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RECENT SOLAR SIMULATION DEVELOPMENTS AT THE JET PROPULSION LABORATORY

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Biography

Ralph E. Bartera first became involved in solar simulation in 1963 when the first generation of large space simulation facilities was becoming operational. The solar performance of these early facilities was markedly disappointing. As a member of a group formed at the Jet Propulsion Laboratory to find ways to improve this performance, he was heavily involved in the development of the JPL Solar Simulation System, recognized as being the one with the best potential performance. He currently supervises a group which is striving to advance space simulation technology in several areas.

INTRODUCTION - THE JPL SPACE SIMULATORS

There are now two large Space Simulation Facilities at the Jet Propulsion Laboratory. They are discussed in detail by Barnett in another paper at this meeting, but I will very briefly describe them here to help clarify the succeeding comments. The 10-ft Space Simulator, shown schematically in Fig. 1, has a solar simulation system capable of providing a 6.5-ft-diameter beam with an irradiance level in excess of 290 w/ft^2 (> Venus), a uniformity of ±5%, a field angle of just over 2 deg and a spectrum typical of unfiltered xenon arc lamps. The spectrum could of course be adjusted (with proper filters) to a fair solar match with about a 50% reduction of irradiance. This JPL developed and designed solar system is quite versatile and can be easily converted to an 8-ft beam at 140 w/ft^2, ±8% uniformity and 1.5-deg field angle. We are currently evaluating a configuration to produce 900 w/ft^2. The 25-ft Space Simulator is now being modified to incorporate the JPL Solar System as indicated in Fig. 2; it will be operational in the early summer of 1967. While it too will be versatile, its initial performance will be a 15-ft-diameter beam with an irradiance level of 140 w/ft^2, a uniformity of ±5%, and a field angle of about 1 deg and the xenon spectrum. This facility will be one of the first large scale uses of the new 20-kw xenon short arc lamps in solar simulation.

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.

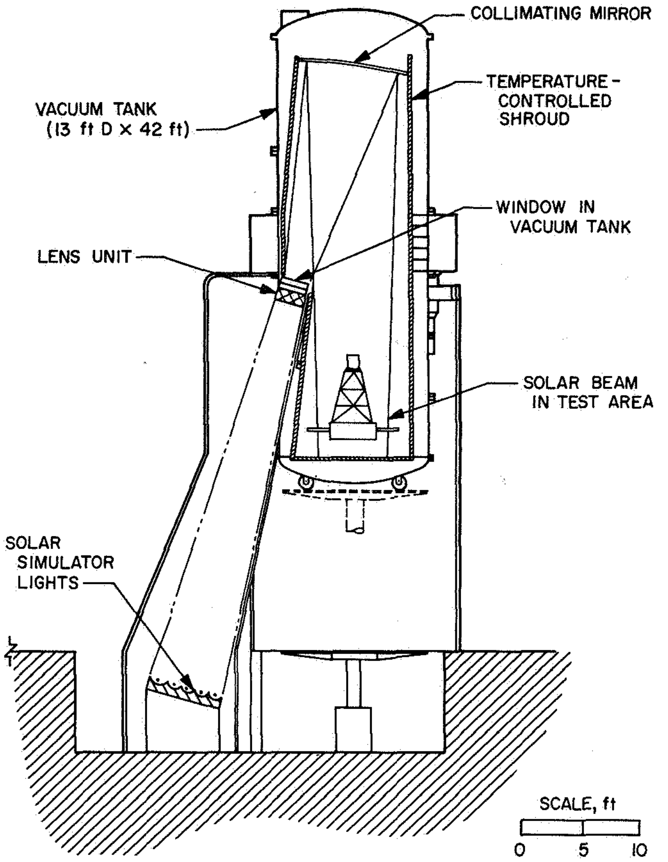

Figure 1. The JPL 10-ft space simulator

THE 20-kw ARC LAMPS

One of the design objectives for the 25-ft Space Simulator was to achieve the smallest field angle compatible with an operational irradiance level of 140 w/ft^2 ("operational" means 40% reserve power to allow for lamp degradation, etc.). Our experience with the 10-ft Space Simulator indicated that 1 deg was possible if we made full use of the potential of the JPL Solar System and the new 20-kw arc lamps; these lamps also presented a significant cost improvement over the alternative 5-kw lamps. After we decided to go in this direction, but before we were committed to it, the number of suppliers of this size lamp was reduced to one. Not only because of the potential cost saving, but also because the 20-kw lamp had a somewhat brighter arc (which would yield higher solar simulation performance), the selection of lamp size was put off as long as possible while an intensive evaluation program was begun. The manufacturer (Hanovia Lamp Division of Englehardt Industries) was very cooperative and participated heavily in this phase.

It soon became apparent that the then-existing lamp design could survive for the 400 hours which was our objective; at least one which we tested did. Unfortunately a lamp was just as likely to fail in

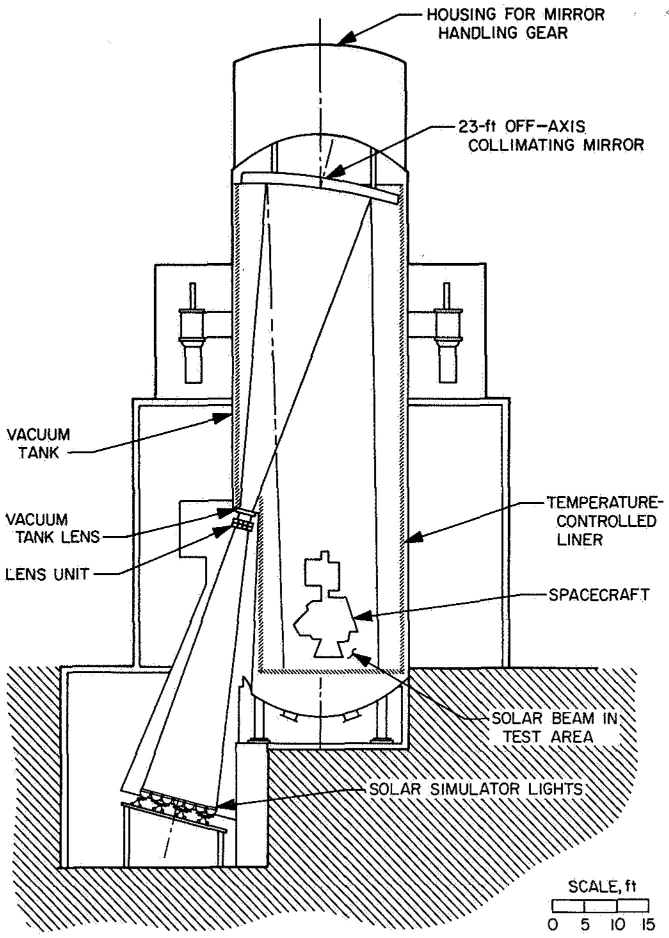

Figure 2. The JPL 25-ft space simulator

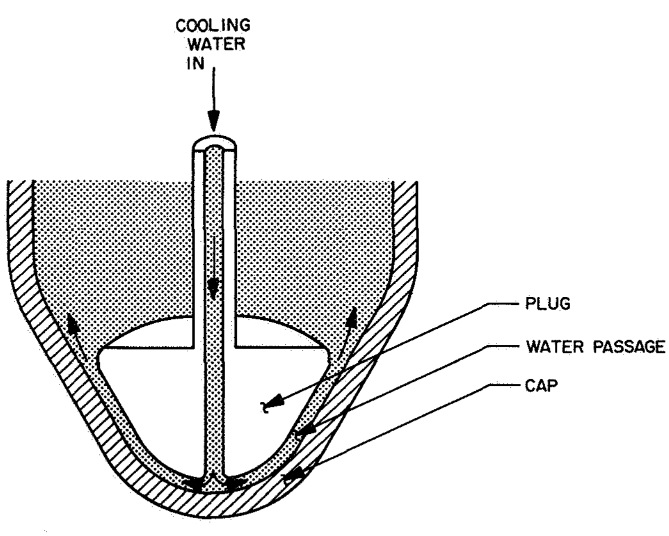

Figure 3. Configuration of original copper-anode water cooling passages

200 hours, 20 hours or, as one did, in 20 minutes. A section view of the copper anode used in these early lamps is shown in Fig. 3. A jet of water is directed onto the inside surface of the anode cap at the point where the arc is striking the outside. The water is then forced by the plug to flow along the inside surface of the anode cap before exiting. The typical mode of failure is illustrated in Fig. 4 which shows the copper anode with a hole burned through, off center. The central cavity is the result of softening and deformation of the copper which presumably precipitates the failure by restricting the flow of cooling water.

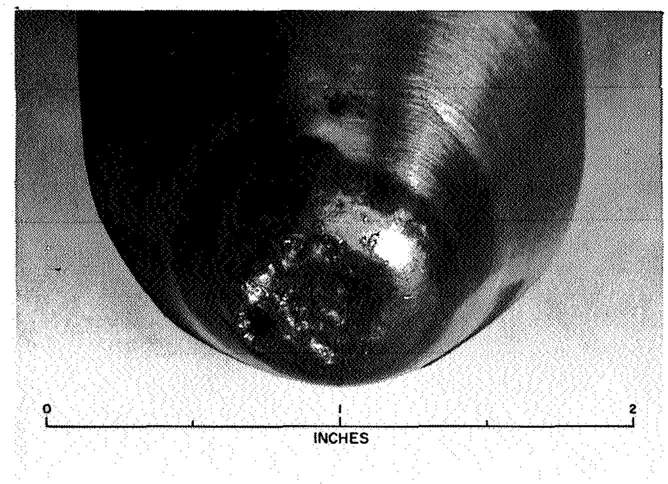

Figure 4. Typical failure of original copper anode

THE TUNGSTEN ANODE - HANOVIA

While we made no detailed calculations on the conditions existing inside the anode, we presumed that, because of the wide variation in lamp life, the heat transfer efficiency was excessively dependent upon the water flow rate and geometry at the nose of the anode. After a series of meetings between JPL and Hanovia, it was decided that a suitable tungsten anode could probably be designed in time to meet the requirements of the 25-ft Space Simulator, on which construction had already started; Hanovia bravely agreed to try. We also jointly decided that a copper anode, if it could be adequately and reliably cooled, would have distinct advantages; Hanovia had recognized this when they originally chose copper. The man spearheading the 20-kw lamp work at JPL was Mr. H. N. Riise who had had extensive experience in heat transfer between metal plates and fluids; he undertook to design a suitable copper anode.

In a reasonably short time and with a minimum of wasted motion, Hanovia produced a water-cooled tungsten-anode design which allowed a reliable lamp life in the 200-hour range, just one-half of what we required. The mode of failure was different, of course. A few nodules would form on the anode adjacent to the arc and, as time went on, would grow in size and number. In some cases a ring of nodules completely surrounded the arc resembling a crown as in Fig. 5. Although this growth was not considered to be a failure, it certainly contributed to tungsten evaporation and consequent darkening of the envelope which eventually reduced the energy output by the 30% which was considered failure.

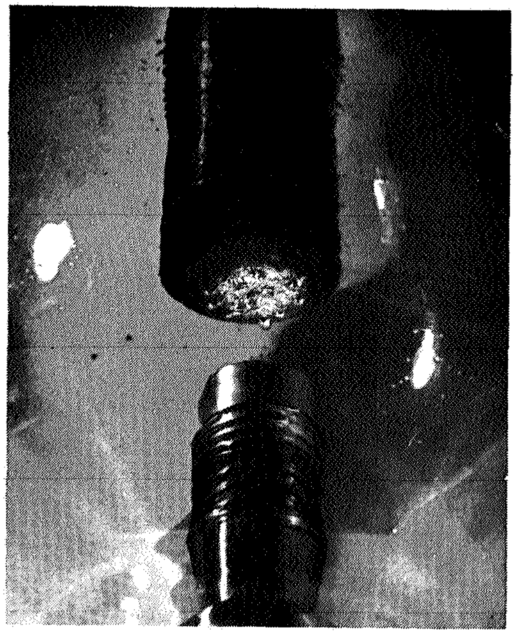

Figure 5. Nodules formed on tungsten anode of 20-kw arc lamp

Meanwhile, the copper anode had been designed and a model had been built to select the final dimensions using empirical water flow data: PEK Laboratories had entered the market with a water-cooled, tungsten-anode, 20-kw lamp (one of which we had evaluated with very good results, but PEK was not then in a position to accept our relatively large order or to offer a performance warranty). At this point the time to select and order lamps for the 25-ft Space Simulator arrived. Based upon our confidence in Hanovia, their confidence in themselves (the lamps were to be warranted for 400 hours of useful life) and the promising appearance of the copper anode design, we decided to place an order for 20-kw lamps without specifying the anode configuration. While we had to order the lamps then to maintain our construction schedule, there were several months left before the anode design had to be finalized. All lamp parts were to be manufactured and assembled leaving the anode until last. Our confidences were justified; by some further anode modification and a slight change in another location, a tungsten anode lamp was achieved which is expected to have a life in excess of 400 hours and we now have a complete set on hand (37 lamps).

THE COPPER ANODE - JPL

The copper anode development continued at JPL and resulted in several prototypes being fabricated. Figure 6 is an attempt to show the water flow path. The shell is a constant thickness cylinder and hemispherical cap. The plug is a matching cylinder with two sides milled to provide water inlet and outlet passages. The end of the plug has a compound curvature: in the plane normal to the water flow (Fig. 6b), the curvature matches the inside of the cap but is displaced to leave a lune-shaped passage with maximum thickness of about 0.01-in.; in the plane parallel to the water flow (Fig. 6a), the radius of curvature is less than the cap, providing the

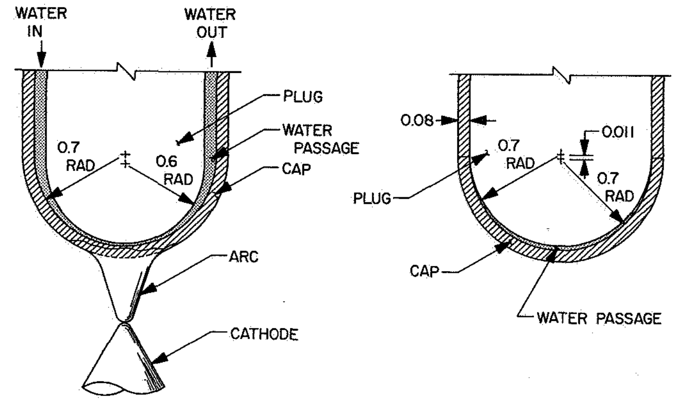

Figure 6. JPL copper anode for 20-kw arc lamps

minimum flow passage and maximum velocity at the nose of the anode where the maximum heat flux occurs. With this design, the flow is always tangential to the heat transfer surface, the curvature of that surface maintains the flow in contact with it, the wiping velocity is high (on the order of 100 fps), and accelerations are smooth in the vicinity of the heat load. The available heat transfer is consequently very high. If the heat input from the arc were increased to the point where boiling occurs, the incipient vapor bubbles would be swept away so quickly that a vapor film and the consequent drastic reduction in heat transfer is avoided. It is also possible to increase the total water pressure to suppress the boiling. Before I describe how this design was tested and how it performed, let me say that we consider it to be a significant enough advance that we call it after the man who conceived it, i.e., the Riise Anode.

The first prototype Riise Anode was installed in an otherwise conventional Hanovia 20-kw lamp and operated for 400 hours with 20-kw power input. It was performing so well that the power was then raised to 25-kw and allowed to run without adjustment for an additional 100 hours during which time the power gradually rose to 27 kw. Tests with the other prototypes have conclusively demonstrated that the present Riise Anode configuration can be used for several hundred hours with a power input of 30 kw (580 amperes). One manufacturer, Hanovia, has redesigned the anode to reduce its weight and cost for mass production and another, PEK, has shown a considerable interest. We are continuing to work with the Riise Anode to determine the limits of formance of the present configuration, which is certainly higher than 30-kw. We believe that the Riise Anode may be the basis for achieving practical short arc lamps in the 100-kw to 0.5-Mw range.

SPECTRAL FIDELITY

Judging from information we receive from others working to improve solar simulation, notably Duncan at the Goddard Space Flight Center, it is now possible to filter the xenon-arc spectrum to achieve a much better solar match; and to do so with a reasonable confidence that the adjusted spectrum will remain constant over a reasonable period of time. While we have concentrated on other parameters, which seem to be of more significance to JPL spacecraft, we have not abandoned spectral fidelity. In the past, those responsible for thermal control of JPL spacecraft have been able to largely avoid problems arising out of poor spectrum simulation; spectrally sensitive coatings are used on isolated components where their effect on the rest of the vehicle is minimal. For the thermally inter-dependent bulk of spacecraft components, "grey" coatings are typically selected to make reasonably realistic thermal testing possible. There are too many real restrictions on spacecraft design to allow this artificial one to continue indefinitely.

It is, of course, not necessary to duplicate the solar spectrum to perform an accurate thermal balance test: it is sufficient to duplicate the effect of the solar spectrum, i.e., to provide the same net absorptance for a given set of surfaces. However, to give the thermal control engineer a wide choice of materials and coatings it is desirable to duplicate the solar spectrum as nearly as possible. Consider one of the more useful coatings, white paint. About one-half of the net absorbed energy from solar irradiance is obtained in the UV region; it is therefore important to adjust the simulated sunlight to have the same irradiance as true sunlight in the UV. But, we have two equally reliable estimates of solar UV irradiance (Johnson's and Nicolet's) which differ by 30%! We have therefore attacked the spectrum simulation problem by first trying to resolve this difference.

SOLAR SPECTRUM MEASUREMENT

Toward this end a flight qualified filter type spectroradiometer has been developed to take solar spectrum data outside the influence of the earth's atmosphere. This instrument and its associated electronics are mounted in a wing tip pod of an X-15 Aircraft and, with the cooperation of the NASA Flight Research Center, exposed to the Sun at an altitude of about 240,000 ft. Figure 7 shows the device mounted in the pod. During each flight, the hatch is opened and the instrument is erected (oriented to the Sun) on a schedule which yields about 60-sec of data per flight. The equipment is then returned to the ground in good condition and will be used in the space simulators. There are twelve channels which are scanned continuously with an 8-sec cycle time. The twelve channels include two total flux detectors, as well as two broad-band and eight narrow-band filtered channels. The instruments have proven themselves to be accurate and flight worthy through repeated calibrations and a preliminary flight. Engineering flights are scheduled for April and May 1967, and scientific flights during the summer. We plan to work with Dr. Kostkowski of the NBS Heat Division and his unique UV-irradiance standard to calibrate the narrow-band UV filter channels.

In the latter half of FY '68 we plan to be in a position to define a realistic spectrum for solar simulators in terms of readings on an instrument which will have been directly exposed to the primary standard - the Sun - and will be available for use as a "secondary standard" in ground testing - a unique situation. Then, utilizing the work by others who have been involved in spectrum control, we plan to attempt the adjustment of the xenon-arc spectrum to a more realistic simulation of the solar spectrum.

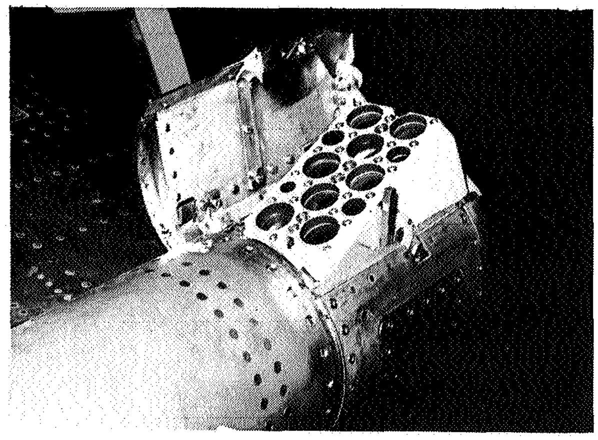

Figure 7. JPL spectroradiometer mounted in the X-15 wing-tip pod

VARIARC

There is a class of problems in the thermal control of spacecraft which requires nearly exact simulation of the solar field angle to investigate properly: the so-called cavity problems. On spacecraft with the complex geometries which the weight restrictions imposed by interplanetary missions require, there often occur conditions which make it extremely difficult to predict local variations of solar irradiance. Consider two plane surfaces making an acute angle but open at the bottom and with sunlight streaming into the cavity. How is the energy redistributed onto the surfaces and through the bottom? What is the distribution of energy in the throat of a solar-oriented rocket nozzle? This kind of question is relatively easy to answer when the surfaces are completely specular or completely diffuse, but extremely difficult when they are neither, i.e., when they are real engineering surfaces like the rocket nozzle which has been fired once. These problems are important because of the focusing of energy, and require extreme field-angle simulation to investigate.

As stated above, the best we can now do is 1 deg compared with the solar 1/4 deg. The parameter which controls the intensity/field angle relationship is the brightness of the energy source - the arc lamp. The Riise Anode is going to help here, of course, but it won't be enough. The usual proportionality between intensity and $\sin^2 \alpha/2$ would indicate a required increase in arc brightness of 16. Fortunately the JPL solar system sun is much brighter in the center than at the edges; in fact, a doubling of the brightness of the arc would allow a reduction in field angle to 1/2 deg. The Riise Anode can probably get us this far. The additional arc brightness (a factor of 4 at most) will have to come from other means than merely increasing the arc current density. By operating with only 10% reserve power rather than the usual 40%, we can pick up a factor of 1.3 which leaves a factor of about 3.

One of our major goals for the coming year will be to see if an increase by a factor of 3 or 4 is feasible. We will be using a device which we call the VARIARC - for variable arc lamp. With this tool we plan to make an organized, extensive, and quantitative determination of the effect upon arc brightness and anode loading of such things as magnetic fields, gas mixtures, pressure, electrode temperature and configuration, voltage gradients and cold gas injection. Any useful sets of parameters which we discover will probably be given to lamp manufacturers to be designed into practical lamps which we would then buy as needed. We don't intend to go into the business of making arc lamps but we do intend to continue encouraging improvements in them.