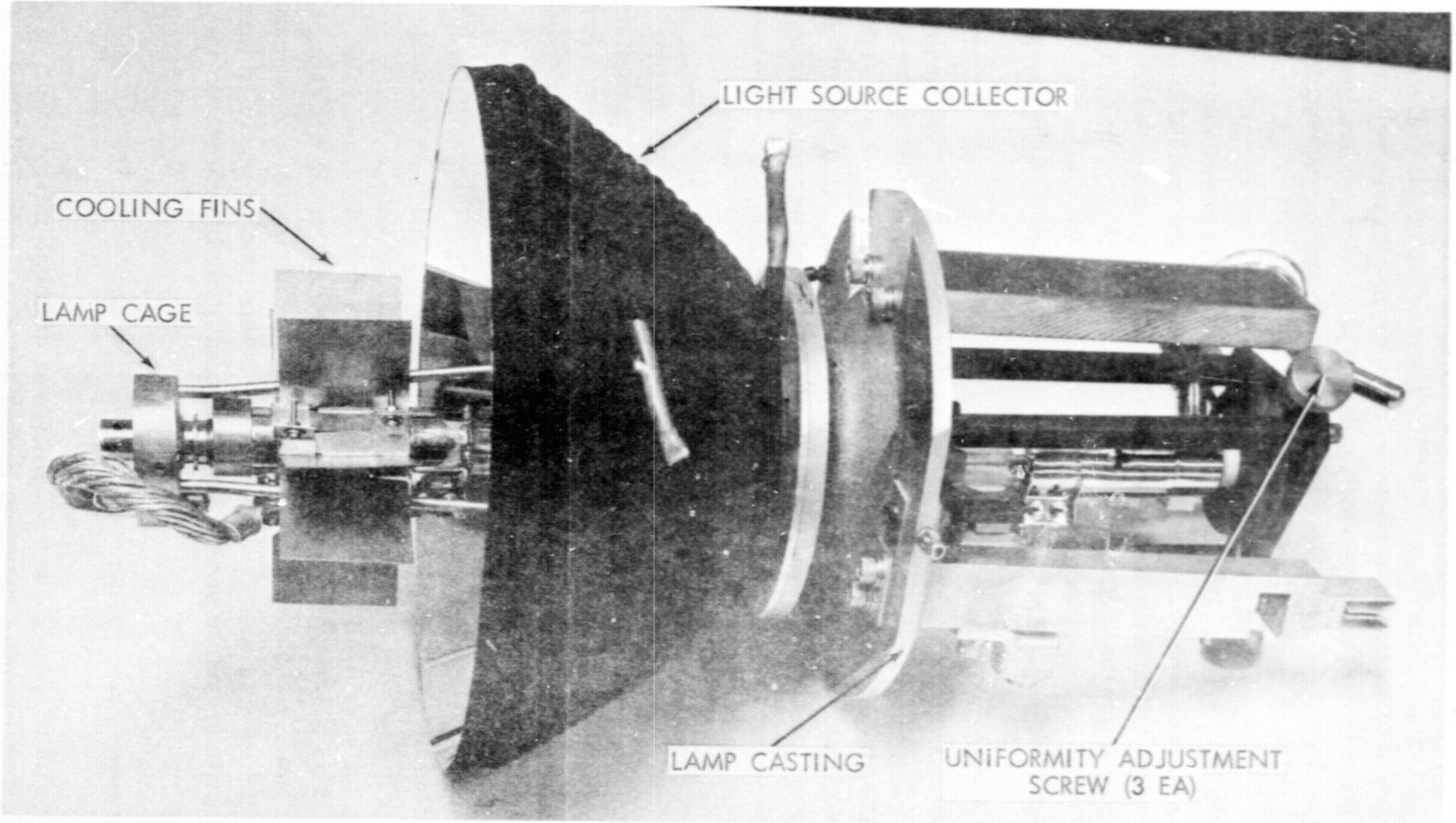


Figure 5. Light Source Module

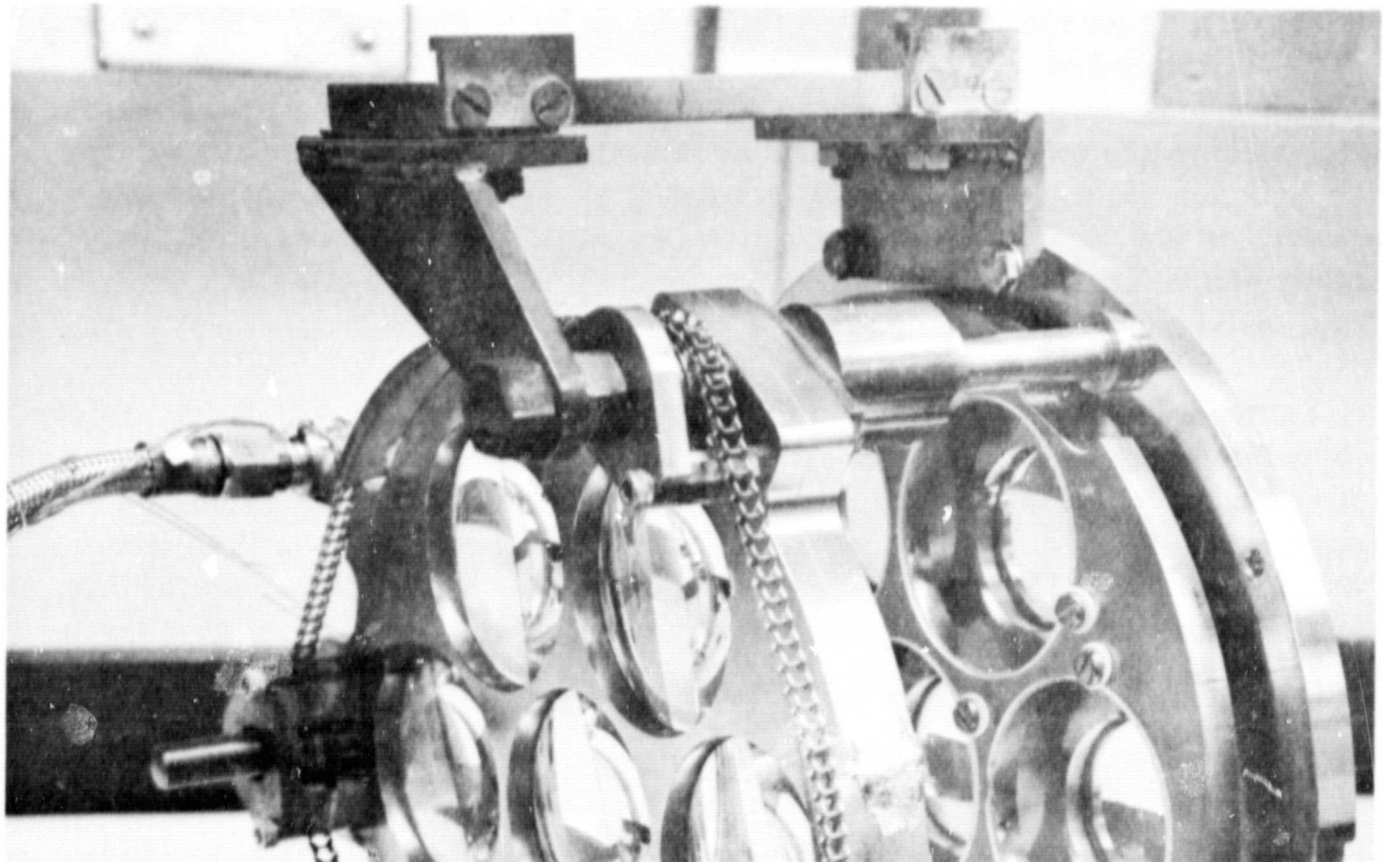


Figure 6. Lens Assembly

optical elements in the lens assembly were fabricated from UV grade quartz. The converging lens also serves as the vacuum chamber port. A seal at this port is accomplished with a Dow Corning 916 silastic hot vulcanized gasket around the lens which is flanged into place. Both the converging lens and field lens housings are water cooled. The projection lens housing is shadowed by the field lens housing and thus does not require water cooling. The entire lens assembly is housed within a 16-inch diameter stainless steel transition tube vacuum sealed at one end by the converging lens and at the other end with indium compressed between two flanges.

Figure 7 is a picture of the uniformity filter now in use. The filter(s) is mounted directly behind the field lens. Attenuation of light at this point results in a reduction of radiation in the test volume. Evaporated platinum, on UV grade quartz, with an SiO_X protective overcoating is used to form the filter. A prescription for the deposition pattern can be obtained from planar uniformity scans in the test volume. This type of filter has proven quite durable in the past with no apparent adverse spectral effects.

The spectral filters differ from the uniformity filters in coating and location. These elements (normally seven are used) are mounted directly in front of the projection lenses. A uniform multi-layered titanium oxide coating is used to reject energy primarily from approximately 0.8 to 1.1 microns. This is the region of the intense xenon lines. This yields a much closer solar spectral match. These filters have been used for several hundred hours with no serious deterioration even though the filters are mounted in an area of large ozone concentrations, intense UV radiation, and high heat levels.

As required by the new optical design, the lens assembly was relocated 16 inches forward (toward the collimator) from its original position. This necessitated the fabrication of a new transition tube. In addition, other modifications were performed to the lens assembly to accommodate the new optical elements. Moving the lens assembly forward resulted in a less efficient transfer of radiation from collector to field lens for several lamp modules because of physical obstructions.

COLLIMATOR

The 60-inch parabolic collimating mirror hitherto used was replaced with a spherical collimator 91.5-inches in diameter by 4 inches thick with a 204.4-inch radius of curvature. The spherical mirror was formed from a blank of 6061 aluminum using an explosive forming technique. After final machining to the desired contour, it was Kanigen coated and polished. The mirror was then

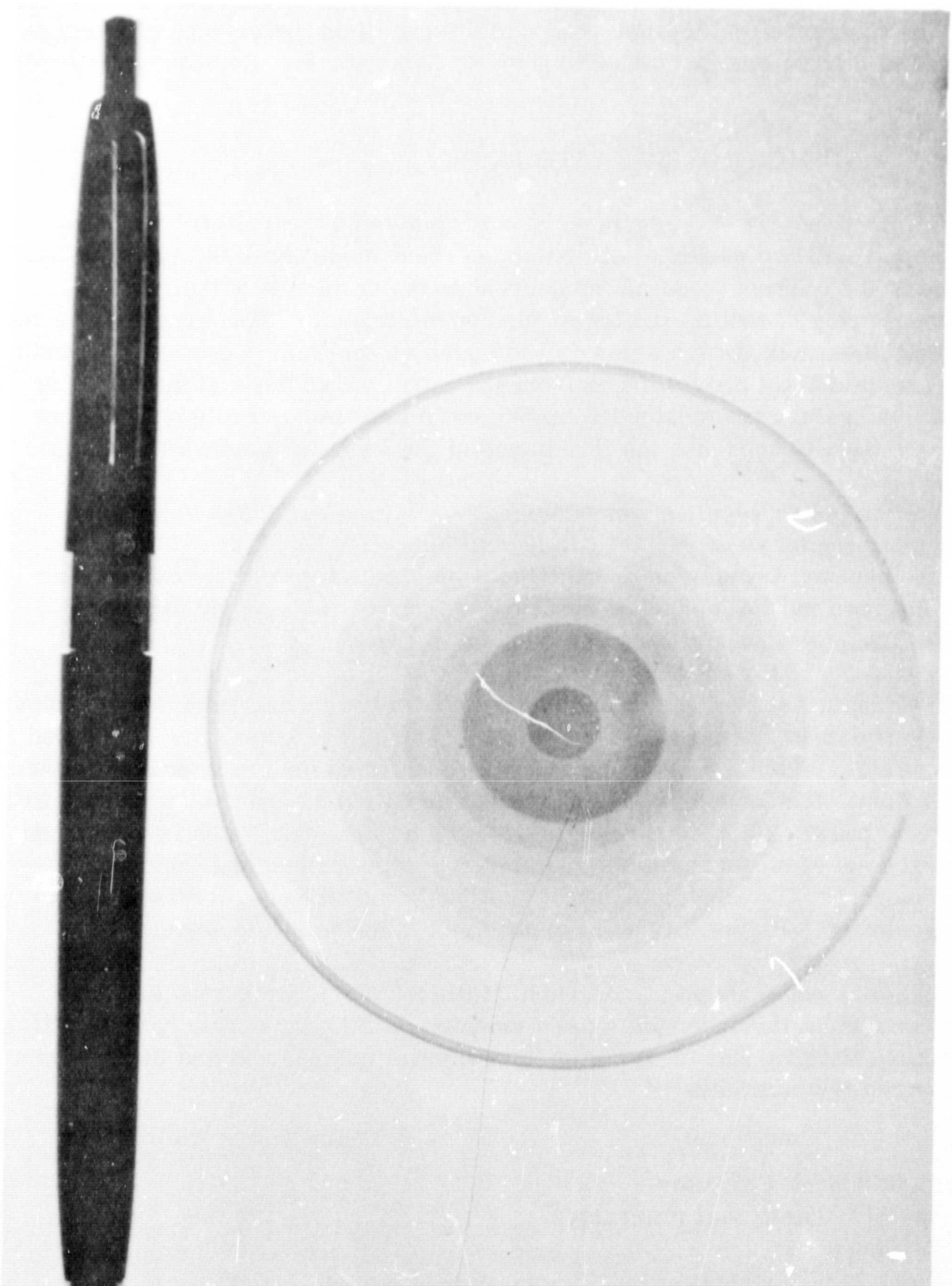


Figure 7. Uniformity Filter

installed in the TVSS vacuum chamber and aluminized. The mirror met or exceeded all contract specifications and exhibits excellent reflectance characteristics. The mirror was fabricated by Tinsley Laboratories, Berkeley, California.

CONTROL AND MONITORING SYSTEMS

Each lamp has its own regulated power supply and control circuit. The power supply has two modes of operation, current mode and light mode. When operated in the current mode, lamp current is maintained at a desired level determined prior to testing and set at the control console. See Figure 8. In the light mode, feedback from a solar cell mounted on the light source module maintains a constant level of irradiance from the lamp. This mode of operation is particularly useful during extended testing when tungsten deposits on the lamp envelope gradually decrease the irradiance of the lamp for a constant wattage.

Since the power supplies were designed for a nominal 2.5 kw operation, several components were replaced to permit operation at 4.2 kw. For each supply the chokes, transformer, one diode, and lamp leads required changing. In addition, two muffin fans were mounted on front of each supply for extra cooling. The power supply rack can be seen in Figure 9.

The scanner used for obtaining planar uniformity measurements in the test volume is shown in Figure 10. The scanner consists of a mounting frame and scanning arm. When in use the assembly is hung from the top rail on the vacuum chamber door. The scanning arm is remotely controlled and can be rotated to any desired angle $\pm 1°$. The sensor is a 1 x 1 cm solar cell which is calibrated during each set of scans against a radiometric standard (normal incidence pyrheliometer). The electrical output and location of the sensor is plotted on an x-y recorder. Figure 2 is a uniformity plot taken with this scanner.

In order to preclude any catastrophic failures due to excessive heating, copper constantan thermocouples were mounted on all components having critical temperature limits. The table below lists several components and their maximum desired temperatures.

Component	Temperature Limit °C
Light Source Collector	130
Negative Lamp Seal (warranty)	200
Turning Flat	80
Field Lens Housing	90
Indium Seal on Transition Tube	135
Converging Lens Holder	90

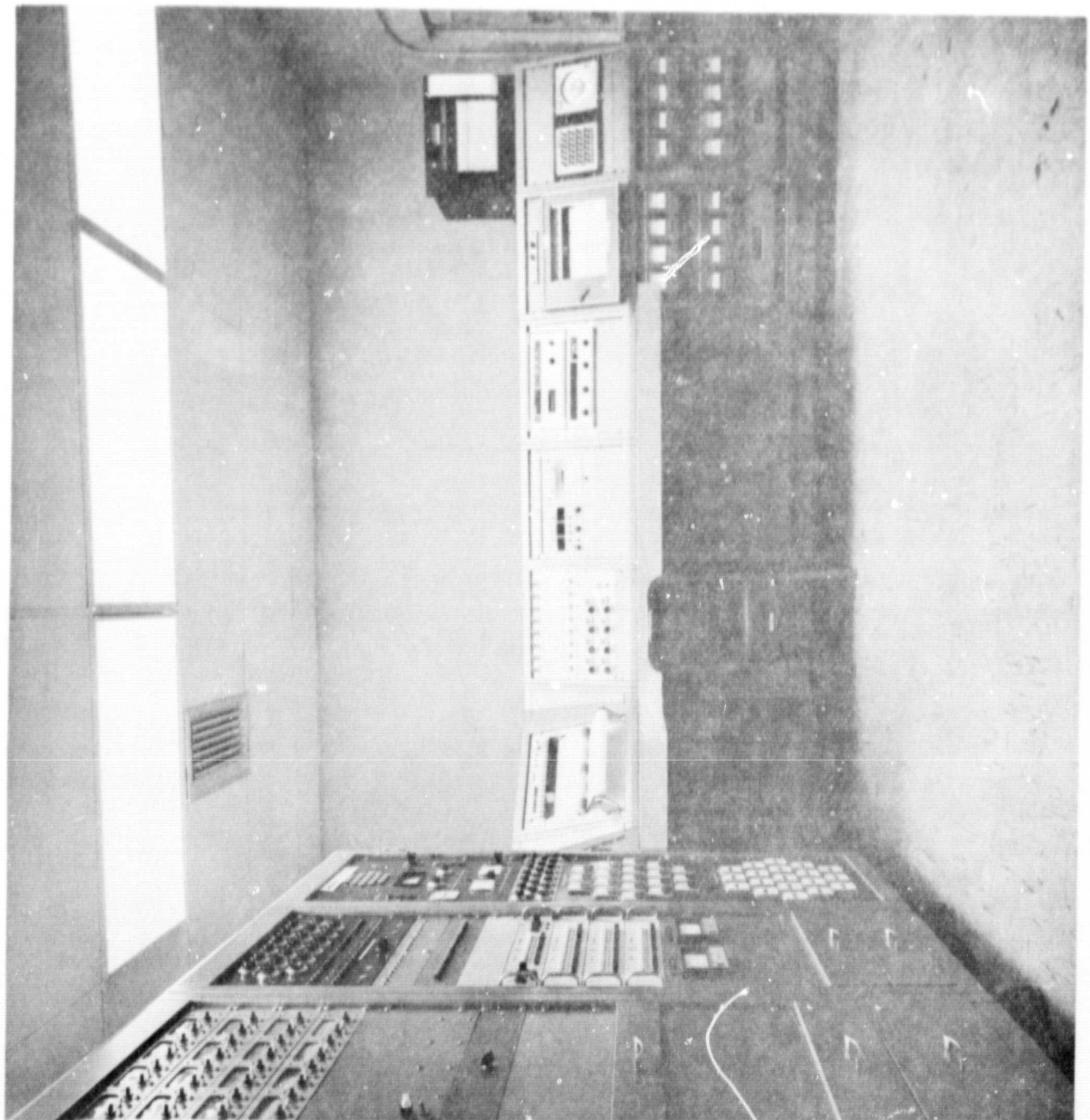


Figure 8. A1200 Control Console

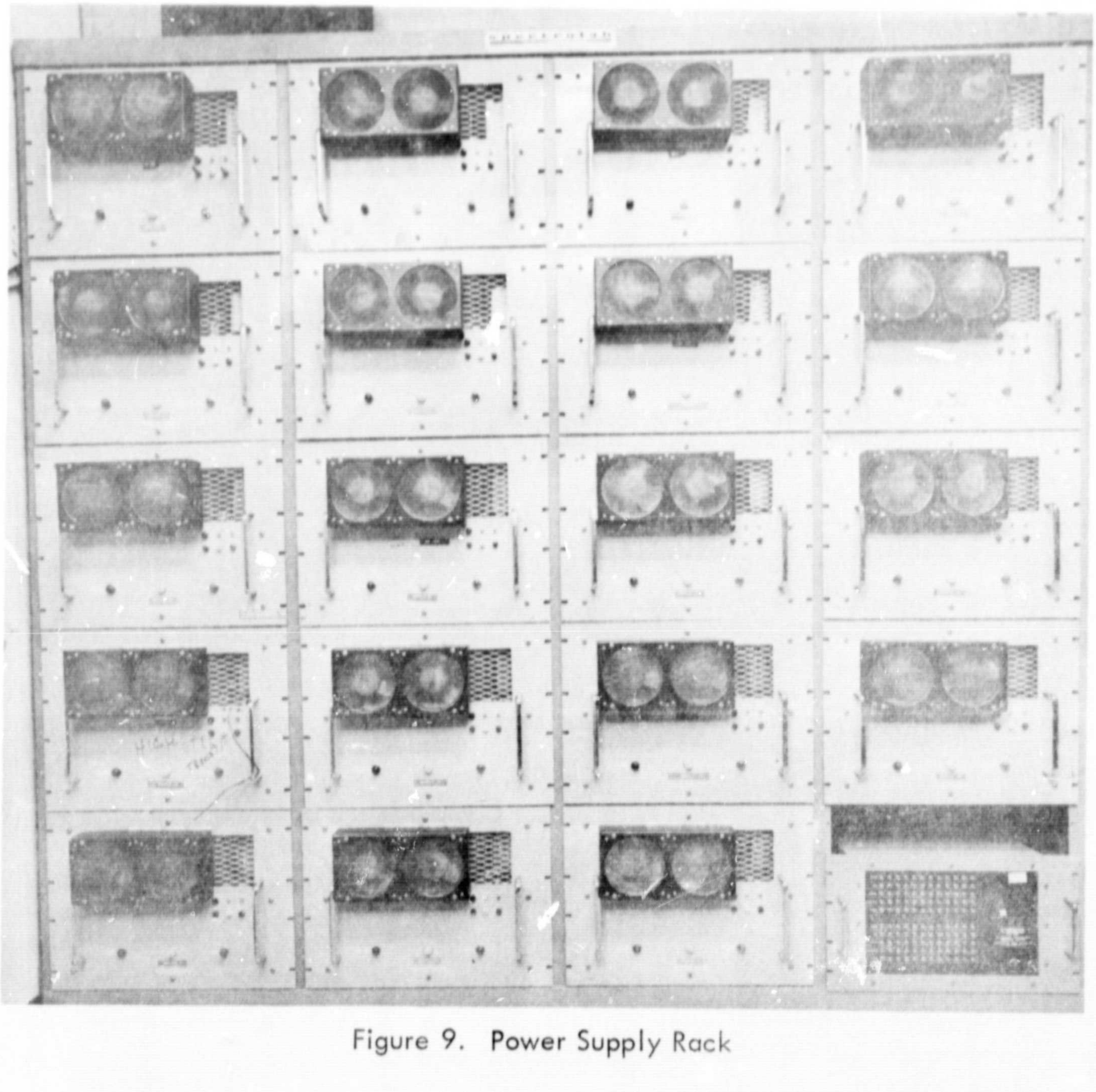


Figure 9. Power Supply Rack

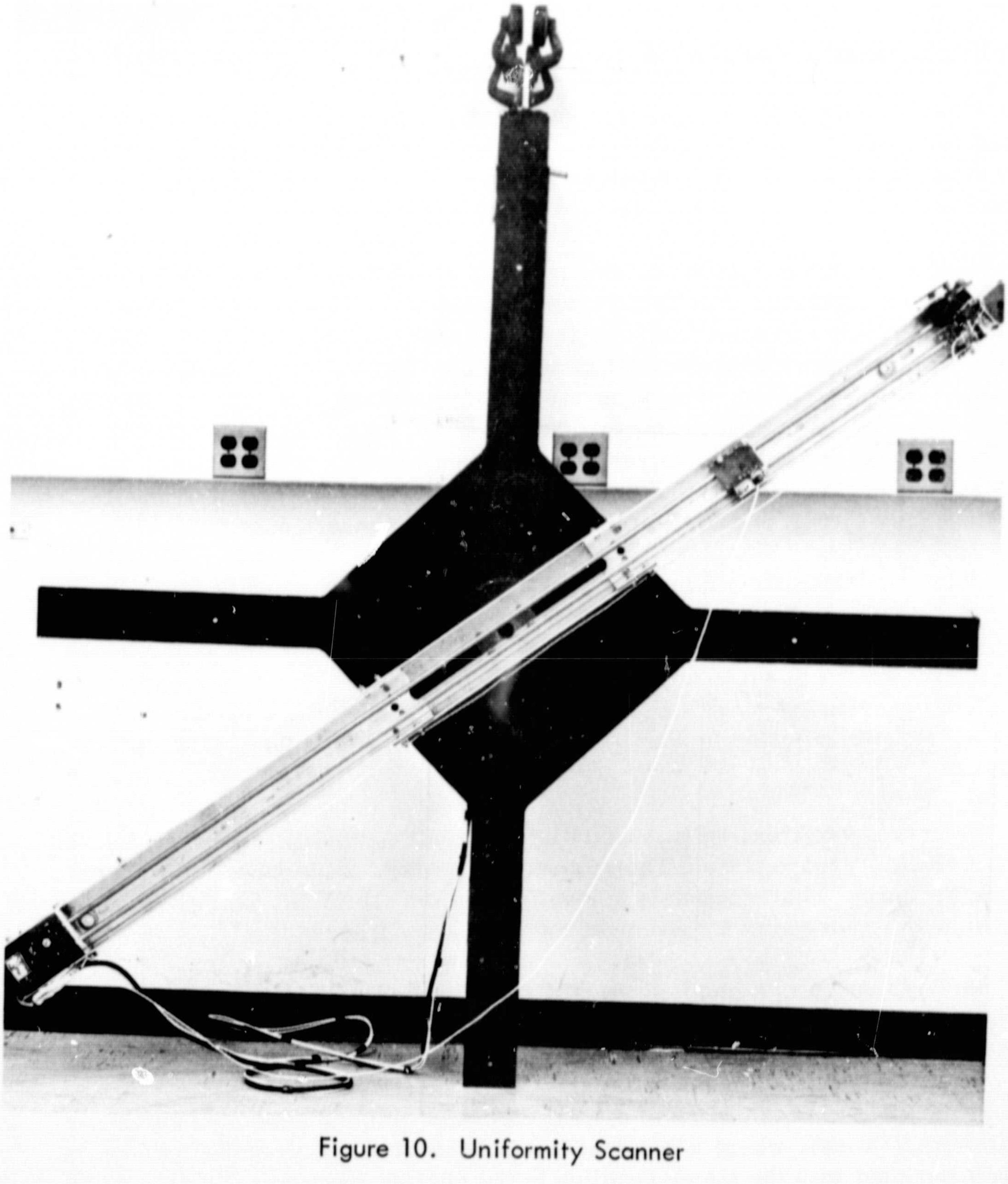


Figure 10. Uniformity Scanner

Spectral irradiance measurements are taken through a quartz port in the vacuum chamber door with a Leiss double prism monochromator.[1] Typical spectral distribution curves are shown in Figures 3A and 3B.

24-HOUR SHAKEDOWN TESTS

Two 24-hour shakedown tests, conducted on April 10, 1968 and May 1, 1968, were run prior to testing the RAE-A. The primary objective of these tests was to ascertain the reliability and performance of the A1200. No serious malfunctions or failures were encountered during either test.

With 19 lamps in operation, the first test was conducted at three different power levels. Starting with an average lamp power of 2.2 kw the A1200 was allowed to reach a temperature equilibrium. After checking all components (i.e., temperature limits vs. equilibrium temperature), the average lamp power was increased to 2.8 kw. Following the same procedure used before, the lamp power was then increased to an average power of 3.6 kw. At this level the average total irradiance in the test volume was 126 mw/cm^2. It was planned to increase the lamp power to a higher level; however, the malfunction of several power supply circuit breakers prohibited operation above 3.6 kw.

After replacing the power supply circuit breakers, the second test was conducted. Again, 19 lamps were used. The average lamp power throughout this test was maintained at approximately 3.8 kw. The corresponding average test volume irradiance for this level of operation was 135 mw/cm^2. The only problem experienced occurred toward the end of the test. A lamp developed a leak in the bulb indicated by low operating voltage. This lamp was immediately shut off.

Temporal variations of test beam intensity during the tests were monitored with a black V groove plate. Thermocouples mounted on its back surface serve as the sensors. This monitor is normally used for all TVSS tests involving the A1200 and is mounted at a convenient location in the test volume.

During both tests a small downward trend in the total irradiance was detected by the V groove plate. This trend was attributed to contamination of optical elements and reduced energy output from the lamps. The latter could have been compensated by operating the power supplies in the light sensing mode. However, since contamination of optical elements would still be a problem during the RAE-A test, where a constant level of irradiance is required, the tests were conducted with the power supplies in the current mode.

The A1200 performed satisfactorily during both tests with only minor difficulties. In addition, all components operated within their temperature limits. After the many weeks of modifications, the A1200 was now ready for the RAE-A spacecraft.

RAE-A TEST PREPARATION

Several small anomalies, discovered during the 24-hour shakedown tests, were analyzed and corrected. In addition, all optical elements, including the light source collectors, plano mirror, and lenses were cleaned to maintain the spectral integrity of the system.

An adequate size test beam having one solar constant of irradiance was the basic requirement for the test. In order to deliver one solar constant to the test volume all 19 lamps were used with no spectral filtering. The average lamp power needed to attain the required level of total irradiance was 3.8 kw.

The uniformity was tailored to ±2.5 percent at the plane of maximum uniformity by using the filter shown in Figure 7. Only one filter was necessary to obtain the preliminary uniformity.

A pre-test spectral distribution measurement was made with the Leiss instrumentation mentioned earlier. The spectrum was found to be the same as that shown in Figure 3A. Ordinarily, a spectral analysis is made during a test; however, during the RAE-A test the viewing port was obscured by the satellite.

THE RAE-A TEST

The RAE-A was instrumented into the vacuum chamber on May 9, 1968. It was suspended from a holder mounted on the upper rail of the vacuum chamber door. The holder was manually rotatable from outside the vacuum chamber to permit spacecraft tests in two opposite positions. Figure 11 shows the RAE-A instrumented into place on the vacuum chamber door.

The location of the RAE-A with respect to the plane of maximum uniformity is shown in Figure 12.

Intensity monitors were mounted in various positions in the test beam. One of these monitors was the V groove plate used during the 24-hour shakedown tests. By using these monitors any shift in the test volume intensity (e.g., reduced intensity due to contamination of optical components or a lamp failure)

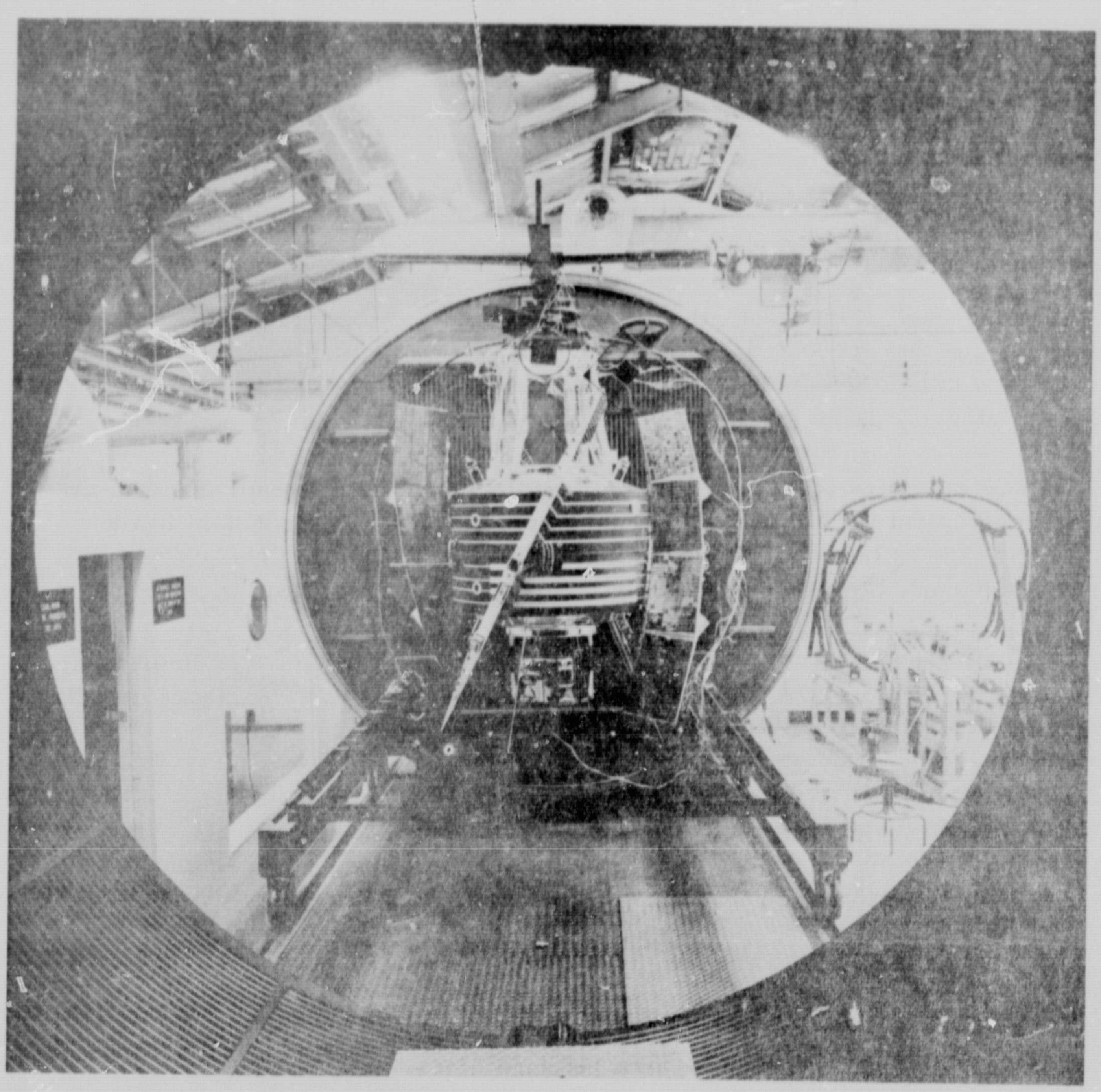


Figure 11. RAE-A Instrumented in Place

while testing could be compensated with an adjustment of lamp power at the control console; however, since each lamp module has its own particular uniformity pattern in the test volume, the required adjustments could induce minor uniformity alterations.

After electrical checkout of the RAE-A, pre-test uniformity scans were obtained using the planar uniformity scanner (shown earlier in Figure 10). For the RAE-A test, scans were taken at the plane of maximum uniformity, and the uniformity was found to be ±2.5 percent. This uniformity is illustrated in the contour map in Figure 13.

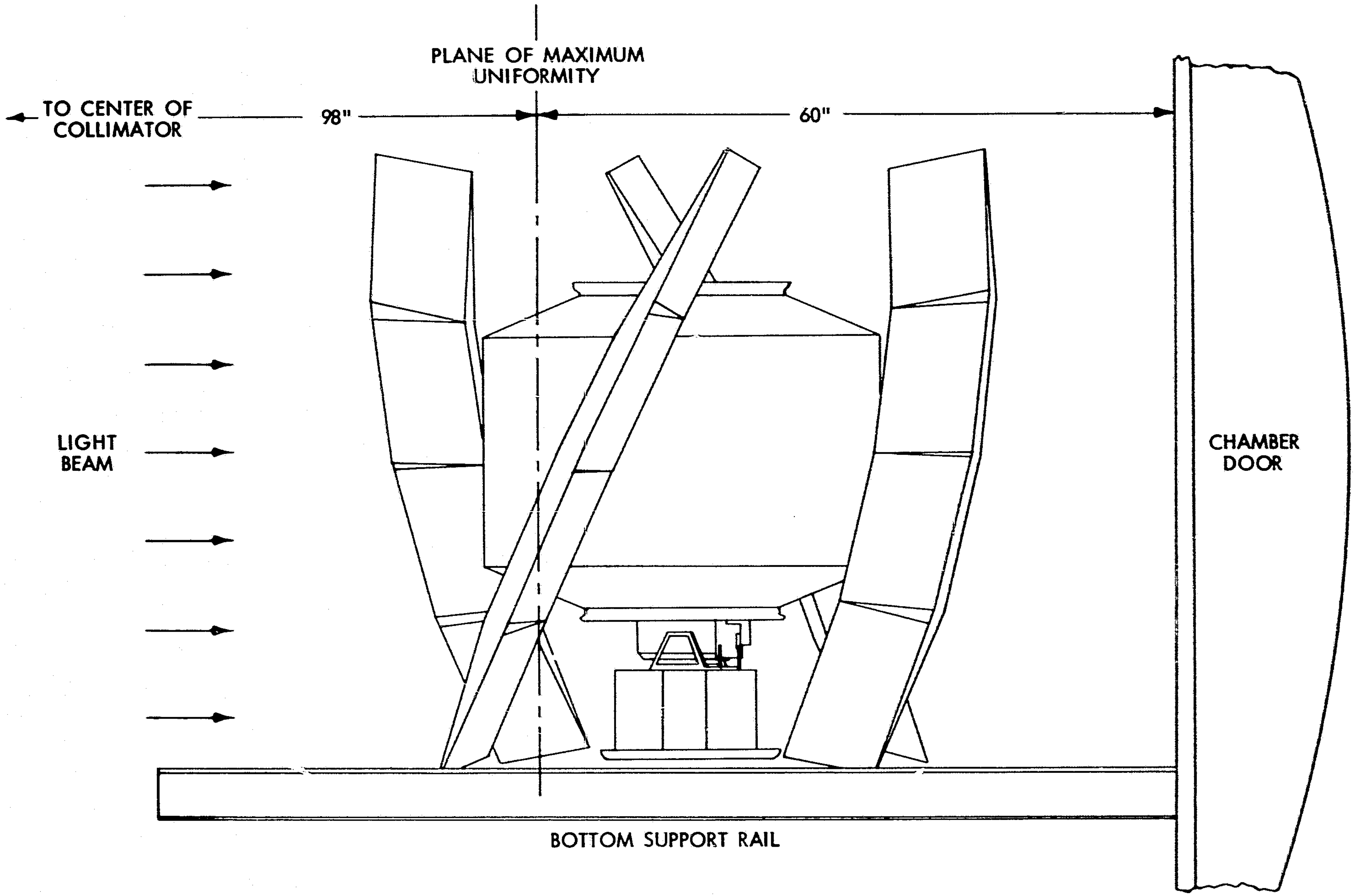
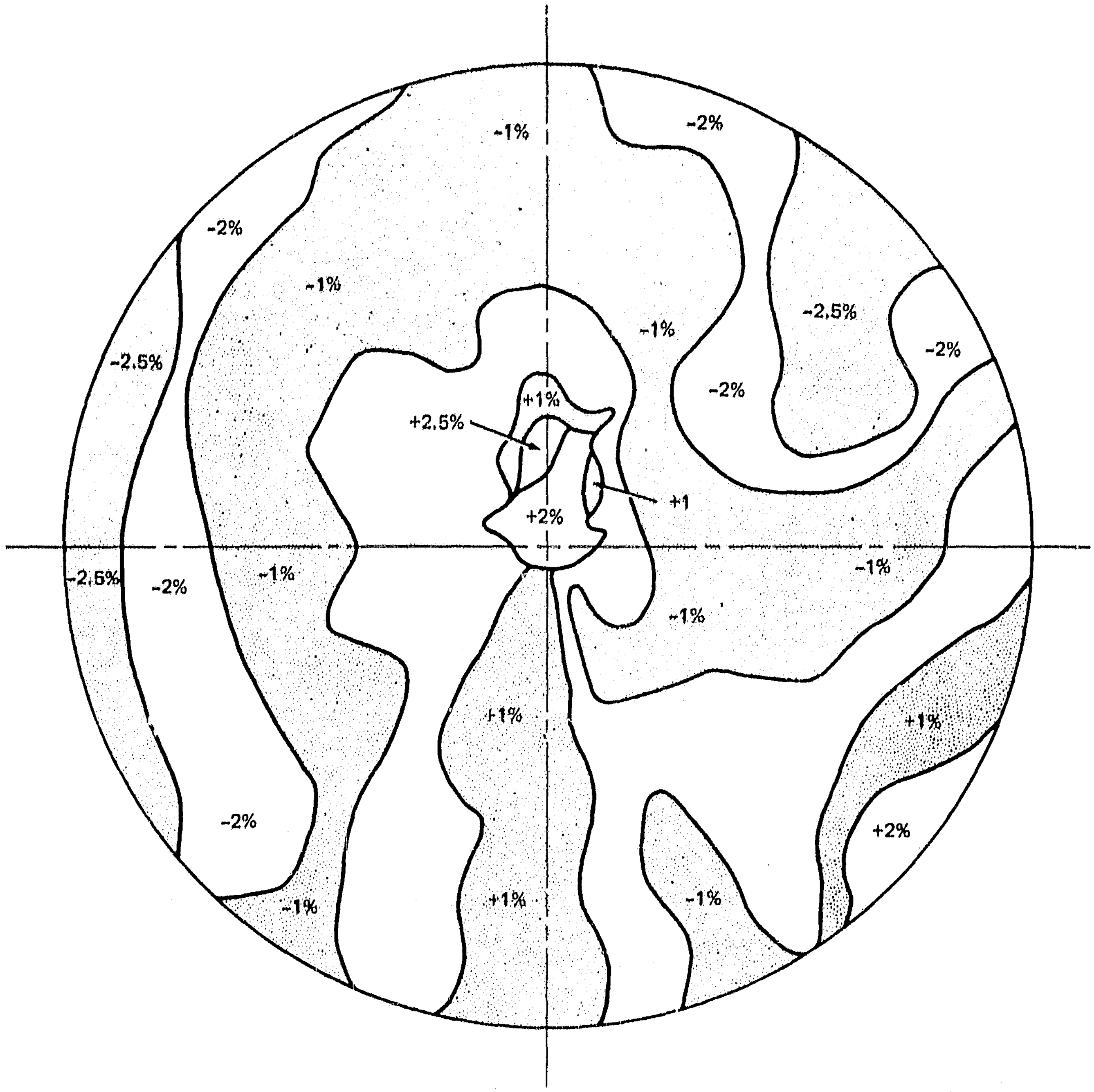


Figure 12. Side View of RAE-A in Test Volume



MEASUREMENTS TAKEN AT THE PLANE OF MAXIMUM UNIFORMITY

Figure 13. Contour Map of Pre-Test Uniformity

For thermal testing the satellite was divided into zones as shown in Figure 14. An accurate knowledge of the total irradiance during the test, in each of the zones on both the main body and solar paddles of the satellite, was required. Reducing this information from planar uniformity scans would have been a time consuming task; hence, the measurments were taken with a Hy Cal pyrheliometer. This pyrheliometer is approximately 1 inch in diameter by 3/4 inch thick and has a wide viewing angle to minimize alignment problems. While taking the measurements the vacuum chamber door was closed so that each zone would be in its

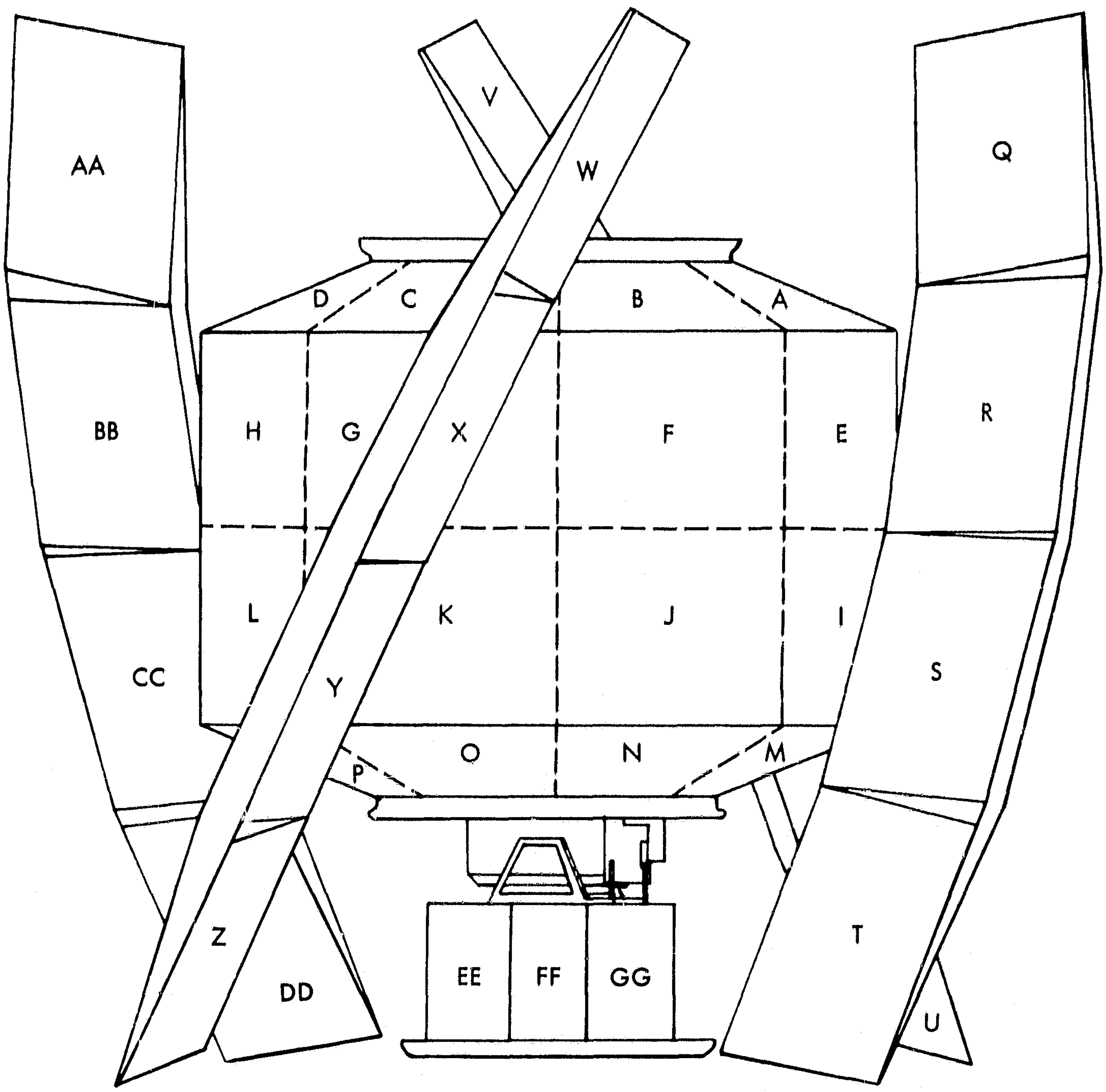
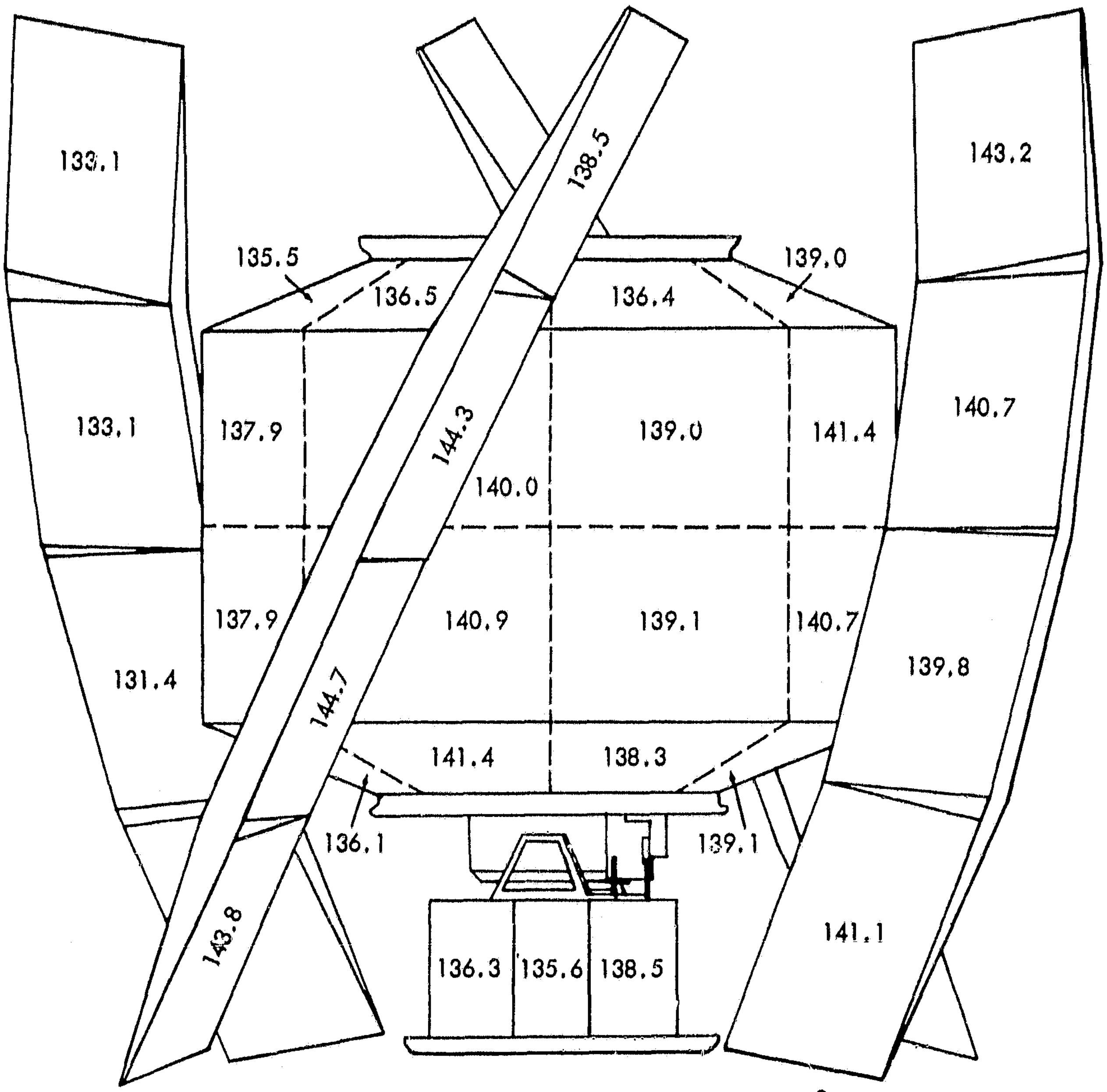


Figure 14. Zones on Spacecraft for Thermal Analysis

respective test location. For each zone the intensity was read in several locations (e.g., each corner and center). These readings were then averaged to obtain one level of irradiance for each zone. In order to determine a mean value of total irradiance in each zone during the test, measurements were taken before and after testing and averaged. The zonal intensity derived by this method for the RAE-A test is shown in Figure 15. The level and uniformity of irradiance across the main body and solar paddles of the spacecraft was 138 mw cm^{-2} ±4.8%.



ALL VALUES ARE TOTAL IRRADIANCE IN MW CM $^{-2}$
UNIFORMITY OF IRRADIANCE +4.8%

Figure 15. Test Intensity in Each Zone

Since the satellite is symmetrical in both test positions only one set of pre- and post-test intensity measurements were required. Accurate measurements of individual lamp power and voltage were taken during all phases of scanning and testing to insure consistency in the level and uniformity of irradiance.

On May 10, 1968, the test was started. After pumping down the vacuum chamber and flooding the cold wall with LN_2, the A1200 was turned on. All but two of the nineteen lamps started without difficulty. After minor power supply adjustments, the last two lamps were ignited. With nineteen lamps in operation, the total system power was adjusted to the level (72.2 kw) set during the pre-test scans.

The first satellite equilibrium required 18 hours of sun and the second required 11 hours. During this 29-hour period the only A1200 anomaly was an unstable power supply at the beginning of the test. This was quickly corrected with an adjustment of the supply gain control before it could affect the satellite equilibrium.

As expected, the system power had to be gradually increased to maintain a constant level of test volume irradiance. This was accomplished by holding the equilibrium temperature of the V groove plate constant with power adjustments to individual lamps. The resulting uniformity change at the plane of maximum uniformity for the pre- to post-test scans was a negligible ±0.3 percent. A graph of total system power vs. time is shown in Figure 16.

All A1200 components functioned well within their temperature limits throughout the test. The maximum temperature attained by several components is shown below:

Component	Maximum Test Temperature °C
Lamp negative seal (average)	152
Converging lens housing	72.5
Indium seal on transition tube	82
Turning flat	37.5
Field lens housing	62.5
Projection lens housing	146
Light source collector (average)	79.5
Internal atmosphere	60.5

CONCLUSION

The RAE-A was launched on July 4, 1968. Temperature data received during both the transfer orbit and circular orbit agree with the predicted temperatures derived from the analytical model within a few degrees C.

With the successful completion of the RAE-A solar simulation test and the excellent correlation between in-flight data and that data obtained in the TVSS, the ability of the A1200 to simulate earth orbital solar irradiance is clearly defined. The scope of the system as a tool for spacecraft thermal design has been significantly increased by the recent modifications. Enlargement of the test beam permits environmental testing of thermal models and satellites

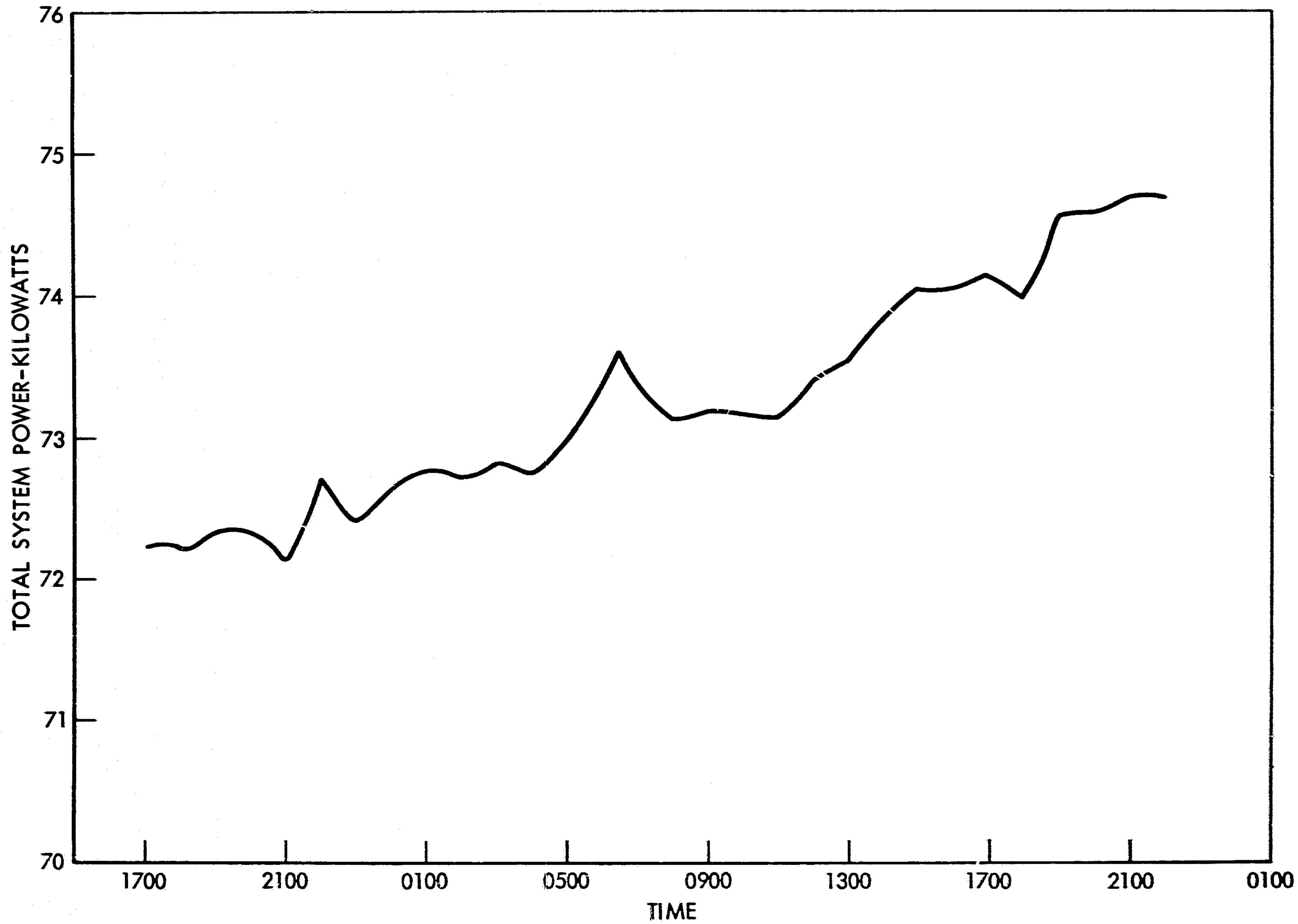


Figure 16. System Power vs Time for RAE-A Test

heretofore rejected because of physical dimensions. In addition, the present uniformity of irradiance for investigating the thermal qualities of planar objects is superior to most systems in the country having a comparable beam cross section.

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