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Solar Simulator for Solar Dynamic Space Power System Testing

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SOLAR SIMULATOR FOR SOLAR DYNAMIC SPACE POWER SYSTEM TESTING

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ABSTRACT

Planned vacuum tank testing of a solar dynamic space power system requires a solar simulator. Several solar simulators were previously built and used for vacuum tank testing of various space systems. However, the apparent solar subtense angle, i.e., the angular size of the apparent sun as viewed from the experiment, of these solar simulators is too large to enable testing of solar dynamic systems. A new design was developed to satisfy the requirements of the solar dynamic testing. This design provides $1.8 \, kW/m^2$ onto a 4.5 M diameter test area from a source that subtends only $1°$, full cone angle. Key features that enable this improved performance are: (1) elimination of the collimating mirror commonly used in solar simulators to transform the diverging beam into a parallel beam, (2) a redesigned lamp module that has increased efficiency, and (3) the use of a segmented reflective surface to combine beams from several individual lamp modules at the pseudosun. Each segment of this reflective surface has complex curvature to control the distribution of light. By developing a new solar simulator design for testing of the solar dynamic system instead of modifying current designs, the initial cost was cut in half, the efficiency was increased by 50 percent reducing the operating costs by one-third, and the volume occupied by the solar simulator was reduced by a factor of 10.

INTRODUCTION

Planned ground testing of a solar dynamic space power system (Shaltens and Boyle, 1993) requires duplication of the high vacuum, low sink temperature, and intense solar flux that are present in space. The high vacuum will be provided by a large vacuum tank at NASA Lewis Research Center; the low sink temperature will be provided by nitrogen cooled cold walls; and the intense solar flux will be provided by the solar simulator described in this paper. A solar simulator is required for this vacuum tank testing because natural sunlight cannot be brought into the vacuum, the solar flux in space is more intense than sunlight that has been attenuated by the Earth's atmosphere, and to enable solar dynamic testing, the light source must subtend less than three times the $0.5°$ angle subtended by the Sun's diameter.

Several solar simulators were built previously and used for vacuum tank testing of various space systems. One of the first of these solar simulators which served as a pattern for others is the Jet Propulsion Laboratory (JPL) facility described by Bartera et al. (1970). The large space simulator at ESA/ESTEC, described by Brinkmann (1984), is similar to the JPL design. The initial conceptual design for our solar simulator was based on these classical solar simulator designs. Three major modifications resulted in the smaller, less expensive, advanced solar simulator, shown in Fig. 1, that was designed specifically to satisfy the flux and subtense angle requirements of the solar dynamic testing.

The three major modifications in this new design are: (1) elimination of the collimating mirror, (2) a redesigned lamp module, and (3) the use of a segmented reflective surface at the pseudosun. Each segment has complex curvature to control the distribution of light.

REQUIREMENTS

The requirements for the solar simulator are based on the requirements for solar dynamic (SD) system testing. The solar simulator must illuminate the concentrator so that it can focus the light to the receiver aperture to power the SD system. To properly test the SD system, the simulator must be capable of providing at least as much power as will be provided by the Sun in low Earth orbit. To enable focussing into the SD receiver aperture, the angular size of the pseudosun must be comparable to the Sun. Matching the angular size and the power of the Sun is extremely difficult. Existing solar simulators have pseudosun diameters that typically subtend more than $4°$. This is about eight times the $0.5°$ angle subtended by the Sun's diameter as viewed from Earth. Meaningful testing of the solar dynamic system requires that the pseudosun diameter subtend less than $1.5°$, three times the angle subtended by the Sun. The spectral distribution is not important for SD testing, except that any spectral bands that are not reflected by the concentrator and absorbed within

Figure 1.—Advanced solar simulator.
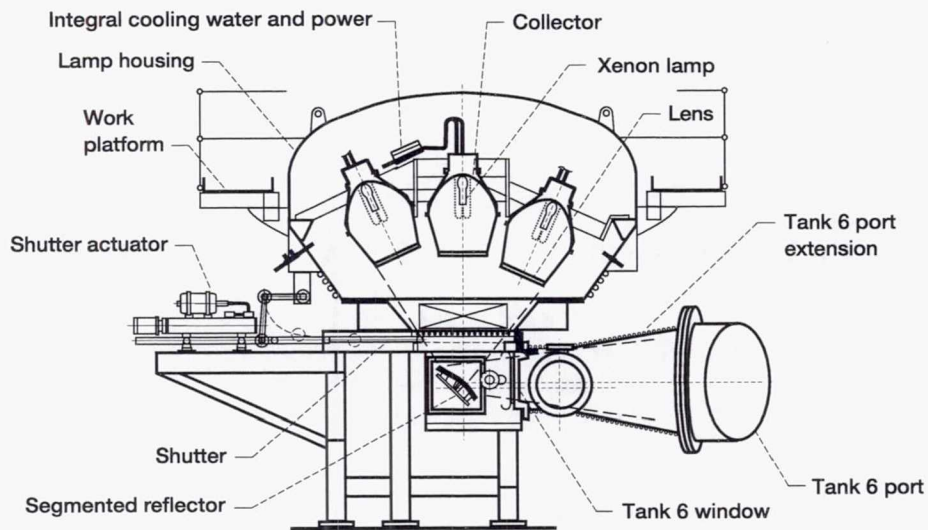
Solar simulator characteristics	
Beam size	188.5-in. diam at 56-1/2 ft from apparent sun
Collimation	None - point source
Irradiance	1.8 kW/m^2 (1.27 sun) max
Uniformity	±10%
Subtense angle	About 1 deg

Labels in Figure 1: Integral cooling water and power, Collector, Lamp housing, Xenon lamp, Work platform, Lens, Shutter actuator, Tank 6 port extension, Shutter, Tank 6 port, Segmented reflector, Tank 6 window

Figure 2.—Solar simulator shines diverging beam on concentrator.

Labels in Figure 2: Concentrator, Radiators, Solar simulator, Receiver, Liquid utilities pallet, Turbomachinery, recuperator, and cooler, Power conditioning and control unit, Parasitic load radiator

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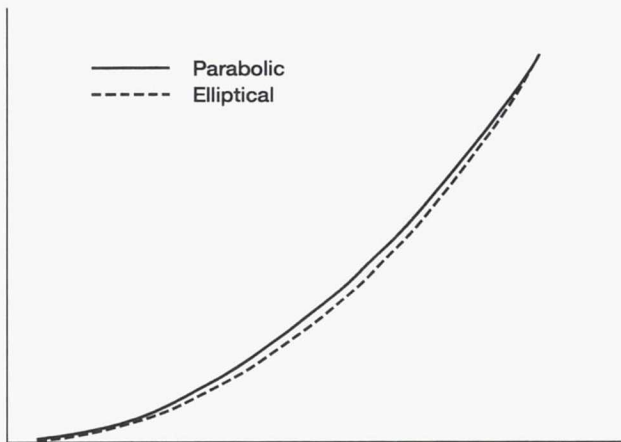
Figure 3.—Concentrator design change (parabolic to elliptical).

Figure 4.—Lamp module.

the receiver would be wasted. Hence, the unfiltered spectral distribution coming from xenon arc lamps would be adequate for SD testing. Uniformity of illumination on the SD concentrator is important, because the SD receiver is sensitive to flux maldistribution. However, it was determined that ±10 percent nonuniformity on the SD concentrator would be acceptable, although classical solar simulators had achieved uniformity better than ±5 percent. In summary, full AM0 solar intensity is required, the diameter of the pseudosun must subtend less than 1.5° which is much smaller than the subtense angle in existing simulators, spectral distribution can be ignored, and light distribution can be less uniform than existing simulators.

ELIMINATION OF COLLIMATING MIRROR

Most solar simulators use a collimating mirror to provide a parallel beam. A major breakthrough in designing the solar simulator for this test was the realization that portions of the beam illuminating different parts of the concentrator are not required to be parallel to each other. In fact, a diverging beam originating at a small port in the vacuum tank as shown in Fig. 2 can be focussed into the SD receiver aperture. Eliminating the collimating mirror changed the design of the SD concentrator slightly, from a parabolic contour to an elliptical contour. The small difference between an elliptical contour and a parabolic contour is shown in Fig. 3. There was no increase in SD concentrator cost, because the decision to not collimate the beam was made before the SD concentrator was designed.

There are major advantages resulting from eliminating the collimating mirror. With a collimating mirror the available tank volume is limited because a clear area is required for the parallel beam between the collimating mirror and the solar dynamic concentrator. Collimating mirrors are major cost items in solar simulators. For example, the JPL simulator has a one-piece collimating mirror which costs about as much as the rest of JPL's solar simulator. The collimator mirror surface inaccuracies add to other errors in the optical system and would have been a major concern in SD testing. Elimination of the collimating mirror resulted in a major savings in cost and space within the vacuum tank and removed a major source of inaccuracy in the beam.
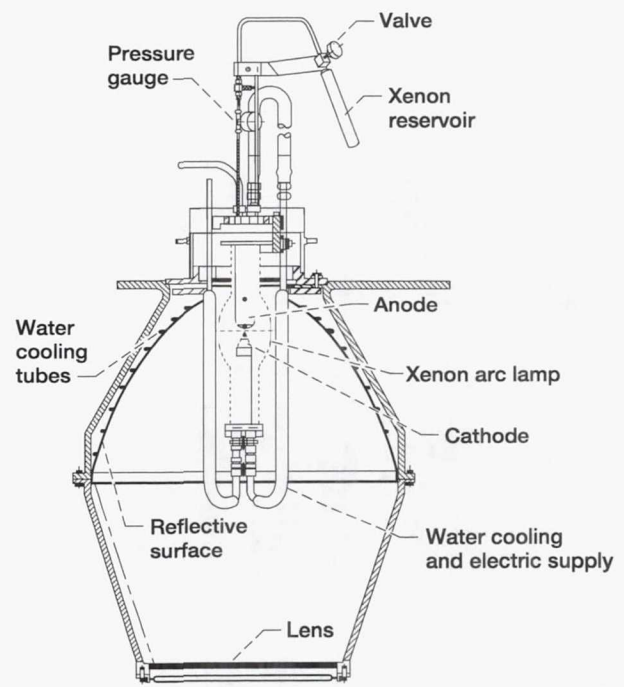
REDESIGNED LAMP MODULE

The arc lamp module consists of a xenon arc lamp, a reflector, and a lens. The arc lamp reflector is approximately an ellipse both in this simulator and in classical simulators. However, the major axis length was reduced by a factor of about 5 (from about 10 m to about 2 m) and the concentration ratio was drastically reduced from corresponding dimensions of classical solar simulators. The geometric concentration ratio of this solar simulator is about 70. This is the ratio of the area of the turning mirror segment at the second focus to the area of the fireball at the focus. The geometric concentration ratio increases approximately as the square of the major axis length and is typically in the thousands for classical solar simulators. The lens (which is not included in classical solar simulators) is between the reflector and the turning mirror segment. In the unlikely event of a lamp explosion, this lens would shield the turning mirror and the other lamp modules. The lamp module is shown in Fig. 4.

SEGMENTED REFLECTIVE PSEUDOSUN

A reflective surface segment at the focus of each of the lamp modules redirects illumination to the solar dynamic concentrator. The nine reflectors are arranged in a circle to form the pseudosun as shown in Fig. 5. Advantages of this design feature are better cooling, a much smaller lamp house and the capability to redirect the beams. Each reflector segment has a complex curvature to control the distribution of light. Direct water cooling of the reflective surface is possible and much simpler than the cooling systems required for mixing lenses at the focus of classical solar simulators. In these simulators two arrays of quartz lenses as shown in Fig. 6 perform optical mixing to produce uniform light distribution. This elaborate device with gold plated copper structure for cooling the lenses is
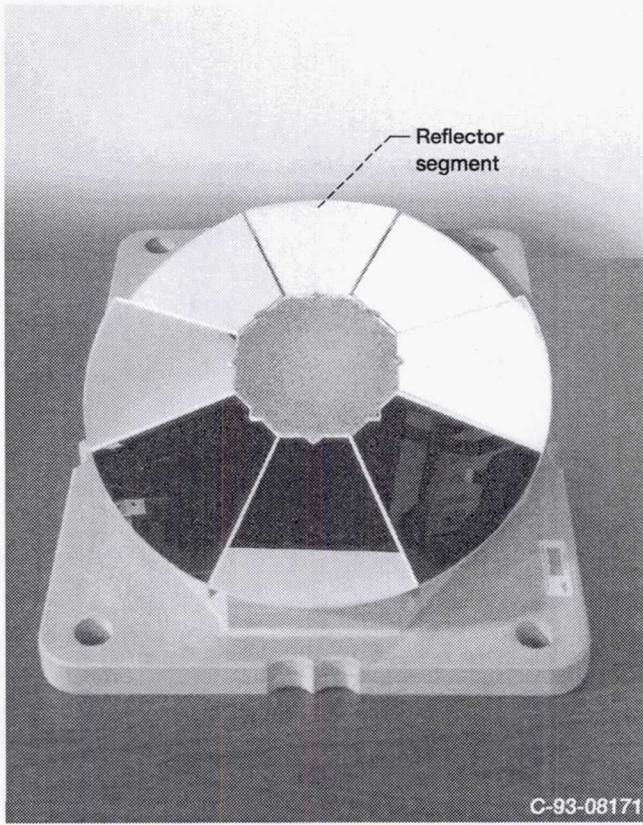
Figure 5.—Nine reflector segments at pseudo sun.

replaced in the new design by nine reflector segments with complex curvature. The smaller lamp house is possible because the projection angle from the pseudosun to the test area is the same as the angle looking back from the pseudosun to the lamp modules. With this approach, each module is independent. The distance back to encompass a single module is less than would be required to encompass the entire array of lamp modules. This reduces the length and thus the volume of the lamp house by a factor of 3. The capability to redirect the beams is important because it enables the arc lamps to be mounted nearly vertically (thereby prolonging their useful life) and the beam to shine horizontally along the axis of the vacuum tank.

SCALED OPTICAL TESTING

Analytically, it was determined that there could be major benefits from the revised optical design. However, the results appeared to be too good to be true. In particular, the analysis predicted that more power could be collected from each arc lamp with the revised optical design. Also there were doubts about the capability to control and predict the flux distribution at the test plane. It was therefore decided to test the concept using a 1-kW scaled system before committing to use this approach for the full-scale solar simulator.

The experimental test of the 1-kW system was done under a grant with the Advanced Manufacturing Center at Cleveland State University which was technically directed by Kent Jefferies of NASA Lewis. This test compared a classical optical system to the advanced system. The two systems used the same arc lamp and were designed to the same geometric constraints. A lens was used instead of the turning mirror segment, but it had the same optical characteristics as the complex curvature reflector. The classical system for this test did not include an optical mixer for producing uniform illumination.
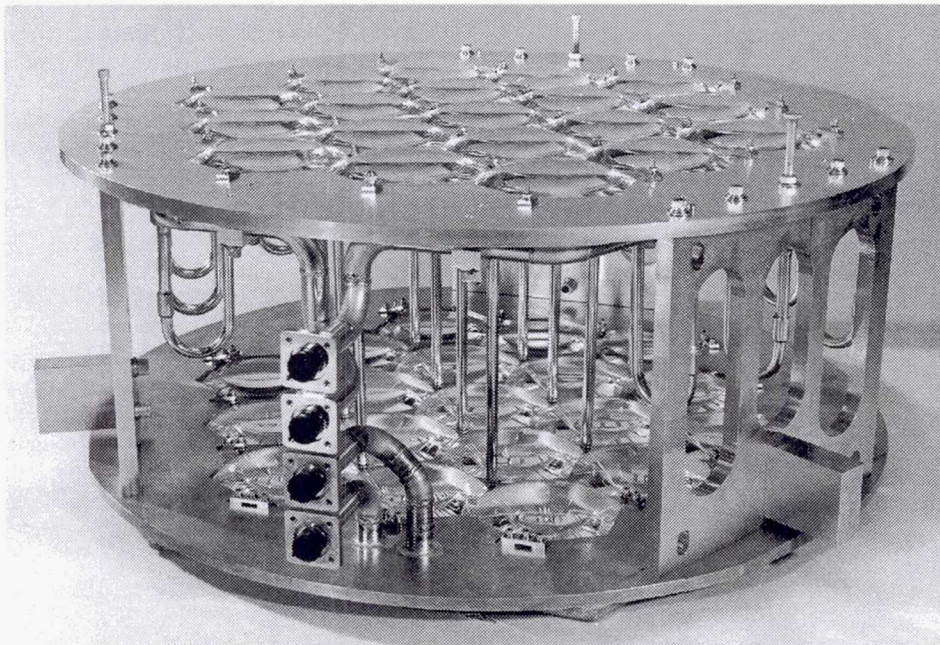

Figure 6.—Mixer lens array for classical simulator.

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Depending on interpretation, the uniformity measurements at the test plane were the "worst case" or "best case" extreme of what had been predicted. The variation of flux intensity for the advanced optical system very closely matched the intensity that had been calculated by ignoring expected spillage. There was very little smoothing of this flux due to spillage of light to surrounding portions of the test area or to a central unilluminated area. Thus the flux distribution was the worst extreme of maldistribution that had been predicted, but because of the lack of spillage, the flux distribution could be easily predicted. This is the best case for designing for uniform distribution, because the design can be done directly without compensating for expected spillage. Results of the test compared
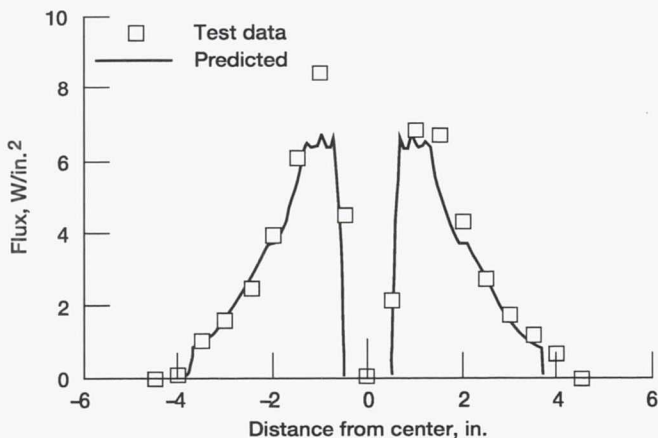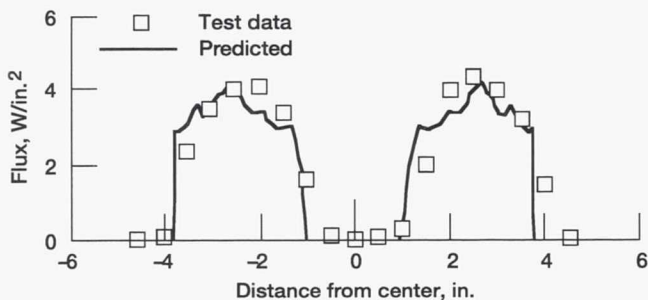
to analytical predictions are shown in Fig. 7 for the classical system and in Fig. 8 for the advanced system.
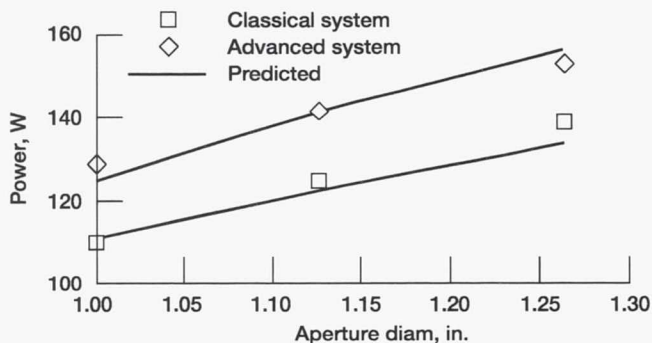
The analytical predictions for efficiency indicated that 9 lamps were required in the advanced design for the full-scale simulator compared to 19 lamps that were planned for the classical design. Expectations for the experimental test were that the efficiency measured by the amount of light from each arc lamp would therefore be twice as much with the new design. Actually, the 9 to 19 lamp difference was due to a number of factors including a decrease in surplus capacity and elimination of optical losses in the classical optical mixer. Analytical predictions indicated only a 10-percent increase in efficiency for the advanced system compared to the classical system without an optical mixer. These analytical predictions were confirmed by the experimental data as shown in Fig. 9.

COST, VOLUME, AND EFFICIENCY

By developing a new solar simulator design for testing of the solar dynamic system instead of modifying current designs, the initial cost was cut in half, the volume occupied by the solar simulator was reduced by a factor of 10, and the efficiency was increased by 50-percent thus reducing operating costs by one third. These benefits are the result of eliminating the large, expensive collimating mirror and eliminating its reflection loss, eliminating the expensive mixing lens array and its transmission and blockage losses, reducing the number of lamp modules, reducing the length of the lamp house, and increasing lamp module efficiency.

POSSIBILITY OF MATCHING SUN

It is possible to exceed the power per unit area within the angle subtended by the Sun using xenon arc lamps. A new xenon arc lamp operating at 30 kWe produces about 15 kW of total radiated power. This power is distributed over a solid angle of about 3π steradians. At a distance of about 1 m from the arc, the intensity is about 1.6 kW/m^2 which is greater than the 1.37 kW/m^2 of natural sunlight in space. The spacing of the arc lamp electrodes is 12 mm and most of the power is within one-half of this diameter. A 6-mm diameter circle at a distance of 1 m subtends 6 mrad which is a smaller angle than the 9.29 mrad subtended by the Sun. Thus a new lamp operating at full power, without any optics, exceeds the goal of matching the flux and subtense angle of the Sun.

In designing a solar simulator, it is not enough to match the flux and subtense angle of the Sun. Efficiency is also important. The brute force approach would require an arc power of 12 MW to achieve an intensity of 1.6 kW/m^2 at the 20-m distance of the solar dynamic test.

The optics presented herein are a major step forward in reducing solar subtense angle by a factor of about 4 and improving efficiency compared to classical simulators. This technology is approaching the goal, which was once thought impossible (Polak and Palmer, 1968), of enabling the 9.29-mrad solar subtense angle to be achieved with a 1.37-kW/m^2 intensity thus matching the Sun. If the efficiency of the actual system is on the high side of our current estimates, it would be possible using new lamps operating at full power to achieve this goal by reducing the turning mirror to one-half of its current diameter. Proportionately smaller reflective segments with complex curvature would be required. This is not desirable for the planned testing because the solar dynamic system has been designed to accommodate the 1° subtense angle solar simulator.

Figure 7.—Flux at test plane (classical without mixer).

Figure 8.—Flux at test plane (advanced system).

Figure 9.—Power collected from arc lamp.

CONCLUSIONS

A solar simulator was designed for vacuum tank testing of a solar dynamic space power system. This design differs from classical simulators in the optical design of the lamp module, the elimination of the collimating mirror, and the use of a turning mirror with reflective segments of complex curvature instead of a mixing lens array at the pseudosun.

Elimination of the collimating mirror was accomplished by changing the solar dynamic concentrator optics to accept a diverging light beam.

The pseudosun is composed of nine reflective segments that are water cooled. This enables a reduction in length of the lamp house and provides much better cooling than classical simulators that have lenses at the pseudosun. The reflective segments have a complex curvature which controls the distribution of light.

Experimental testing of the advanced optical system demonstrated the capability to analytically predict and control light intensity distribution. The testing also demonstrated an analytically predicted optical efficiency improvement in a scaled unit.

This solar simulator design has lower initial cost, reduced operating costs, requires less space, and has increased efficiency compared to classical simulators. It has the potential to approach the goal of matching both the subtense angle and the intensity of the Sun.

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