

Solar Simulators at the Jet Propulsion Laboratory

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The large JPL solar simulation systems are unique in their ability to furnish well collimated light over large areas with good uniformity and high efficiency/intensity. These systems furnish simulated solar irradiance to 10-ft (3-m) and 25-ft (7.6-m) space simulation chambers. The discussion is divided into two parts. In the first part (Sec. II) the existing facilities are described and some potential improvements discussed. In the second part (Sec. III) some results of a high-intensity lamp development program are presented.

I. Introduction

Some background information on the JPL solar simulation systems appears elsewhere in this journal in the article by Johnston and Powell. These large solar simulation systems are unique in their ability to furnish highly collimated light over large areas with good uniformity and high efficiency. They furnish simulated solar irradiance to the JPL 10-ft (3-m) and 25-ft (7.6-m) space simulation chambers. The smaller chamber has a single piece, 3-m spherical, collimating mirror and is capable of a 2.4-m simulated solar beam, while the larger chamber has a 7-m diam mirror and is capable of a 6.1-m solar beam.

II. Existing Facilities

The 7.6-m space simulator is shown schematically in Fig. 1. The optical arrangement for the 3-m simulator is similar. A simple ray trace of the arrangement is shown in Fig. 2. Light is generated by an array of compact arc lamps, each mounted with the arc at the focus of an ellipsoidal collecting reflector. The reflector directs the energy to the multiple lens unit, at the center of which is located the second focus of each collector. The lens unit is located at the focus of the spherical collimating mirror and condenses the light and projects it to the collimator. This multiple lens unit, or *mixer*, is the heart of the system and consists of two sets of nineteen hexagonal lenses, one of which is shown in Fig. 3. The nineteen light channels are superimposed in the test volume, thereby producing highly uniform illumination from an inherently nonuniform input. Details of this optical arrangement are discussed in Ref. 1.

Beam size can be varied by adjusting the spacing

between the mixer lens arrays or by substituting complete mixer units. Also, improved lamps can be substituted to enhance system performance since the light from each lamp fills the entire test volume. Beam intensity can be varied by changing the power to the lamps, by changing the number of lamps operating, or by *stopping* the system at the mixer. Collimation can be controlled by varying mixer diameter or by stopping the system at the mixer. Beam cross sec-

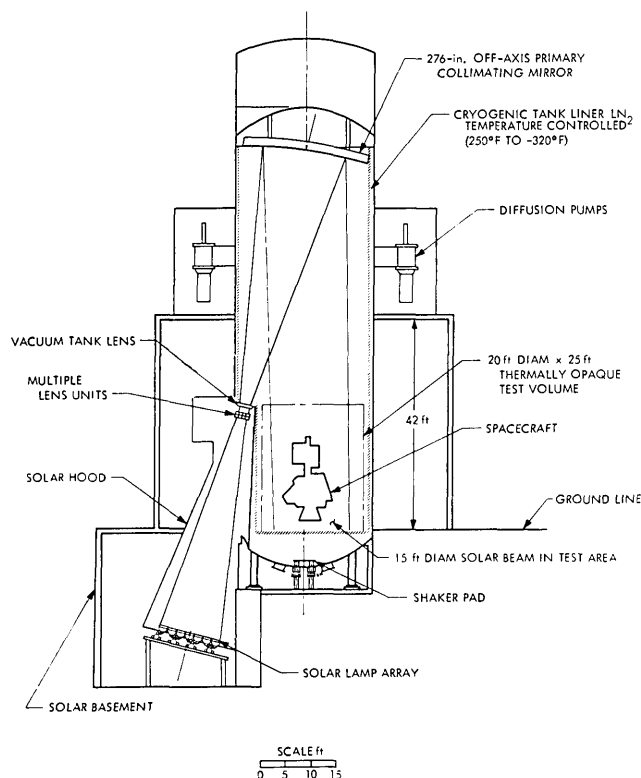


Fig. 1. The 7.6-m space simulation chamber.

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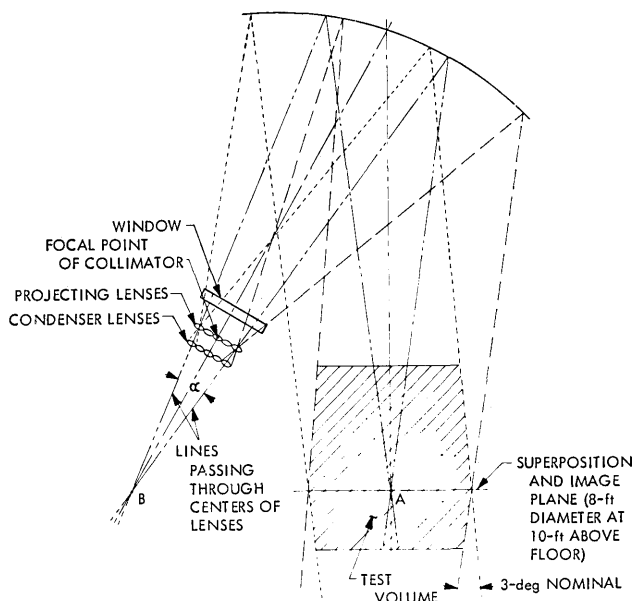


Fig. 2. Optical schematic of JPL solar simulation systems.

tion shape can be controlled by masking the lenses in the first array of the mixer, and spectrum control can be obtained by mixing light sources or by filtering. Therefore, rather broad flexibility results from this arrangement.

A. Performance

Present operations are at a 1-deg collimation angle (maximum angle of any light ray with reference to the beam centerline) with intensity set to simulate earth distance from the sun. Collimation angle can be decreased to 0.6 deg at this intensity. At the present time, approximately 10% of the electrical energy put into the light source provides useful energy in the test volume. Uniformity of light in both the large and small simulation chambers is within $\pm 5\%$ in the test volume. Presently installed in the small chamber is a 2.4-m earth intensity solar beam which is powered by twenty-five 5-kW xenon lamps. An available alternate is a 2-m diam Venus intensity mode which was used in test-

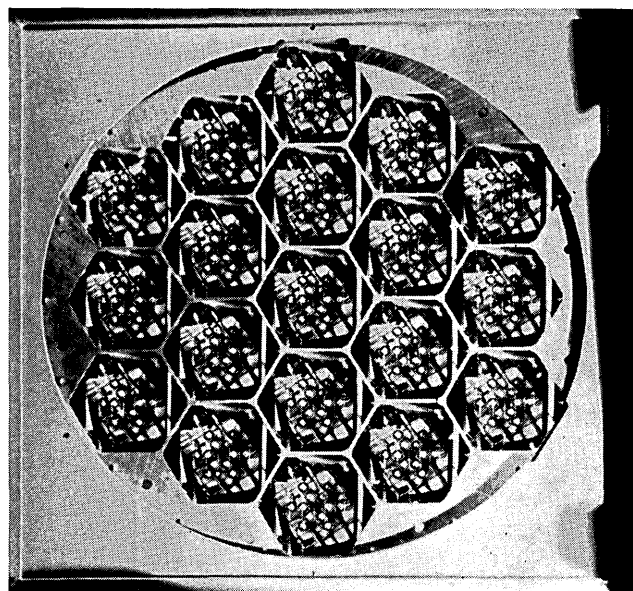


Fig. 3. Projection lens array—3-m space simulation chamber.

ing the Mariner Venus 1967 spacecraft. Installed in the large chamber is a 4.6-m beam with power furnished by thirty-seven 20-kW xenon lamps. If all thirty-seven lamps were operated at full power (20 kW), the test volume intensity would be higher than that required for Venus distance from the sun. These solar beams have much improved characteristics over the original 1% efficient system with ± 5 -deg collimated light initially provided for the 7.6-m space simulation chamber. It was an effort to improve that system in 1962 that led to the development of the present JPL systems.

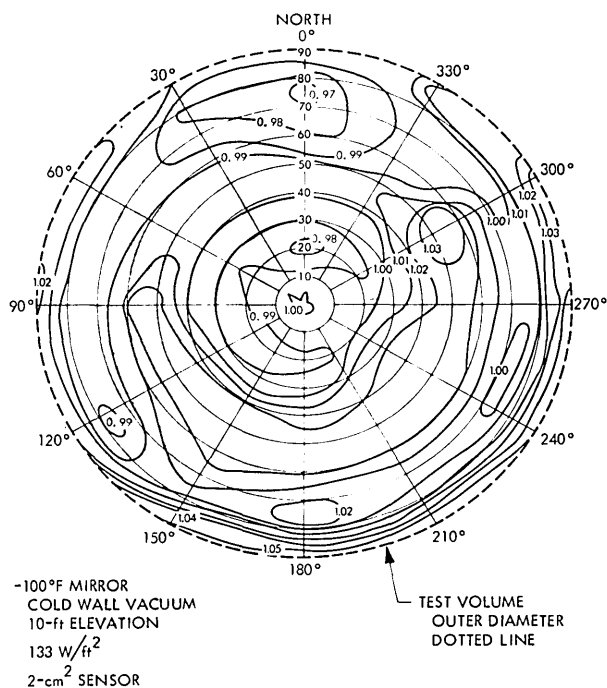
Figure 1 shows the 7.6-m space simulator and the orientation of the solar simulation beam in the chamber. By adding twenty-four collecting reflectors and lamps to the present solar lamp array and reworking the mixer lenses (multiple lens unit in Fig. 1), the system is capable of Venus intensity in a 6.1-m diam beam. Versatility of the system in beam size and intensity is illustrated in Table I.

Table I. Solar Performance of the JPL 25-ft Space Simulator, Uniformity at $\pm 5\%$. Intensity in W/m^2

Parameters		Units						
Beam diameter, m		4.6	2.5	6.1	6.1	2.5	1.6	2
No. of lamps		37	7	37	61	37	37	61
Collimation $\frac{1}{2}$ angle, deg		1	1	1	1	2	3	3
Maximum ^a intensity obtainable with lamp power at:	20 kW	3300 ^b	2300 ^b	2650	3150	19,000	—	—
	24 kW	3950 ^b	2770 ^b	2230	3750	15,800	—	—
	30 kW	4900	3950	3950	5250	19,500	41,400	41,400

^a Operational intensity is 75% of maximum.

^b Presently available.



Like the 7.6-m space simulator, the 3-m space simulator is also capable of high intensities. With a new mixer unit, this simulator is capable of Mercury intensity in a 1.1-m diam solar beam. If the present 5-kW solar lamp array were replaced with nineteen 20-kW lamps in a larger reflector, the system would be capable of Mercury intensity in a 2-m diam beam. If the lamps were to be run up to 30 kW (instead of 20 kW), a 2.4-m light beam would be available.

Probably the most important single requirement in solar simulation at the present time is the achievement of uniform irradiance in the test volume. We have had excellent success in this regard as the data in Fig. 4 will attest. Design requirements for this system were $\pm 5\%$ uniformity. One can see that $\pm 4\%$ over the 4.6-m diam has been achieved.

B. Theory and Components

The optics required for solar simulation in these systems are illustrated in Fig. 2. The condensing and projecting lens arrays make up the multiple lens unit which superimposes images sufficiently to accept grossly nonuniform entering light and, by the process of superposition, decreases nonuniformities to acceptable values in the test volume. Condenser and projector lens arrays of nineteen elements each have proven sufficient to meet present uniformity requirements.

The principle of operation of the solar simulation optical system is as follows (see Ref. 1). The condensing lens unit (nineteen lenses) images the lamp bank on the entrance plane of each projecting lens. The projecting lenses are figured so that they will, in combination with the vacuum seal window and spherical col-

limating mirror, superimpose images of the entrance planes of the condenser lenses on some arbitrary plane in the test volume.

The energy of the light is focused on the mixer by elliptical reflectors nested as closely together as possible to concentrate the light energy. Figure 5 shows the array of 20-kW lamps and reflectors in the 7.5-m space simulator solar system. No attempt is made to flatten or distort the arc image at the second focus of the collector.

C. Fabrication and Construction

One of the most difficult problems in large solar simulation systems is that of collimating the light. In our system this is accomplished by using large one-piece spherical mirrors. Focal length was chosen as long as practical to minimize spherical distortion. The system was finally slightly defocused (mirror moved down relative to the integrating lenses, see Ref. 2) in order to further improve uniformity.

The 7-m diam mirror was fabricated by welding, annealing, machining, grinding, electroplating, fine grinding, polishing, and coating (see Ref. 3). Figure 6 shows the large collimating mirror (7-m diam) being hoisted into place in the 7.6-m space simulation chamber. The 3-m diam mirror was fabricated by a similar process except that it was of cast material and the plating was of electroless nickel.

The possibility of fabricating the mirror of smaller sections was considered but discarded in view of the difficulties in alignment. This is especially critical in systems with small collimation angle requirements. Since our systems have good collimation and were designed for considerable improvement in this parameter if it should become necessary, a single piece collimating mirror was selected.

The collimating mirrors are required to be heated (93°C) and cooled (-73°C). The mirror is heated in a vacuum to clean it. This process minimizes degradation of the delicate aluminized surfaces with time, and the magnitude of the increase in reflectivity achieved by a bake out has often been surprising. With a spacecraft in place, the collimating mirror is required to run at -73°C . Since the value of the surface emissivity, with the contaminants acquired during a test, is not precisely known, the mirror is run cold to prevent a

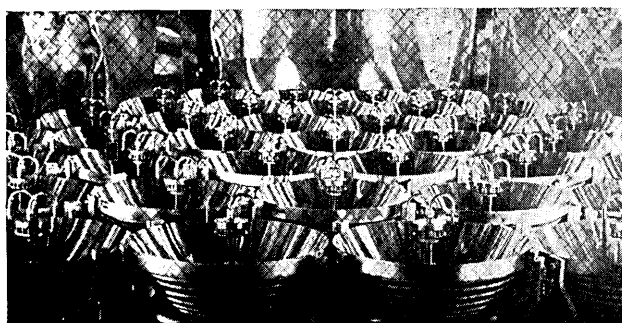


Fig. 5. Lamp array in the JPL 7.6-m space simulation chamber.

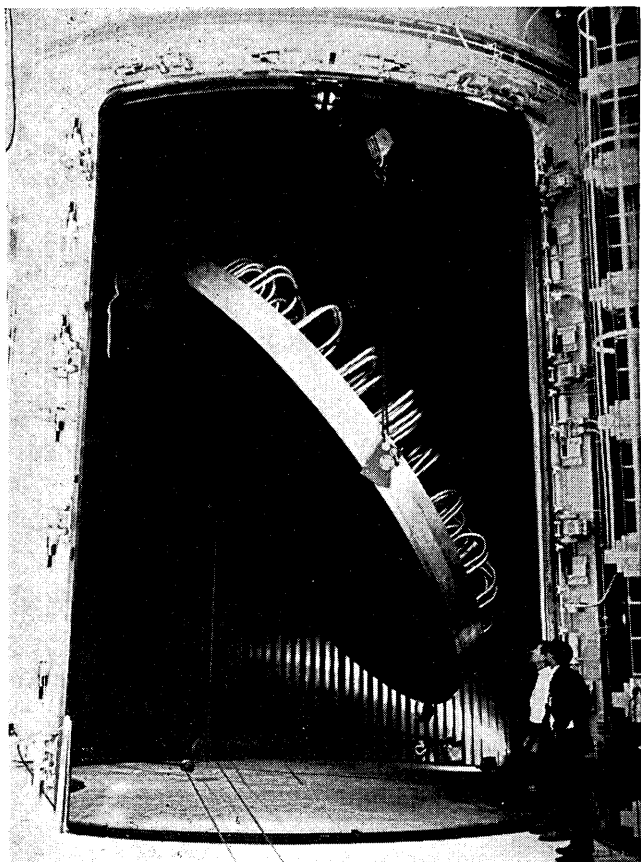


Fig. 6. 7-m diam collimating mirror for the 7.6-m space simulation chamber.

possible influence on the thermal balance of the spacecraft.

The first integrator condensing lens support was machined from Invar and was satisfactory for a 2-m solar beam at earth intensities. It failed, however, when tested for Venus intensity in the same size beam, so an alternate method was chosen. Lenses were then made thick enough to be banded together around the outside and be self-supporting (see Fig. 7). This method has the advantage of having no supporting structure exposed to the high-energy flux except around the outside (which is easy to cool). Also, since it blocks no energy in between the lenses, more energy is available for direction into the solar beam. The only serious objection to this type of support is the possibility of a stress concentration on the quartz in bearing which could cause a fracture and precipitate failure of the whole assembly. A second objection is that the lenses will run hotter since they will of necessity be thicker. The perimeter clamping method has been used successfully in the 3-m simulation chamber, while new type supports have been developed for the 7.6-m simulator. The entrance lens support for the 4.6-m diam earth intensity beam is made of 7.5 cm thick copper to conduct the heat to the edge where it could be taken away by a water channel. It is chromium plated to minimize absorptivity.

Support temperature vs test volume irradiance was determined for this support (see Fig. 8), and it was found to be unsatisfactory for test area irradiance of Venus intensities. Above 330°C , the chromium would be expected to darken and the resultant absorptivity increase would allow the temperature to rise to prohibitive values.

A completely water-cooled mixer has been designed for Venus intensity, and above, in the 4.6-m diam beam for the 7.6-m space simulation chamber. It has the advantage of the lens array clamping type in that it does not obstruct any of the usable light beam except at the corners of the hexagon. Also, with this mixer, lenses are supported at the corners so that they are not subject to possible catastrophic stress failure. The lenses can be made as thin as possible to keep their temperature at a low value. This lens support system has the disadvantage of being more expensive and more difficult to fabricate.

Recent cold lamp explosion tests (Ref. 4) have led JPL to develop a lamp depressurizing technique whereby the xenon in the arc chamber is drawn into a small flask (permanently attached to the lamp) by means of a cryogenic fluid. The flask is then valved off from the arc chamber which renders the lamp safe to handle without cumbersome safety clothing. It can be repressurized at any time by opening the valve. In addition to rendering the lamp safe to personnel, a great deal of time is saved in operations which require exposure to the lamp (such as aligning or cleaning) since there is no suiting-up into cumbersome safety clothing. Figure 9 shows a Hanovia 20-kW lamp with the JPL depressurizing unit installed.

Present collectors are made of cast aluminum and are 69 cm in diameter in the large chamber, 41 cm in the small chamber. They are machined, figured, coated with electroless nickel, polished, and then given a highly reflective coating of vacuum deposited aluminum.

Humidity and the high-energy flux from the 20-kW lamps, in combination with the low operating temperature of the water-cooled reflectors, tend to degrade

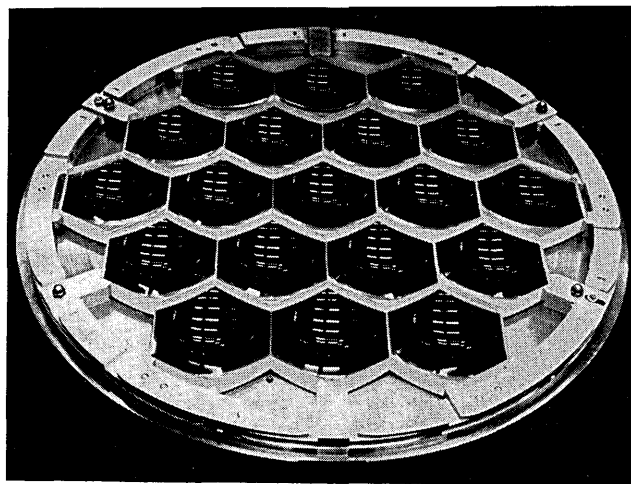


Fig. 7. Self-supporting condenser lens assembly.

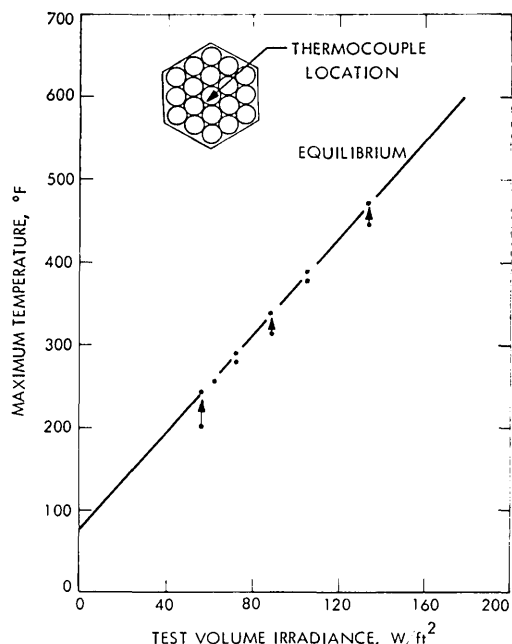


Fig. 8. Condenser lens support frame temperature vs 4.6-m solar beam intensity.

the delicate aluminized surface rapidly. Overcoating does not appear to help this phenomenon. Air dryers have been placed in the lamp bank enclosure to improve reflector life. A method has been developed here of replicating these collectors with epoxy using a glass master and the same aluminum coating. Replacements are thus obtainable at a substantial cost reduction.

III. Lamp Development

The performance of any solar simulation system is limited by the efficiency of light transfer within that system, but more importantly it is limited by the brightness of the light source used. If the brightness of the light source were to be doubled, then the net performance of a solar simulator could also be doubled. In the JPL facilities, such improved performance could be realized in improved intensity, solar subtense angle, or spectrum. It is important to remember that the basic parameter is the brightness of the light source and not its total power output. In practice, however, higher power light sources tend to be brighter. This is especially true of xenon short arc lamps of the type shown in Fig. 9. When operating with a gas pressure of about 12 atm (180 psi), the arc has an extremely bright zone near the cathode with peak brightness a few mm from the tip. To obtain maximum performance, solar simulators typically accept light only from a small volume centered on this hot spot. As shown in Fig. 10, the brightness of the arc falls off very rapidly away from this spot. Because the average brightness of the accepted volume is controlling, the accepted volume is kept at the minimum consistent with the power output required from each lamp.

One of the aims of the lamp development programs at JPL is increasing the average brightness of the arc in a small volume near the cathode. The approach which has yielded the most practical benefits to date is that of increasing current density. Experiments have shown that, for a given lamp configuration, the average brightness of the small accepted volume is nearly proportional to the current. The arc dimensions do not change appreciably with increased current, while the power which is dissipated in the arc does.

A. Hot Tungsten Anode

The current at which an arc lamp is operated is typically the maximum which the lamp components are physically capable of withstanding and still yield a useful lifetime. Of the total electrical power input to a xenon compact arc lamp, about 10% appears as cathode heating, 40% as light emission from the arc, and 50% as heat in the anode. It is this last which now limits the amount of current that can be handled by a particular lamp because the heat is delivered to the anode in a very small area. For lamps with power ratings of less than 10 kW (electrical input), the anode is typically a large tungsten slug which is run at a high enough temperature so that the heat is radiated away. The point at which the arc strikes such an anode is in a molten or near molten condition.

At power levels above approximately 10 kW, it is not practical to design a suitable radiation cooled anode and some forced cooling is necessary. The first designs for 20-kW lamps also used a tungsten anode which was molten or near molten where the arc struck. A water jet inside the anode about 12.7 mm from the arc was used to dissipate the excess heat. However, the thermal strain involved quite often led to cracking of the tungsten which then allowed water to leak into the arc space causing the lamp to fail. Such lamps are now available at 20 kW with an expected lifetime of a few hundred hours.

B. Riise Anode

Meanwhile, at our laboratory a radically different method of anode cooling was developed under the direction of one of the authors (H. N. R.). The configuration which resulted has become known as the Riise anode (Fig. 11). In this configuration, the arc strikes a

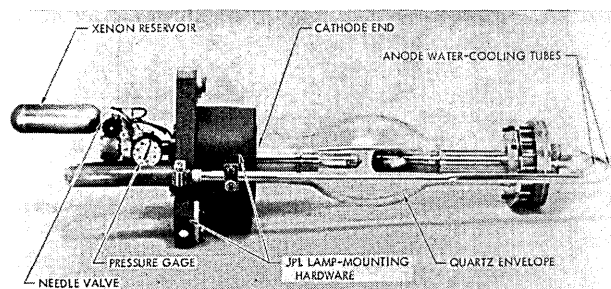


Fig. 9. 20-kW lamp with depressurizing apparatus.

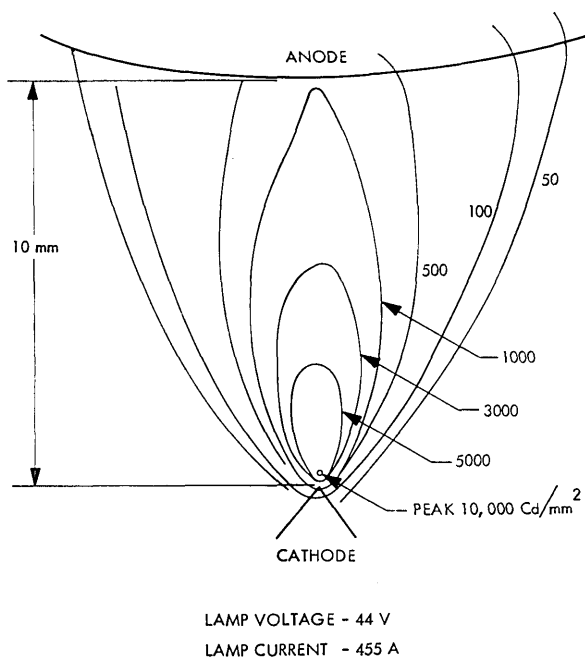


Fig. 10. Brightness distribution of 20-kW xenon short arc lamp.

copper surface 1 mm or 2 mm thick, which has a high-velocity (30–60 m/sec), high-pressure, tangential water flow on the other side. Under these conditions, the tiny vapor bubbles formed by the nucleate boiling on the hot surface are swept away before they can interfere with the copper-to-water heat transfer. This type of anode appears capable of operating indefinitely if the correct coolant pressure and flow are maintained.

Several lamps have been run with this anode at power levels in the 20–30-kW range for a few hundred hours. The mode of failure is always the same: a constriction in the water passage develops which reduces the anode cooling until the copper melts and a catastrophic failure results. Such a constriction can arise from scale formed when untreated water is used for cooling or from an insoluble residue formed when organic coolants are used which decompose at the hot surface. These two things can be easily avoided.

More important is creep of the relatively hot copper anode cap. The xenon gas pressure in currently available lamps is about 12 atm during operation. A static water pressure of 2.4 atm exists at the tip of a Riise anode under normal conditions (12-atm inlet, 1.7-atm outlet, 0.3-l/sec, 0.25-mm passage). The differential pressure causes the anode cap to deform slowly inward to reduce the water flow. As the flow decreases, the copper becomes hotter, the creep rate increases, and eventually insufficient cooling is available and the arc burns through the cap.

Youngberg⁵ has shown that it is possible to achieve a static water pressure at the tip of a Riise anode equal to the xenon gas pressure by raising the water outlet pressure to 10 atm (20-atm inlet); this reduces the mechanical stress on the anode cap. Also the higher boiling point of the pressurized water improves heat transfer.

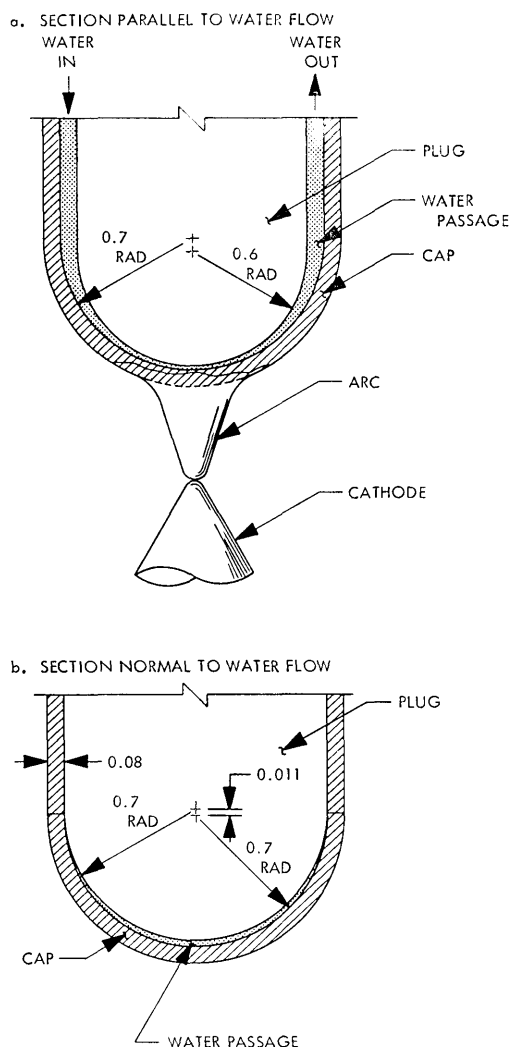


Fig. 11. Riise anode configuration.

C. Multiple Anodes

Another approach to improve the lamps is to use a number of anodes, typically three or six, arranged with their tips in a tight circle around the line of the cathode axis (Fig. 12) and with the separation of the cathode to any one anode remaining at the usual 12.7 mm. The anodes are connected to the terminals of a 3-phase or 6-phase, 60-cycle, current-limiting transformer with the cathode return connected to the neutral point of the transformer. The current flow goes to each anode in turn during the passage of an electrical cycle, and only to that anode that has the momentary maximum (positive) potential, the others being inoperative during the part of the cycle when they do not have maximum positive polarity. Each anode, thus, has a duty cycle of $\frac{1}{3}$ or $\frac{1}{6}$, but each can handle its normal design maximum as a long-time average load. Thus, the single cathode with three anodes (or six anodes) has a power capability of three (or six) times that of a single anode lamp, although the luminous emitting area and location are little changed from that of a single anode lamp.

Although the electron or negative ion stream flows to each anode in turn, the hot gas cathode jet is electrically neutral and does not depart from its axial flow direction. This jet, with its initial velocity a few hundred meters per second, passes through the central opening between the ring of anode tips and gradually slows and spreads as it passes along the distance in the flow direction. It is eventually stopped and cooled by a water-cooled end baffle. The cathode jet, thus, should not add its heat load to the concentrated heat load of the electron stream on the anode tip.

As reported in Ref. 6, the multiple anode structure was built to operate in the JPL Variarc facility. A tungsten cathode was used with three tungsten-tipped, water-cooled copper anodes, and set up to operate at 5 atm using argon gas. The lamp operated as expected with the cathode light spot being time-modulated to the extent of 16%, which corresponds to the current modulation in a 3-phase current. A 6-phase operation would give a 4.2% current modulation and presumably a 4.2% light modulation. Such modulations with fractional second periods are far faster than any anticipated thermal time constant of spacecraft elements to be tested in space simulator, and are thus acceptable.

The lamp was operated as a single cathode, single anode lamp by connecting all three transformer outputs to one anode. The 6.3-mm diam tungsten-tipped anode was raised to the melting point at 60 A. The three transformer outputs were then connected separately to each of the three anodes, and the current needed to raise the tips of the tungsten anodes to the melting point was then 150 A (50 A in each anode leg and 150 A through the single cathode). This current of 150 A would then be the operating limit for the lamp as a single cathode, 3-anode lamp. The fact that the limit was reached at 150 A instead of 180 A was attributed to the hot anode tips giving additional heat load to the neighboring anodes. In a practical lamp with Riise anodes, the copper would be much cooler and the additional heat load should be negligible.

IV. Conclusion

JPL has designed and built two large space simulation facilities with excellent solar-simulation capability. An important feature of the facilities is their flexibility wherein tradeoffs can be made between intensity, beam size, or collimation. The net performance of any system is limited by the brightness of the light source used, and the JPL facilities were specifically designed to be able to use improved light sources as they become available; the system is in no way tailored for any specific lamp. JPL maintains an active development program which has yielded the system designs and numerous component improvements. This is a continuing program (current emphasis is on light source brightness); we expect further improvement in our ability to simulate solar radiation in space.

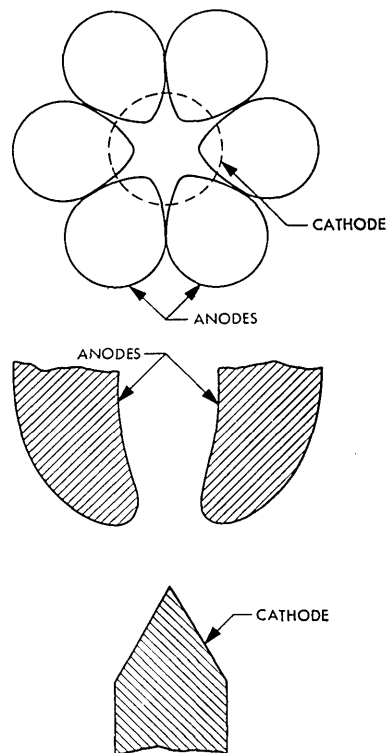


Fig. 12. Multiple anode geometry.

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

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