NASA TECHNICAL MEMORANDUM

NASA TM X-68048

NASA TM X-68048

ENVIRONMENTAL SIMULATION FROM 0.01 TO 100 SOLAR CONSTANTS

by John R. Jack and Ernie W. Spisz
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER for presentation at
Sixth Space Simulation Conference sponsored by the
Institute of Environmental Science, the American
Institute of Aeronautics and Astronautics, and the
American Society for Testing and Materials
New York, New York, May 1 - May 4, 1972

ENVIRONMENTAL SIMULATION FROM 0.01 TO 100 SOLAR CONSTANTS

John R. Jack* and Ernie W. Spisz** Lewis Research Center
Cleveland, Ohio

INTRODUCTION

To meet the needs of space technology, there is a large demand for accurate thermal radiative property data on engineering materials over a wide range of environments. For example, passive spacecraft temperature control is generally achieved by a radiation heat exchange between the spacecraft and the environment. Another example is the proposed space shuttle system that not only has the temperature control problem in orbit but, in addition, must consider re-entry heat transfer where a large part of the heat exchange is by thermal radiation. This shuttle characteristic requires a very special exterior surface that not only has the proper thermal radiative properties but must also withstand the re-entry environment and be re-usable. Currently, neither experimental data nor theoretical predictions are sufficient to fill these special needs. This is especially true at high temperatures were experimental data for some of the popular spacecraft materials is very meager and for some of the newer surfaces being considered for the shuttle system are nonexistent. These needs for thermal radiative property data have led to the development of two new solar

---

*Head, Environmental Physics Section, Member AIAA.
**Aerospace Research Engineer, Member AIAA.

radiation simulators at the Lewis Research Center with an intensity variation ranging from 0.01 to greater than 100 solar constants that can be provided under vacuum conditions.

It is the intent of this paper to discuss the characteristics of the simulators in terms of spectral content, beam uniformity and stability. In addition, the radiometer problems encountered over such a wide intensity range and their solutions will be discussed. Preliminary thermal radiative property data obtained at high intensities (temperatures) will also be presented.

ENVIRONMENTAL FACILITIES

Figure 1(a) and 1(b) are schematics of the facilities that are being used. Both facilities are basically similar in that blackened LHe cooled walls are used in both facilities to provide a 4° K radiant background, high pumping rates and low pressures.

The test section of the facility in figure 1(a) is cylindrical with a 36-cm diameter and 120-cm length. Liquid nitrogen cryosorption pumps are used for "rough pumping" the facility and the LHe cooled walls provide the final pumping capability yielding pressures below 10^{-10} torr.

The test section of the facility in figure 1(b) is also cylindrical with a 2-m diameter and 4-m length. Two 32-inch diameter diffusion pumps are used in this facility to permit testing with warm walls. When space simulation is required LHe cooled walls are used providing pressures less than 10^{-10} torr.

DESCRIPTION OF SOLAR SIMULATORS

The solar simulator that was used to cover the 0.01 to 1.0 solar constant range was purchased from Genarco, Inc., as a standard Model TME4CWM high-intensity carbon are solar simulator with associated collecting optical elements. The positive carbon electrode is 22 inches (55.9 cm) long with a diameter of 13.5 millimeters and operates at a current level of

185 to 200 amperes. The primary requirement of the simulator was to provide a 12-inch- (30.5 cm) diameter beam with a radiant intensity of 0.140 watt per square centimeter (1 solar constant) in a test plane located 10 feet (3.05 m) from the last optical element. Figure 1(a) includes a schematic drawing of the basic features of the simulator.

The general operational characteristics of the simulator are automatic starting, control of both positive and negative electrodes, and uninterrupted operation for periods in excess of 24 hours. The unique characteristics of the simulator are (1) variable intensity by incorporating screens as shown in figure 1(a), (2) continuously variable radiant intensity by a factor of two over the initial intensity by adjustment of the objective lenses (see fig. 1(a)), (3) interchangeable carbon and nonconsumable tungsten negative electrodes, and (4) a constant-current electrical power supply.

The continuously variable radiant intensity by objective lens adjustment is required to provide a convenient method for the control of the radiant intensity as required for the experimental program discussed in reference 1.

The interchangeable carbon and tungsten negative electrodes were incorporated to provide flexibility in operation. The carbon negative was included for the anticipated better spectral match of the solar energy spectrum. The nonconsumable tungsten negative electrode was included for long-term (longer than 24 hr) running capability.

A constant-current electrical power supply was used in conjunction with automatic control of the electrode position to stabilize the power dissipation in the arc column in order to minimize the instabilities of the carbon arc and provide a stable radiant intensity beam.

The simulator that is used to cover the intensity range from 0.5 to 20 solar constants utilizes the same high intensity carbon arc source that was used for the 0.01 to 1.0 solar constant range along with an appropriate set of collecting optics. The optical system that is used is shown in figure 2. The optical system consists of eight quartz elements and includes a pair of lenticular lens plates consisting of 36 hexagonal lens elements to improve the uniformity of the beam irradiance in the test plane. A movable lens is also incorporated into the design to vary the radiant intensity continuously by a factor of two over the initial intensity setting. Large intensity variations are achieved by screens or apertures as shown in figure 2.

The simulator for the 10 - 100 solar constant radiant intensity range consists of a 20 kW xenon compact arc lamp as the source and the collecting optical system shown in figure 3. This solar simulator is designed for use with the environmental simulator shown in figure 1(b). The xenon lamp is mounted in a vertical position with the anode in the top position. The xenon pressure at the 20 kW operating point (500 amp, 40 V) is approximately 145 psig.

The collecting optical system consists of a 51-cm elliptical collector with a 440-cm focal length and four quartz elements. The quartz elements include a 40-cm and 31.5-cm diameter plano-convex lens and a pair of lenticular lens plates which are composed of 37 hexagonal lens elements. The entire optical system is mounted within the housing shown in figure 3 and is capable of operating in a vacuum or inert atmosphere.

SOLAR SIMULATOR CHARACTERISTICS

Stability

Fluctuations in the radiant intensity is the primary disadvantage of the carbon arc solar simulator. For the intended application, the fluctuations were of utmost importance because of the requirement for a low-frequency, small-amplitude sinusoidal variation in radiant intensity (ref. 1).

Figure 4 is a typical stability trace of the radiant intensity for the one solar constant source. These data were obtained with a fast-response thermopile radiometer. The intensity fluctuations amount to approximately $\pm 1\frac{1}{2}$ percent of the mean intensity level.

Long-term drift of the mean intensity level can be detected in figure 4. This variation, however, was considered to be of minor importance because the simulator was later modified to include an intensity control system which could easily handle the small, slowly varying changes.

Since the 20 solar constant simulator utilized the one solar constant source with modified optics, its stability is exactly as that described above.

The stability of the 20 kW xenon short arc source used in the 100 solar constant simulator is shown in figure 5. Intensity fluctuations are approximately ±3 percent of the mean intensity level with no appreciable long-term drift once the 20 kW source was temperature stabilized. This degree of stability was considered good and completely acceptable.

UNIFORMITY

The uniformity of the radiant intensity in the test plane of the one solar constant simulator was studied on the principal vertical and horizontal axes of a 12-inch- (30.5-cm-) diameter circle at a distance of approximately 11 feet (3.35 m) from the last objective lens. Figure 6 shows the beam uniformity, as obtained with a 1-cm by 2-cm silicon solar cell, at a mean intensity setting of one solar constant. The uniformity is within ±4 percent on both the vertical and horizontal axes.

The uniformity is relatively insensitive to intensity level. However, considerable care was required in the relative positioning of the two objective lenses because small changes in the positions of the objective lenses could influence the uniformity. In order to maintain good uniformity, it was essential that the lenses be moved together. The sensitivity of beam uniformity to lens position was considered to be a major limitation of the optical system used for this simulator, and had to be overcome as described to obtain the desired uniformity.

A 1-cm by 1-cm silicon solar cell was used to obtain the radiant intensity uniformity of the 20 solar constant carbon arc simulator shown in figure 7 for a mean intensity level of 20 solar constants. The intensity uniformity over the required beam diameter is within ±3 percent and is considered quite good. The small amount of drop off in intensity at the edges is attributed to a small misalinement of the optics.

The 100 solar constant simulator produced an irradiance with a distribution uniform to 1 percent (fig. 8). The gradual dropoff in intensity across the beam diameter noted here is believed due to misalinement of the optics. The design of this simulator is discussed fully in reference 2.

Controlling the intensity level of the 100 solar constant simulator was desirable for our research purposes. The most convenient controlling parameter, lamp power level, was studied, and the results are shown in figure 9. Absolute intensity varies linearly with lamp power level from approximately 10 kW, the minimum power recommended by the lamp manufacturer, to about 22 kW. For intensity levels between 10 and 75 solar constants, we plan to use the neutral density screens that were used successfully with the one solar constant simulator.

SPECTRAL DISTRIBUTION OF RADIANT ENERGY

Several methods are available for measuring the spectral distribution of the radiant energy from the carbon arc solar simulator (refs. 3 and 4). The method used herein involves a single-beam, double-pass monochromator having a lithium fluoride or quartz prism and a thermopile detector.

The spectroradiometer was initially calibrated for spectral irradiance over the wavelength range from 0.36 to 2.1 microns using a 1-kilowatt quartz-iodine, coiled-coil tungsten filament lamp with an irradiancy calibration traceable to the National Bureau of Standards (NBS). The NBS calibration method is described in reference 5. The calibration establishes the correspondence between the irradiance of the uncollimated standard lamp at the entrance slit of the spectroradiometer and the electrical output of the thermopile detector for a fixed spectrometer slit width.

The spectral irradiance data obtained for the one solar constant simulator are compared with the solar spectrum curve of reference 6 in figure 10. These data were obtained at a total radiant intensity setting of 0.140 watt per square centimeter as measured by a calibrated radiometer at the entrance slit of the spectroradiometer. Spectral irradiance curves are presented for both the carbon negative electrode and the nonconsumable tungsten negative electrode. The spectral irradiance distributions obtained for the two different negative electrodes are very similar. The anticipated improvement in spectral match for a carbon negative as compared with the tungsten negative (which requires an envelope of argon gas to prevent oxidation of the tungsten) was not observed. Apparently, the spectral irradiance of the carbon arc is governed primarily by the composition of the positive electrode. The influence of the negative electrode is minor.

The application of the simulator over the total radiant intensity range from 0.01 to 1.0 solar constants is achieved by introducing fine-wire, 30-mesh screens into the beam between the front surfaced alummized folding mirror and the first limiting aperture. The use of screens as neutral density filters has been investigated in reference 7 and their effect over the solar wavelength range is small.

The spectral irradiance of the 0.5 to 20 solar constant carbon arc simulator and the 10 to 100 solar constant xenon lamp simulator are shown in figure 11. These data were obtained by operating each simulator at its nominal high intensity level. In each case a 6-inch diameter fused quartz disk was used as a 45^0 reflector to reduce the beam intensity to a suitable low level before it was introduced into the spectrometer. The curves in figure 11 have been normalized to provide equal total energy over the wavelength range from 0.36 μ to 2.25 μ. A correction for the variation of the spectral reflectance of the fused quartz disk has not been included. Calculated values of the reflectance of fused quartz based on Fresnel equations (ref. 8) and the index of refraction of fused quartz (ref. 9) indicate a reflectance variation of approximately 10 percent over the wavelength range of interest.

The spectral distribution of the 0.5 to 20 solar constant simulator is similar to that for the 0.01 to 1.0 solar constant simulator as would be expected because of the identical carbon arc source being used.

The spectral distribution of the xenon arc lamp at a power level of 10 kW indicates a fairly significant departure from the solar spectrum and indicates that some filtering will be required in order to obtain usable solar simulation.

HIGH INTENSITY RADIOMETER

A challenging problem encountered in the evaluation of the Lewis high intensity solar simulators was the accurate measurement and mapping of the absolute radiation intensity distribution in the test planes of both environmental simulators. This problem stems from the requirement that the radiometer must be accurate, repeatable, stable, and, in particular, it must have a fast response time. In the past, solar cells operated in the photovoltaic mode were used (ref. 10) and the short circuit current measured since it approximates the light generated current which is linearly related to the radiant intensity level. However, as indicated in ref. 11, at high intensity levels the short circuit current was not linearly related to the intensity (fig. 12). The nonlinearity occurs because internal series resistance and temperature effects become important at high-intensity levels.

The nonlinear problems associated with a silicon solar cell can be alleviated by operating the cell in a photoconductive rather than a photovoltaic mode, that is, by measuring cell current with a reversed bias voltage imposed upon it. With sufficient reverse bias, the cell current approximates the light generated current which does vary linearly with the radiant intensity level. By biasing the cell with a voltage of approximately -1 volt, the measured current is linearly related to the intensity level over an intensity range from 70 to 2800 milliwatts per square centimeter (1/2 to 20 solar constants) (fig. 12). An additional advantage obtained from this operational mode is that the photoconductive current is relatively insensitive to cell temperature changes. Additional information on this investigation may be found in reference 11.

THERMAL RADIATION PROPERTIES

The type of research we are doing to determine thermal radiation properties at high solar intensities (or high material temperatures) is illustrated in figure 13. The solar absorptance α_S, total hemispherical emittance ϵ, and their ratio α_S/ϵ for molybdenum as determined with the cyclic radiation technique (ref. 1) are shown for temperatures ranging from approximately 200° K to 825° K; where the higher temperature data were obtained with the high intensity, 20 solar constant source. In general, the total hemispherical emittance increased with increasing temperature, the solar absorptance were approximately constant and the absorptance-emittance ratio decreased. The data obtained with the high intensity, 20 solar constant simulator are in line with the data obtained previously with the one solar constant simulator and the hemispherical emittance is in good agreement with the Hagen-Rubens analytical prediction.

SUMMARY OF RESULTS

The characteristics of three solar simulators suitable for determining the thermal radiative properties (solar absorptance and hemispherical emittance) of materials have been determined. The irradiance levels varied from 0.01 to 1 solar constant for one simulator, from 0.5 to 20 solar constants for another and from 20 to 175 solar constants for the third simulator. Spectral content, stability, and beam uniformity were judged good for the purposes intended.

In addition, a silicon solar cell used in the photoconductive mode is discussed for the purposes of measuring very high intensities. Finally, the preliminary thermal radiative properties of molybdenum as obtained with the 20 solar constant simulator are presented.

REFERENCES

1. Jack, J. R. and Spisz, E. W., "Thermal Radiative Property Measurements using Cyclic Radiation." TN D-5651, NASA, Cleveland, Ohio.

2. Buchele, D. R., "Design of Lens Projection System for Solar Simulator of One-Hundred Solar Constant Irradiance." Proposed Technical Memorandum, 1972, NASA, Cleveland, Ohio.

3. Wagoner, R. E. and Pollack, J. L., "Data Reduction for Filter Spectroradiometry," TN D-3073, 1965, NASA, Cleveland, Ohio.

4. Uguccini, O. W., "An Integrating Sphere Spectroradiometer For Solar Simulator Measurements," TN D-4822, 1968, NASA, Cleveland, Ohio.

5. Stair, R., Schneider, W. E. and Jackson, J. K., "A New Standard of Spectral Irradiance," Applied Optics Vol. 2, No. 11, Nov. 1963, pp. 1151-1154.

6. Anon., "Solar Electromagnetic Radiation," SP-8005, 1965, NASA, Washington, D.C.

7. Heidt, L. J. and Bosley, D. E., "An Evaluation of Two Simple Methods for Calibrating Wavelength and Absorptance Scales of Modern Spectrophotometers," Journal of the Optical Society of America, Vol. 43, No. 9, Sept. 1953, pp. 760-766.

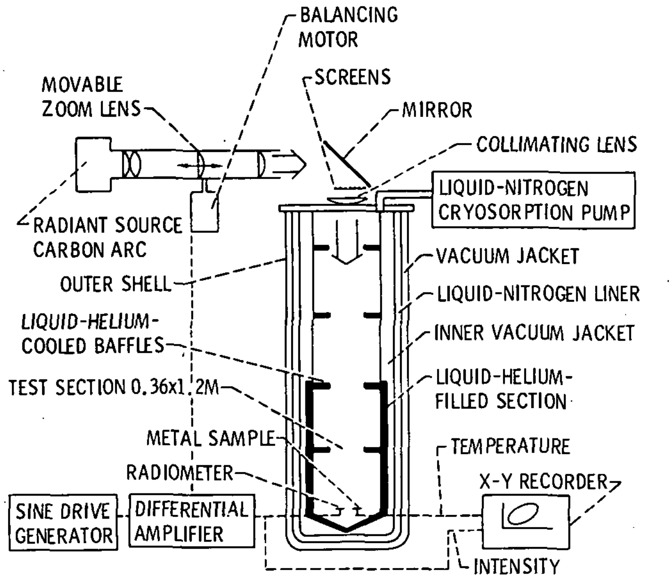
8. Siegel, R. and Howell, J. R., Thermal Radiation Heat Transfer, McGraw-Hill, New York, 1972.

9. Amersil, Inc.: Optical Fused Quartz and Fused Silica.

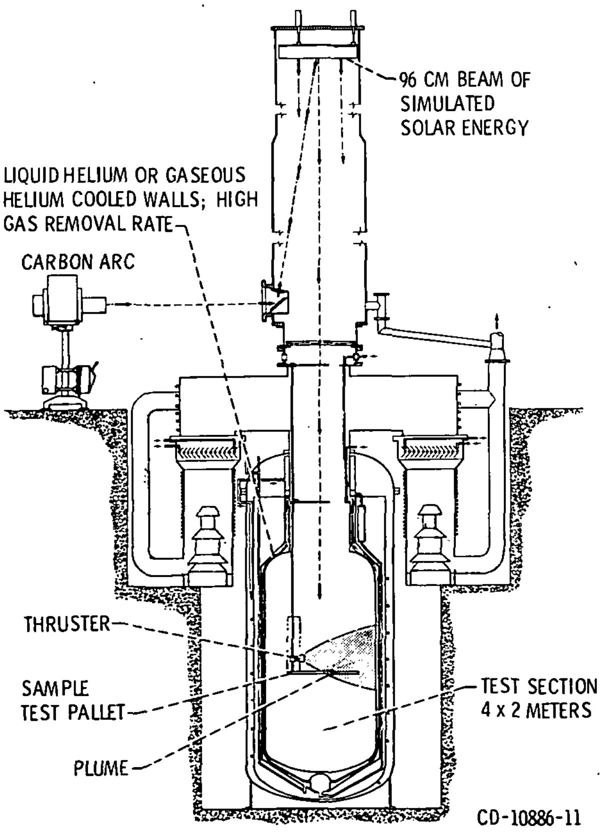
10. Witherell, P. G. and Faulhaber, M. E., "The Silicon Solar Cell as a Photometric Detector," Applied Optics, Vol. 9, No. 1, Jan. 1970, pp. 73-78.

11. Spisz, E. W. and Robson, R. R., "Silicon Solar Cell as a High-Solar-Intensity Radiometer," TM X-2412, 1971, NASA, Cleveland, Ohio.

E-6888



(a) 0.36 x 1.2 M SPACE ENVIRONMENT FACILITY.



(b) 2.0x4.0 M SPACE ENVIRONMENT FACILITY.

Figure 1. - Environmental simulators.

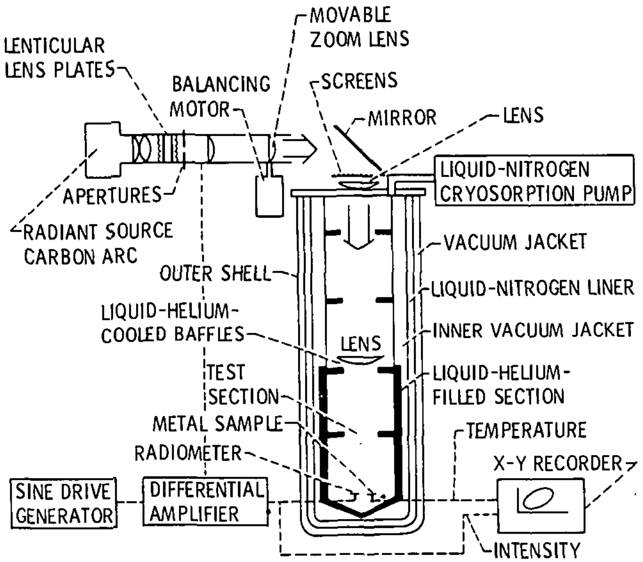


Figure 2. - Schematic drawing of environmental facility with 0.5 to 20 SC solar simulator.

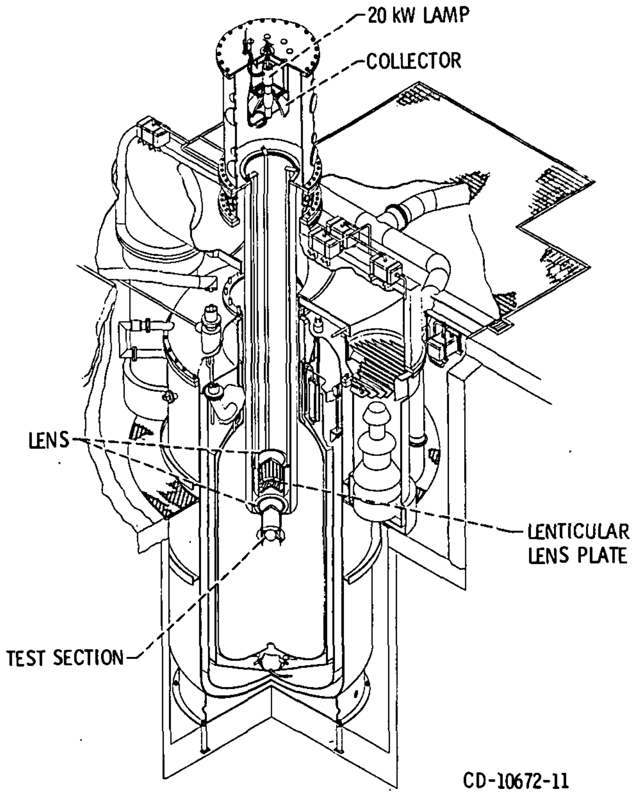


Figure 3. - 10 to 100 SC simulator.

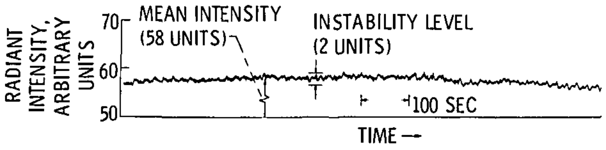


Figure 4. - Stability level of carbon arc solar simulator.

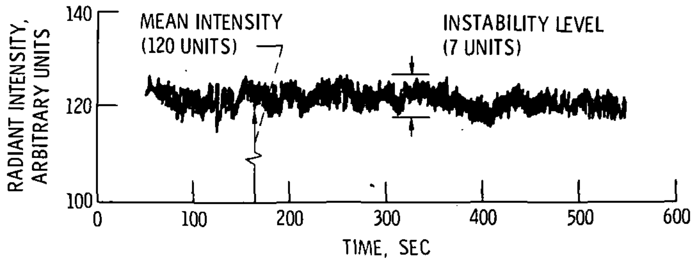
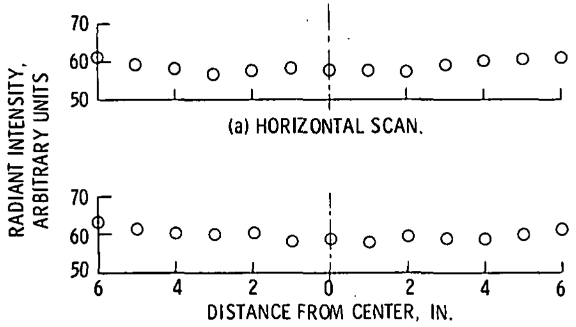


Figure 5. - Stability of 20 kW Xe compact arc lamp.



(a) HORIZONTAL SCAN.

(b) VERTICAL SCAN.

Figure 6. - 1 Solar constant radiant intensity profile along major horizontal and vertical axes.

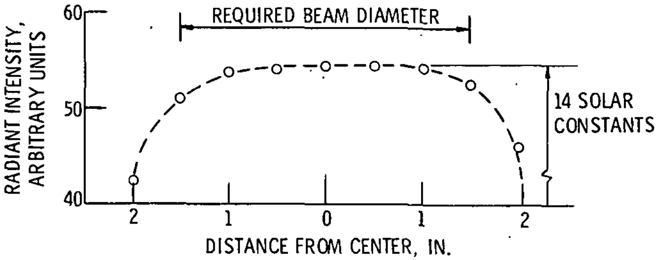


Figure 7. - 20 Solar constant radiant intensity profile.

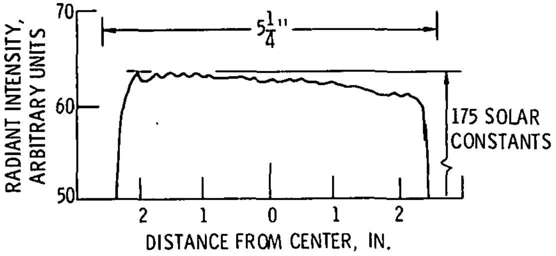


Figure 8. - 100 Solar constant radiant intensity profile.

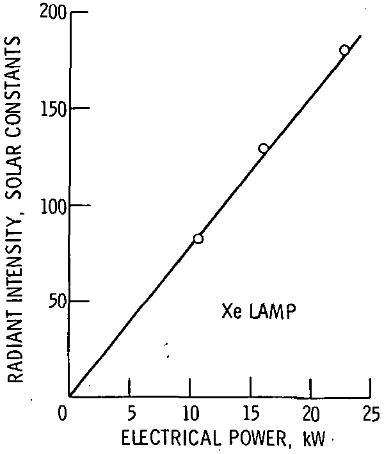


Figure 9. - Intensity output characteristics of 100 solar constant simulator.

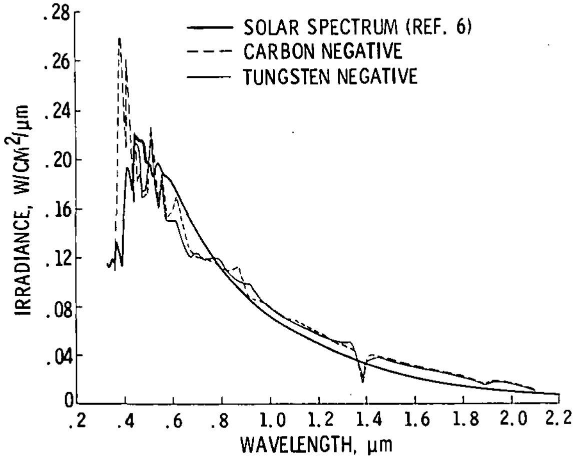


Figure 10. - Spectral irradiance of carbon arc.

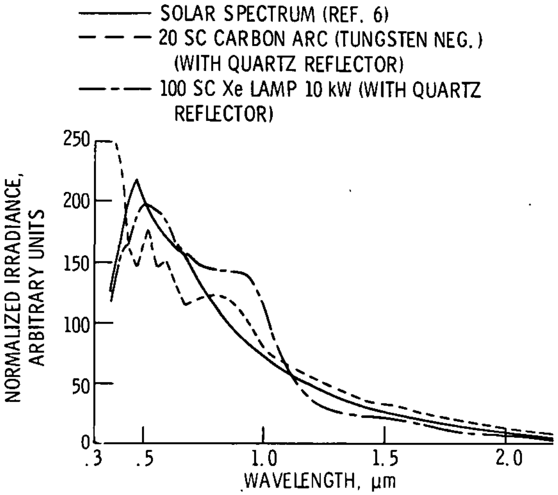


Figure 11. - Spectral irradiance of 0.5 to 20 SC and 10 to 100 SC solar simulator.

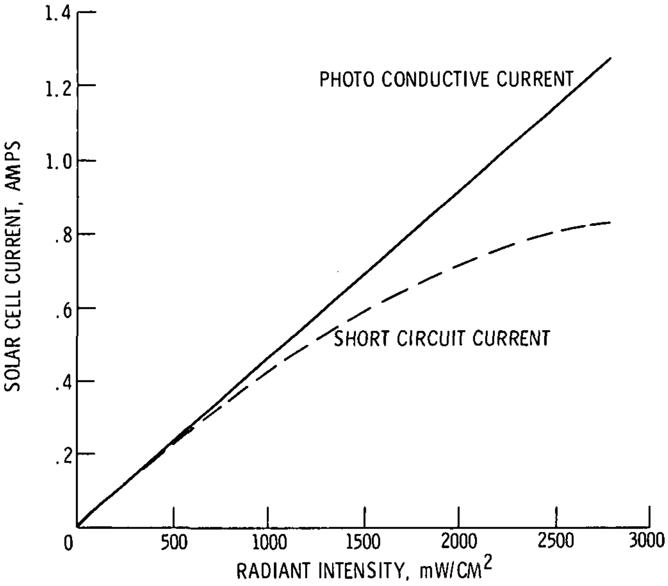


Figure 12. - Calibration curve of silicon solar cell.

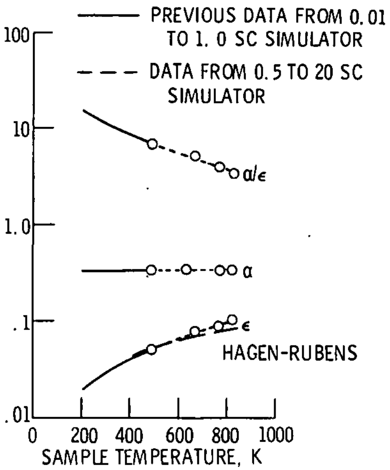


Figure 13. - Radiation property data of molybdenum.