JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 33, No. 6, November–December 1996

NASA/TM-96- 207373 IN-09-TM

Alignment and Initial Operation of an Advanced Solar Simulator

P 4

Donald A. Jaworske,* Kent S. Jefferies,† and Lee S. Mason‡
NASA Lewis Research Center, Cleveland, Ohio 44135

A solar simulator utilizing nine 30-kW xenon arc lamps was built to provide radiant power for testing a solar dynamic space power system in a thermal vacuum environment. The advanced solar simulator achieved the following values specific to the solar dynamic system: 1) a subtense angle of 1 deg; 2) the ability to vary solar simulator intensity up to 1.7 kW/m^2; 3) a beam diameter of 4.8 m; and 4) uniformity of illumination on the order of ±10%. The flexibility of the solar simulator design allows for other potential uses of the facility.

Introduction

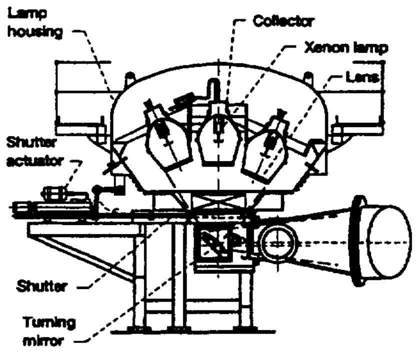
SOLAR dynamic space power systems offer the prospect of generating electric power with an efficiency much greater than existing space power systems. In a solar dynamic system, a concentrator reflects sunlight into the cavity of a heat receiver where much of the energy is absorbed by a working gas that runs a turbine connected to an alternator. Some of the energy entering the heat receiver is stored in a thermal energy storage material to provide energy to the working gas during orbital eclipse. Waste heat from the system is rejected through a radiator. High power conversion efficiency, high energy storage efficiency, the elimination of batteries for storage, and other factors combine to make solar dynamic power systems an attractive alternative to existing space power systems.

To demonstrate the availability of solar dynamic power systems for space, a ground-test demonstration of a complete solar dynamic system is being conducted.[1] A solar simulator was needed to provide the radiant energy for operation in a thermal vacuum environment. Radiant energy from existing solar simulators[2] was too diffuse to be concentrated into the solar dynamic heat receiver; thus, to meet the specific needs of the solar dynamic system, a new solar simulator design was considered.[3,4] Requirements specific to the solar dynamic system test included 1) a subtense angle, i.e., the angular size of the simulated sun as viewed from the solar dynamic concentrator, <1.5 deg; 2) the ability to vary solar simulator intensity at the solar dynamic concentrator up to 1.7 kW/m^2; 3) a beam diameter of 4.8 m at the solar dynamic concentrator; and 4) uniformity of illumination on the order of ±10%. This paper describes the configuration of the solar simulator, the optical alignment procedures, and the performance of the solar simulator.

Description of the Solar Simulator

The solar simulator shown in Fig. 1 consists of nine 30-kW xenon arc lamps, arranged in a 3 × 3 array. Each lamp is surrounded by a nearly elliptical collector and an aspheric quartz lens that work together to perform the two functions of light distribution and focusing. The collector and lens geometries were defined by computer algorithms. Light energy from the intense plasma arc, or fireball, of each lamp is collected over an angular range of 50 to 132 deg. The slope of the collector surface was chosen to distribute light evenly over the surface of the lens. The slopes of the lens surface were chosen to refract light to the secondary focus, located at a turning mirror. Each lamp module has its own turning mirror segment located at the secondary focus. The turning mirror segment redirects light through a planar quartz window and into the vacuum tank. The turning mirror segments have a complex curvature to focus the edges of the beam. When viewed from the vacuum tank, the nine turning mirror segments make up a 30-cm-diam, circular, simulated sun where eight segments are surrounding a centrally located ninth segment. All reflective surfaces are vapor-deposited aluminum with a protective coating of silicon dioxide.

The output of each lamp module is superimposed on the others at the solar dynamic concentrator. The beam pattern is one in which the center beam is surrounded by eight outer beams. Figure 2 shows this, with the spacing of the beams greatly exaggerated. In the actual beam pattern, each beam is equally spaced on a 15-cm-radius circle within a total beam that has a diameter of 4.8 m. This spaced beam pattern smooths out an irregularity at the center of each beam brought about



Solar simulator characteristics	
Beam size	4.8 meter diam at 17.2 meters from apparent sun
Collimation	None - point source
Irradiance	1.7 kW/m^2 max
Uniformity	± 10%
Subtense angle	1.0°

Fig. 1 Schematic diagram of the solar simulator.

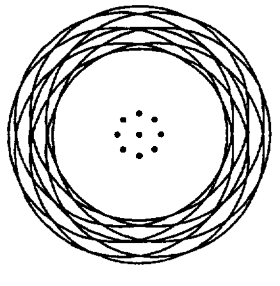


Fig. 2 Pattern of nine beams overlapping at the concentrator (not to scale).

Received Nov. 18, 1995; revision received July 24, 1996; accepted for publication Aug. 16, 1996.

*Physicist, Power Technology Division.

†Distinguished Research Associate, Power Technology Division.

‡Test Engineer, Power Technology Division.

NASA/TM-96- 207306

NIS

IN-09-TM

Alignment and Initial Operation of an Advanced Solar Simulator

D. A. Jaworske, K. S. Jefferies, L. S. Mason

Reprinted from

Journal of Spacecraft and Rockets

Volume 33, Number 6, Pages 867–869

AIAA

A publication of the
American Institute of Aeronautics and Astronautics, Inc.
1801 Alexander Bell Drive, Suite 500
Reston, VA 20191–4344

by a slight swelling of the reflective surface when a flange was welded to the collector neck.

Each lamp is cooled by two water cooling lines that cast two radial shadows in the output beam. The cooling lines are positioned to offset each shadow by 20 deg from adjacent shadows. In the superimposed output, the intensity drops off by about 11% in these shadow regions. One advantage to superimposing the nine beams is that in the event of a lamp failure during a ground test, the concentrator remains uniformly illuminated. There is enough margin in the solar simulator to allow the remaining eight lamps to make up the shortfall.

All nine lamps typically remain illuminated during operation of the facility because turning lamps on and off would drastically reduce their life. Although there are many different orbits, the orbit simulated here is a low Earth orbit where the satellite would be illuminated by about one hour of sunlight followed by one-half hour of eclipse. Simulating eclipse is achieved by moving a water-cooled dousing plate in or out of the beam, just upstream of the turning mirrors. Movement of the plate occurs rapidly in either direction and is complete in less than 2 s.

The beam is directed into the vacuum tank by turning mirrors. These mirrors enable the arc lamps to be mounted with their axes in a near vertical orientation to extend lamp life while the beam inside the tank is in the preferred horizontal orientation. Another advantage of this design is that the angle of the beam converging from an individual lamp module toward its turning mirror equals the angle of the beam leaving the turning mirror and projecting into the tank. Because the angle of convergence is larger with this design than other solar simulator designs, the lamp modules are much closer, enabling a major reduction in the size of the solar simulator.

Downstream of the turning mirrors is a 43-cm-diam planar quartz window that serves as the interface between atmosphere and vacuum. Upon entering the tank, the individual beams continue to diverge until they reach a diameter of 4.8 m at the solar dynamic concentrator, 17.2 m from the simulated sun. Looking back from the concentrator to the 30-cm-diam nine-segment simulated sun, the sun has an angular size of 0.0174 rad or 1 deg. This subtense angle value exceeds the goal of 1.5 deg set at the outset of the solar simulator development and is much better than has been achieved previously. In comparison, the angular size of the sun when viewed from low Earth orbit is 0.53 deg. Note that the system was designed to deliver, nominally, 1.37 kW/m^2 (1 sun) at the concentrator. Enough margin is built into the simulator to exceed this flux value at the concentrator by about 20%. To accommodate future applications requiring greater flux, test articles can be moved closer to the simulated sun and the increased flux can be calculated geometrically. To accommodate other applications requiring less flux, one or more lamps can be purposely extinguished. In applications where the subtense angle, the angular size of the simulated sun as viewed from the concentrator, must be smaller than 1 deg, the apparent size of the sun can be reduced by replacing the turning mirror assembly with a smaller unit or by illuminating only the center turning mirror segment. However, in both cases the available power would be reduced. By using only the center lamp module, a subtense angle of 0.33 deg could be obtained, at a power level reduced by a factor of 9.

The thermal vacuum tank is equipped with liquid-nitrogen-cooled cold walls for simulating the thermal environment of Earth orbit. The vacuum in the tank during operation is typically on the order of 10^{-6} torr, obtained by an array of diffusion pumps backed by roughing pumps. All of the diffusion pumps utilize freon-cooled baffles to prevent backstreaming. A quadrapole mass spectrometer is available to monitor gas composition inside the tank during operation.

Several sensors are located on the solar dynamic concentrator to monitor beam intensity during operation, including 10 photodiodes and a Kendall radiometer. The radiometer was supplied by the Jet Propulsion Laboratory and has a built-in calibration system to ensure less than 1% accuracy error. The photodiodes were calibrated by comparing their output to the output of the radiometer. These sensors are typically used for system monitoring purposes only. However, they can be used in a feedback mode of operation to control lamp output, if needed. To date, maximum radiometer readings corresponding to an average concentrator flux of 1.63 kW/m^2 (1.19 suns) have been recorded during operation of the solar simulator.

Alignment of the Solar Simulator

Alignment of the nine lamps was accomplished through a complex procedure, described here in brief. One alignment and two focusing tasks are needed: 1) aligning each turning mirror to reflect light from the center of the lamp module lens to a target point near the center of the concentrator, 2) aiming each lamp module so that the secondary focus of the lamp module is at the center of its turning-mirror segment, and 3) positioning the fireball of each xenon arc lamp at the primary focus of its lamp module collector.

Each collector-lens combination was installed in its respective location in the 3 × 3 array. A laser placed inside the vacuum tank along the intended centerline of each beam was directed back toward the center of each respective turning mirror. To help with this alignment and to diminish the laser beam diameter prior to reaching the turning mirrors, a cardboard template with nine 2-mm-diam holes was placed adjacent to the quartz window. Laser light impinging on each turning-mirror was reflected to a target temporarily placed in the center of each lamp module lens. The turning-mirror segment was then adjusted to aim the reflected laser light to the center of the target.

Next, a small cotton target was placed at the center of each turning mirror, suspended in place by two cotton threads. Two video cameras located inside the vacuum tank allowed viewing of the turning-mirror segments on monitors. Adjustments were made to each lamp module until the image of the cotton target reflected off the lamp module collector was superimposed on the actual cotton target, as viewed on both video monitors. In this way, the secondary focus of each lamp module was brought to the center of its respective turning mirror.

Much of the radiant energy from a xenon arc lamp emanates from a fireball located adjacent to the cathode.[5] It is this fireball that must be centered at the primary focus of the lamp module. This task was accomplished by viewing each cotton target and superimposed cotton target image from the optical path inside the vacuum tank, again using two video cameras, while making adjustments to the arc lamp position until the image of the cathode tip was centered on the cotton target as viewed on both video monitors. After this adjustment, which positioned the cathode tip at the optimum fireball location, each xenon arc lamp was removed from the lamp module and installed in an alignment fixture equipped with a matching pair of horizontal and vertical micrometers. The cathode position was recorded and then moved axially away from the focus a distance of 3 mm to position the fireball at the primary focus of the lamp module. This final cathode position was also recorded to enable alignment of replacement lamps using only the alignment fixture.

Solar Simulator Beam Survey

As a final measure of documenting beam uniformity and solar simulator output, a beam survey was conducted inside the vacuum tank. The beam survey was designed to measure the radiant flux distribution incrementally, and to sum the incremental flux values over the entire beam area to obtain total radiant power delivered to the solar dynamic concentrator. Total radiant power input compared to total electric power output provided the means to evaluate overall solar dynamic power system efficiency.

The objectives were satisfied by a series of individual lamp tests using a common data collection test stand. Three photodiodes were mounted on a rotating arm that could be extended radially to measure the entire beam diameter. A Kendall radiometer was mounted on the stand to serve as a reference. The test-stand configuration is shown in Fig. 3. As before, the Kendall radiometer used here was supplied from the Jet Propulsion Laboratory and is considered a primary standard for measuring radiant flux. Calibration of each photodiode was accomplished by positioning the photodiode in front of the fixed radiometer prior to each test. The location of the photodiodes allowed measurement of flux at radial positions relative to the beam centerline, from 5 to 175 cm in 10-cm increments. The arm could be rotated to provide angular beam sweeps from 10 to 350 deg.

The test stand was located between the turning mirrors and the concentrator, 11.7 m from the simulated sun. Test results were corrected for the distance from the simulated sun to the concentrator using a $1/r^2$ relationship. The concentrator surface was modeled

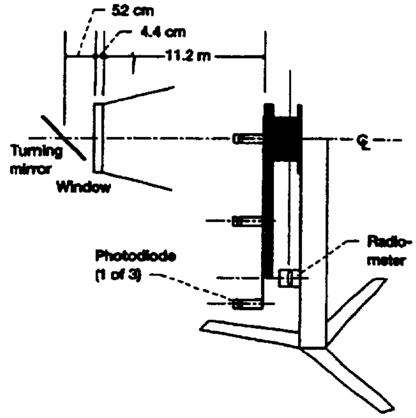


Fig. 3 **Roving photodiode assembly used to conduct the beam survey.**

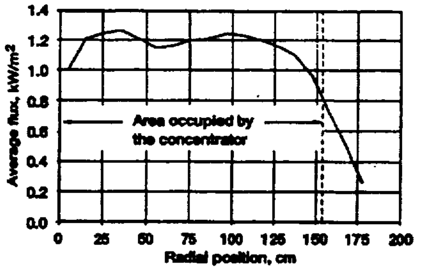


Fig. 4 **Flux variation with radial position, with all nine lamps at 20 kW.**

using a truncated sphere, and the area occupied by this truncated sphere was defined as the optical control surface.

The roving photodiodes provided the means to collect radiant flux data at 18 different radial positions and 67 different angular positions within the 10- to 350-deg rotation of the arm. The data from the photodiodes were processed into an 18 × 67 array of flux data representing the two-dimensional polar target grid. Data for one complete target grid could be acquired in about 14 min, ensuring stable beam operation over the duration of the test.

Each lamp was illuminated individually to understand its contribution to the total beam. All lamps were tested at a power setting of 20 kW. The functional relationship between lamp performance and lamp power was thought to be linear and was confirmed by operating one lamp at multiple power levels. The test results of each lamp were summed to determine the total flux distribution and the total power delivered to the optical control surface.

A spreadsheet program was developed that uses the 18 × 67 flux array for each lamp to determine the total power as a function of the number of lamps operating and the lamp power setting. The spreadsheet program summed the flux contribution from each of the selected lamps into a cumulative flux array and corrected the data for source distance and desired power setting. The average flux was determined for each radial position and then multiplied by the spherical area of the radial segment at the optical control surface to determine incident power. Total delivered power was determined by summing the individual radial power segments. With all nine lamps operating at 20 kW, the total radiant power delivered to the optical control surface was 21.2 kW.

Average flux measured as a function of radial position is shown in Fig. 4 for nine lamps at 20 kW each. Higher flux is evident near the center of the beam where the aim points are located, and the flux is lowest at the outside of the beam. Note that the concentrator is completely included within an angle swept by a 158-cm radial position.

Using the angle swept by a 158-cm radius, the radiant power delivered to this portion of the optical control surface was 19.7 kW. The average area-weighted flux on this portion of the optical control surface was found by dividing 19.7 kW by the spherical area included within this angle. The area-weighted average flux arriving at this portion of the optical control surface was found to be 1.11 kW/m^2. Operation of the nine lamps at their maximum setting of 30 kW should result in an area-weighted average flux of 1.66 kW/m^2, which approaches the 1.7 kW/m^2 goal set at the outset of solar simulator development.

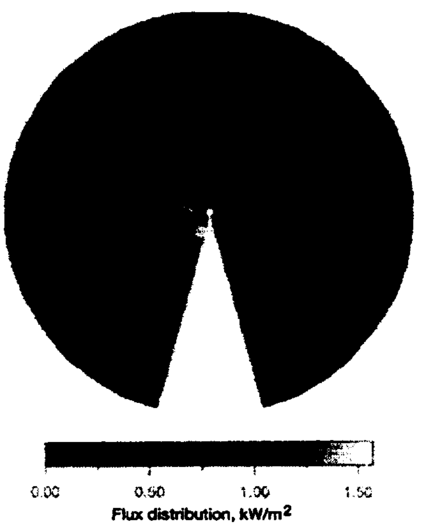


Fig. 5 **Flux distribution on the optical control surface located at the concentrator.**

Figure 5 shows the flux distribution on the optical control surface in detail, again for nine lamps operating at 20 kW each. Figure 5 confirms that the location and alignment of the nine individual beams provided adequate smoothing of the flux to diminish cool spots brought about by the irregularity at the center of each beam and the cooling-tube shadows. Statistical analysis of the normalized data (flux measured at each point divided by the average measured flux) indicated a standard deviation of 0.17 kW/m^2.

To date, the solar simulator has powered the solar dynamic system for over 400 h, with over 100 simulated orbital cycles. Useful lamp life, as predicted by the lamp manufacturer, is on the order of 400–600 h, depending on the number of start-stop cycles.

Conclusions

A solar simulator utilizing nine 30-kW lamps has successfully powered a fully integrated solar dynamic space power system in a thermal vacuum ground-test facility for over 400 h of operation. Optical characteristics of the solar simulator include 1) a subtense angle of 1 deg; 2) the ability to vary solar simulator intensity at the solar dynamic concentrator up to 1.7 kW/m^2; 3) a beam diameter of 4.8 m, large enough to illuminate a solar dynamic concentrator; and 4) uniformity of illumination on the order of ±10%. The nine-lamp design utilizes a collector-lens combination that collects radiant energy from the fireball of each arc lamp. Nine turning mirrors are used to direct the energy into the vacuum tank and to superimpose them on the solar dynamic concentrator. The use of collectors, lenses, and turning mirrors enables this solar simulator to provide a combination of small subtense angle and high efficiency in a compact design. Alignment procedures for the solar simulator are outlined and performance is summarized. Beam survey results show the magnitude and uniformity of illumination produced by the solar simulator. The flexibility that this solar simulator provides in delivering radiant energy to a test article should make this facility useful for testing the performance of a wide variety of space power systems under various operating conditions.

References

[1] Shaltens, R. K., and Boyle, R. V., "Initial Results from the Solar Dynamic Ground Test Demonstration Project at NASA Lewis," NASA TM-107004, July 1995.

[2] Tolbert, C. M., "Selection of Solar Simulator for Solar Dynamic Ground Test," NASA TM-106608, Aug. 1994.

[3] Jefferies, K. S., "Compact Solar Simulator with a Small Subtense Angle and Controlled Magnification Optics," patent pending.

[4] Jefferies, K. S., "Solar Simulator for Solar Dynamic Space Power System Testing," NASA TM-106393, March 1994.

[5] Lienhard, O. E., "Xenon Compact Arc Lamps with Liquid Cooled Electrodes," Illuminating Engineering Society, National Technical Conf., Miami, FL, Aug. 1964.

I. E. Vas
Associate Editor