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SPECTRAL AND OPERATIONAL CHARACTERISTICS OF A HIGH-INTENSITY CARBON ARC SOLAR SIMULATOR

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ABSTRACT

A commercially available high-intensity carbon arc solar simulator was evaluated to determine its suitability as a finely controlled radiant source for experimentally determining the solar absorptance of various materials. The spectral distribution of the radiant intensity is determined over the wavelength range from 0.36 to 2.1 μm, and the stability and uniformity of the radiant beam are evaluated. A control system which provides both a constant radiant intensity and a slowly varying sinusoidal perturbation of the radiant intensity is also discussed.

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SUMMARY

A commercially available high-intensity carbon arc solar simulator was evaluated to determine its suitability as a finely controllable radiant source for experimentally determining the solar absorptance of various materials. The spectral distribution of the radiant energy was determined over the wavelength range from 0.36 to 2.1 microns. The stability of the radiant intensity and the uniformity of the beam over a 12-inch- (30.5-cm-) diameter circle were also evaluated. Initially, considerable difficulty was encountered with intermittent instability of the carbon arc. However, with various modifications the stability was improved and could be maintained for long periods of time at approximately ±1.5 percent of the mean intensity level. The uniformity of the radiant intensity along the principal axis of a 12-inch- (30.5-cm-) diameter circle was ±4 percent. The uniformity, however, was very sensitive to the positioning of the optical elements of the simulator.

A control system was provided for the simulator to control the radiant intensity by movement of the two objective lenses in the optical system. The control system has been found to be very effective for maintaining constant radiant intensity and also for providing a sinusoidally perturbed intensity.

INTRODUCTION

In order to obtain accurate solar absorptance data on various materials, it is necessary to duplicate the solar energy spectral distribution. The carbon arc is considered to be one of the "higher fidelity" artificial high-intensity radiant sources available for the simulation of the solar energy spectrum. A commercially available carbon arc was purchased as a possible radiant source to be used for long-term testing at constant radiant intensity and, in particular, for determining the solar absorptance of various materials by the cyclic incident radiation technique described in references 1 and 2. The carbon arc, however, has inherent unstable operational characteristics which introduce fluctuations in the radiant intensity. These fluctuations, in turn, detract from its applicability as a universal simulation source and also introduce difficult control problems for experiments which require a controlled radiant intensity. The requirements of the cyclic radiation technique of reference 1 are quite demanding in that a controlled, low-frequency, small-amplitude, sinusoidal perturbation of the radiant intensity is required and must be maintained over long time periods. In addition, the mean intensity level must be variable over a fairly large range in order that solar absorptance data can be obtained over a range of material temperatures. A solar simulator to be used for this purpose must be critically evaluated to ensure compatibility with these difficult experimental requirements.

This report summarizes the primary radiative and operational characteristics of a particular carbon arc solar simulator. The spectral energy distribution and the important characteristics of operational stability and radiant intensity are presented. A control system incorporated into the simulator to provide the desired sinusoidally varying radiant intensity is described, and the final performance capabilities of the simulator are indicated.

SOLAR SIMULATOR DESCRIPTION

The solar simulator investigated herein was purchased from Genarco, Inc., as a standard Model TME4CWM high-intensity carbon arc 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 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 is 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) continuously variable radiant intensity from 0.5 to 2.0 solar constants by adjustment of the two objective lenses (see fig. 1), (2) interchangeable carbon and nonconsumable tungsten negative electrodes, and (3) 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 intended experimental program of 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.

The 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 as stable a radiant intensity beam as possible.

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 monochrometer having a lithium fluoride prism and a thermopile detector. The experimental arrangement is shown in figure 2. This arrangement duplicates as closely as possible the optical path and the intermediate components which existed in the application of the simulator.

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 of 165 microns. Figure 3 is the calibration curve obtained.

To verify that the calibration of the spectroradiometer for an uncollimated source also applies to the nearly collimated beam from the simulator, the tungsten filament lamp was installed in the simulator at the location of the carbon arc. The resulting beam is a low-intensity, collimated radiating beam. The comparison between the spectral irradiance of the tungsten filament lamp in the simulator and the NBS calibration of the same lamp as an uncollimated standard source is shown in figure 4. Because of the difference in intensity level the comparison in figure 4 is made by normalizing the radiometer output at the wavelength of 1.58 microns. The comparison between the two curves in figure 4 is generally good over most of the wavelength range of interest except for major differences at wavelengths of 0.85 micron caused by absorption by the aluminized front surface mirror, at 1.4 and 1.9 microns caused by water vapor absorption (caused by the 300-cm optical path length) and at wavelengths greater than 2.0 micron caused by the quartz (Dynasil) optical elements.

The spectral irradiance data obtained for the carbon solar simulator are compared with the solar spectrum data of reference 6 in figure 5. The data are also tabulated in table I. The carbon arc data were obtained for 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 to 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.

Figure 6 presents the ratio of the carbon arc irradiance to the solar irradiance. Generally, the carbon arc is a fair approximation of the solar energy curve. The carbon arc tends to have higher spectral irradiance values for wavelengths up to 0.45 micron as a result of strong band emission from the rare earth elements used in "doping" the positive electrode, lower irradiance from 0.45 to 0.8 micron, and higher irradiance in the near infrared. The largest differences occur at wavelengths greater than 1.5 microns, where the carbon arc spectral irradiance is as much as 50 percent higher than the solar spectrum. These large differences, however, are not of major concern because less than 15 percent of the total solar energy occurs at wavelengths beyond 1.5 microns.

The effect of the differences between the spectral irradiance of the carbon arc and the solar energy spectrum on solar absorptance determination was evaluated for aluminum and platinum. The evaluation was made by numerically integrating the product of the metal spectral reflectance and the solar or simulator spectral irradiance over the wavelength range from 0.36 to 2.10 microns. For aluminum, the calculated absorptances for solar, carbon arc with carbon negative electrode, and carbon arc with tungsten negative electrode spectral irradiance distributions were 0.107, 0.106, and 0.106, respectively. For platinum, the corresponding calculated absorptances were 0.254, 0.257, and 0.258. This comparison indicates that the absorptance of metals, as determined with a carbon arc simulator, is an accurate value for the solar absorptance.

The application of the simulator to the intended experimental program required that large variations in total radiant intensities be available in order to obtain data over a range of material temperatures. Of primary importance were data at low temperatures which required a radiant intensity of less than 0.1 solar constant. The procedure used for achieving the very low radiant intensity levels without altering the spectral distribution was to introduce a fine-wire 30-mesh screen into the beam between the front surfaced aluminized mirror and the first limiting aperture. The literature (e.g., ref. 7) indicates that, with proper use, screens act as neutral density filters over the solar wavelength range and therefore will not alter the spectral distribution. An evaluation of one screen was made to verify that screens are of neutral density. Figure 7 shows the ratio of the normalized spectral irradiance of the carbon arc with a screen to carbon arc irradiance without a screen. The normalization was achieved by matching the radiometer output for both curves at the wavelength of 1.58 microns. The screen introduces a slight effect into the spectral irradiance, but for solar absorptance measurements the screens are of practically neutral density over the wavelength range of interest.

The spectral irradiance distribution of this simulator is compared with that of other carbon arc simulators which had been previously evaluated by the authors in figure 8. The comparison is made on a normalized basis because all of the data were not obtained under similar conditions and the optical system of each simulator was different. The data are normalized on the basis of the total energy between 0.35 to 2.1 microns as compared to the total energy in the solar spectrum (ref. 6) over the same wavelength interval. The overall distributions obtained for the various carbon arc simulators are similar; however, sizeable differences in spectral irradiance do exist.

STABILITY

The instability of the carbon arc with resultant 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. The instability of the carbon arc is a complex phenomenon which appears to be associated primarily with the current level and the consumption, rotation, and axial motion of the positive carbon electrode. Figure 9 is a typical stability trace with the tungsten negative electrode as initially operated according to the manufacturer's directions. These data were obtained with a fast-response thermopile radiometer. Temporal variations of the order of ±5 percent of the mean intensity level are evident. A primary frequency corresponding to the rotational speed of the positive electrode is also present. The magnitude of the variations, however, was quite erratic and intermittent. Variations as high as ±10 percent and as low as ±2 percent frequently occurred. The intermittent character of the instability made a systematic evaluation for the source of the instability very difficult. Many attempts to eliminate the instability were tried with inconclusive or only moderate success. The tungsten negative electrode arrangement was somewhat more stable than the carbon negative electrode arrangement.

Many trial-and-error attempts to improve the operation of the arc resulted in the stability trace shown in figure 10. The intensity fluctuations were reduced to approximately $\pm 1\frac{1}{2}$ percent of the mean intensity level. This was considered to be an acceptable instability level. The most significant modifications which appeared to contribute to achieving this acceptable degree of stability were (1) a change in the relative alinement of the positive and negative electrodes, (2) a separate electrical power supply for the rotation and feed motor of the positive electrode and (3) operating experience to permit "tuning" of the system to operate in a "hands off" mode with only slight corrections. The constant-current power supply coupled with the automatic control of electrode position was also believed to be an influential factor contributing toward the final $\pm 1\frac{1}{2}$ percent stability level. Because of the many interacting parameters, however, it is difficult to single out the primary contributing factors.

Long-term drift of the mean intensity level can be detected in figure 10. This variation, however, was considered to be of minor importance because future modifications to the simulator included an intensity control system which could easily handle the small, slowly varying changes.

UNIFORMITY

The uniformity of the radiant intensity in the test plane was studied only 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 11 shows the beam uniformity at a mean intensity setting of 1 solar constant. The uniformity is within ±4 percent on both the vertical and horizontal axes.

The uniformity at higher or lower radiant intensity levels was approximately the same as that at 1 solar constant. However considerable care was required in the relative positioning of the two objective lenses in order to maintain good uniformity at both the higher and lower intensity levels. Small changes in the relative positions of the objective lenses could radically influence the uniformity. Large nonuniformities in terms of localized peaks or valleys could be introduced into the center of the beam by the indiscriminate positioning of either of the objective lenses. The lenses could not be moved independently of each other and still maintain good uniformity.

The sensitivity of beam uniformity on lens position was considered to be one of the major limitations of the optical system used for this simulator. Fortunately, however, with sufficient patience and proper techniques the correct lens settings could be established for acceptable uniformity at any radiant intensity level or test plane distance.

MODIFICATIONS

The experimental program for which the carbon arc solar simulator was intended was the determination of thermal radiation properties of various materials by the cyclic radiation method of reference 1. In this method a low-frequency, small-amplitude sinusoidal perturbation is imposed upon a mean radiant intensity level. The control system shown in figure 12 was provided to achieve this requirement. The positions of the two objective lenses are controlled simultaneously to provide the desired sinusoidal intensity variation and maintain acceptable beam uniformity. The two objective lenses are driven by a single balancing motor controlled through a differential amplifier. One side of the input to the differential amplifier is a generated reference signal which is composed of a direct-current reference signal to establish the mean intensity level and a single-turn continuous rotation potentiometer that provides a sinusoidal output signal. The combination of signals produces the desired sinusoidal perturbation of the mean signal level. The other side of the input to the differential amplifier is a radiometer located in the test plane of the radiant beam. Any difference in the voltage between the sinusoidal reference voltage and the radiometer output at the input of the differential amplifier results in rotation of the balancing motor and movement of the two objective lenses until the radiometer output balances the sinusoidal reference voltage. The balancing motor drives both objective lenses simultaneously but at different linear rates in order to maintain the desired relative position between the lenses required for good uniformity. Figure 13 shows two typical sinusoidal intensity traces as measured in the test plane; (1) a nominal 0. 10-watt-per-square-centimeter intensity level and a cylic frequency of 30 revolutions per hour and (2) a low radiant intensity level of approximately 0. 003-watt per square centimeter and a cylic frequency of 4 revolutions per hour. In both cases, the amplitude of the sinusoidal variation is approximately one-tenth of the mean intensity level. The noise or high-frequency variations superimposed on the sine wave are of the order of 2 percent of the mean signal and 20 percent of the amplitude of the sine signal. The noise levels for both the high- and low-intensity cases are of the same order. However, the noise is of high enough frequency that it is completely damped out and unnoticeable for the long time constants characteristic of the metal samples being studied. The control of the sinusoidal perturbation of the radiant intensity is reliable and repeatable.

The control system has also been conveniently applied to providing a constant radiant intensity for other experiments.

CONCLUSIONS

A commercially available high-intensity carbon arc solar simulator was evaluated. The spectral distribution of the radiant intensity was determined using both a carbon and a tungsten negative electrode, and a comparison was made with the solar energy spectrum and with the spectral distribution of other carbon arc simulators which had been previously evaluated. Only small differences were noted between the spectral distributions of the carbon and tungsten negative electrodes. The carbon arc spectral irradiance was higher than the solar energy spectrum for the wavelength range up to 0.45 micron, lower over the range from 0.45 to 0.80 micron, and considerably higher in the infrared wavelength range. The effect of these differences on the solar absorptance of metals was found to be small.

Considerable difficulty was initially encountered with the instability of the carbon arc and the corresponding fluctuations in the radiant intensity. By incorporating various modifications into the simulator and with increased experience, a fluctuation level of $\pm 1\frac{1}{2}$ percent of the mean intensity level could be maintained for long periods of time.

The uniformity of the radiant intensity was ±4 percent along the principal vertical and horizontal axes of a 12-inch- (30.5-cm-) diameter circle located a distance of 11 feet (3.35 m) from the last optical element. Due to the optical system used, the beam uniformity was found to be very sensitive to the location of the two objective lenses. The difficulty encountered in maintaining good uniformity by movement of the objective lenses is a serious limitation of the simulator.

A radiant intensity control system incorporated into the simulator is effective and reliable. A low-frequency sinusoidal variation of the radiant intensity can be maintained without amplitude or frequency variation for long periods of time. In addition, the control system can maintain constant radiant intensity for an indefinite period of time.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 16, 1969,
124-09-18-04-22.

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TABLE I. - SPECTRAL IRRADIANCE OF CARBON ARC SOLAR SIMULATOR

Wavelength, μm	Carbon negative electrode		Tungsten negative electrode		Wavelength, μm	Carbon negative electrode		Tungsten negative electrode	
	Irradiance, $W/cm^2/\mu m$	Ratio to solar spectrum	Irradiance, $W/cm^2/\mu m$	Ratio to solar spectrum		Irradiance, $W/cm^2/\mu m$	Ratio to solar spectrum	Irradiance, $W/cm^2/\mu m$	Ratio to solar spectrum
0.361	0.109	0.915	0.140	1.17	0.759	0.118	0.94	0.120	1.96
.366	.124	.962	.155	1.20	.795	.113	.99	.122	1.07
.371	.151	1.14	.179	1.35	.832	.109	1.04	.107	1.02
.377	.189	1.49	.209	1.65	.874	.113	1.19	.100	1.05
.382	.309	2.55	.324	2.68	.918	.086	1.00	.099	1.15
.388	.475	4.21	.478	4.22	.963	.085	1.09	.084	1.08
.392	.436	3.79	.472	4.11	1.01	.080	1.13	.078	1.11
.400	.257	1.67	.261	1.70	1.06	.071	1.11	.071	1.11
.407	.213	1.12	.236	1.24	1.11	.069	1.17	.066	1.12
.414	.284	1.48	.292	1.52	1.166	.062	1.17	.062	1.17
.421	.216	1.13	.209	1.09	1.22	.057	1.19	.055	1.14
.429	.200	1.11	.233	1.30	1.278	.050	1.16	.051	1.19
.438	.165	.86	.177	.92	1.33	.046	1.18	.051	1.31
.447	.224	1.03	.215	.99	1.382	.016	.46	.016	.45
.456	.182	.83	.214	.98	1.433	.040	1.29	.037	1.19
.466	.193	.90	.205	.95	1.483	.037	1.32	.037	1.32
.477	.168	.77	.173	.79	1.535	.035	1.40	.035	1.40
.488	.170	.85	.175	.88	1.580	.033	1.43	.033	1.44
.500	.173	.87	.187	.94	1.627	.031	1.48	.030	1.43
.514	.228	1.20	.222	1.17	1.671	.028	1.48	.028	1.48
.528	.198	1.03	.186	.96	1.718	.027	1.59	.027	1.59
.543	.167	.84	.160	.81	1.762	.025	1.56	.025	1.56
.560	.188	.99	.186	.98	1.80	.023	1.53	.023	1.53
.579	.152	.81	.150	.80	1.85	.020	1.43	.018	1.29
.598	.158	.87	.150	.82	1.893	.017	1.31	.017	1.31
.619	.170	.98	.150	.86	1.937	.019	1.58	.019	1.58
.642	.148	.91	.136	.84	1.978	.018	1.64	.017	1.55
.669	.128	.83	.120	.78	2.02	.016	1.60	.016	1.60
.697	.121	.83	.124	.86	2.06	.014	1.47	.014	1.47
.727	.120	.89	.119	.88	2.10	.012	1.34	.013	1.45

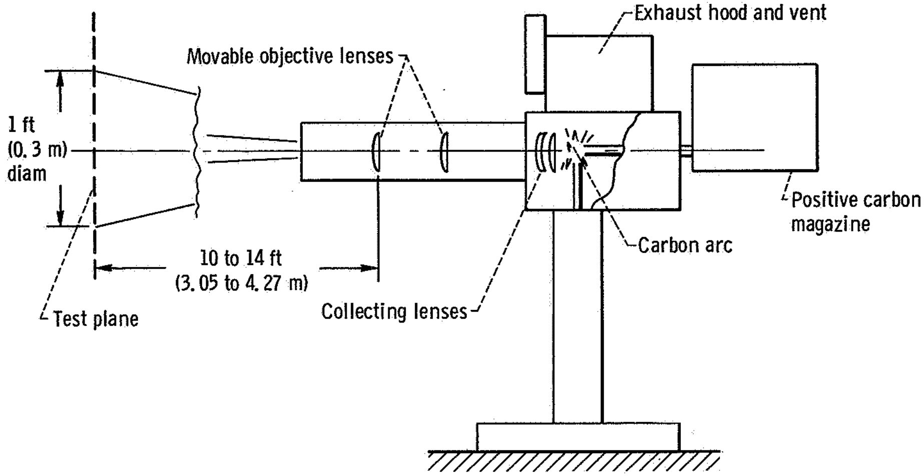


Figure 1. - Schematic drawing of carbon arc solar simulator.

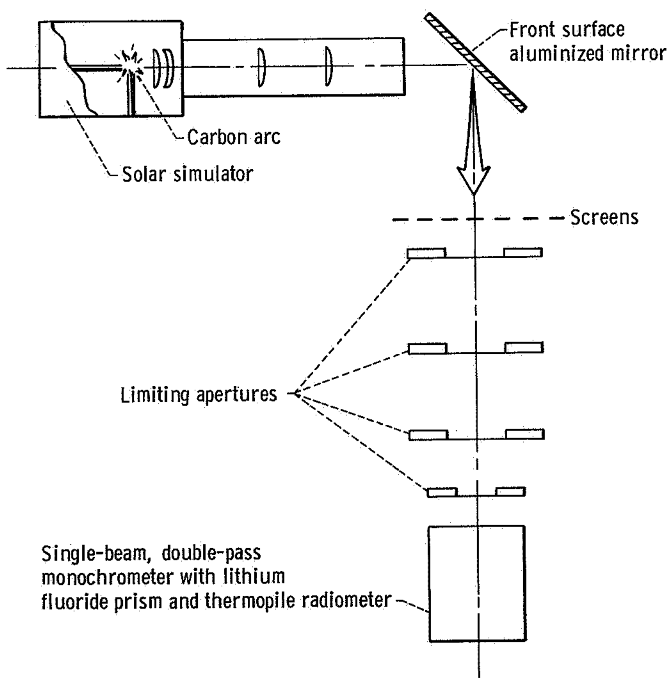


Figure 2. - Experimental arrangement used for spectral irradiance evaluation.

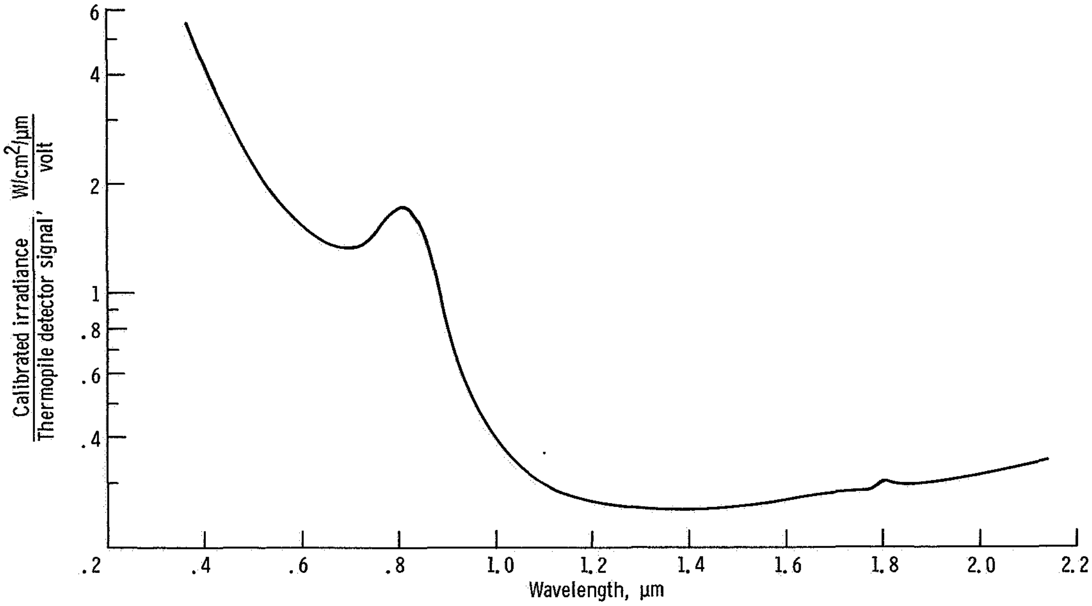


Figure 3. - Spectroradiometer calibration curve for slit width of 165 microns.

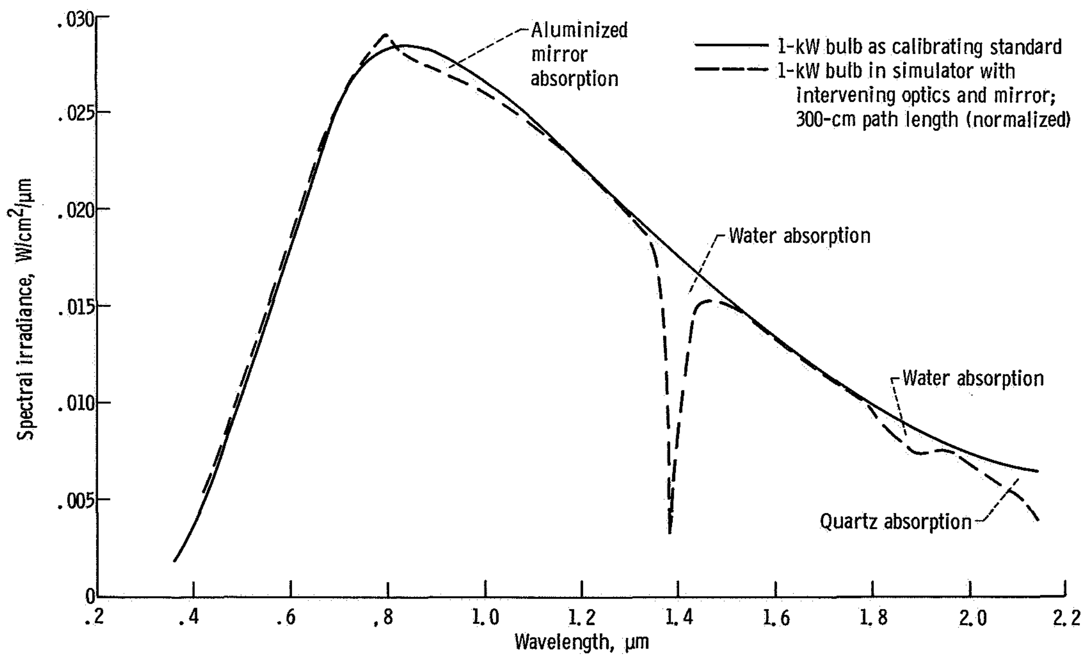


Figure 4. - Comparison between spectral irradiance of 1-kilowatt lamp used as calibrating standard and 1-kilowatt lamp in solar simulator.

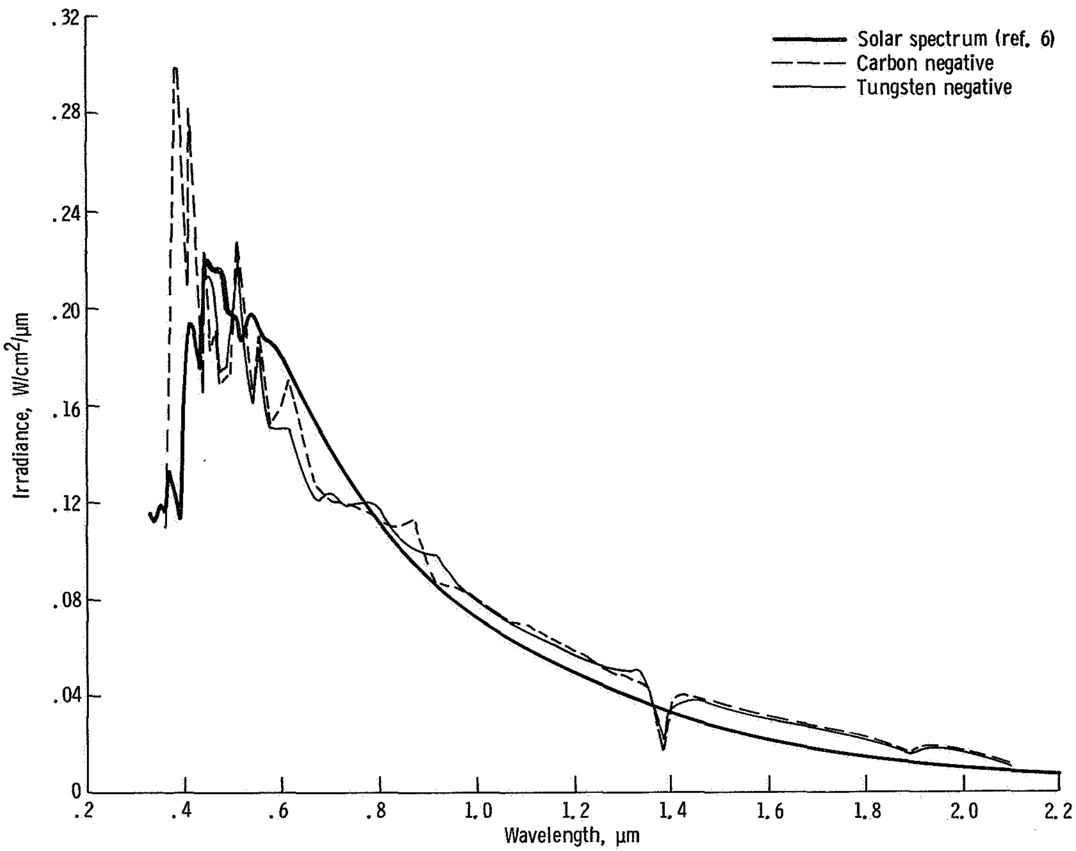


Figure 5. - Spectral irradiance of carbon arc. Diameter of carbon, 13.5 millimeters at 185 amperes.

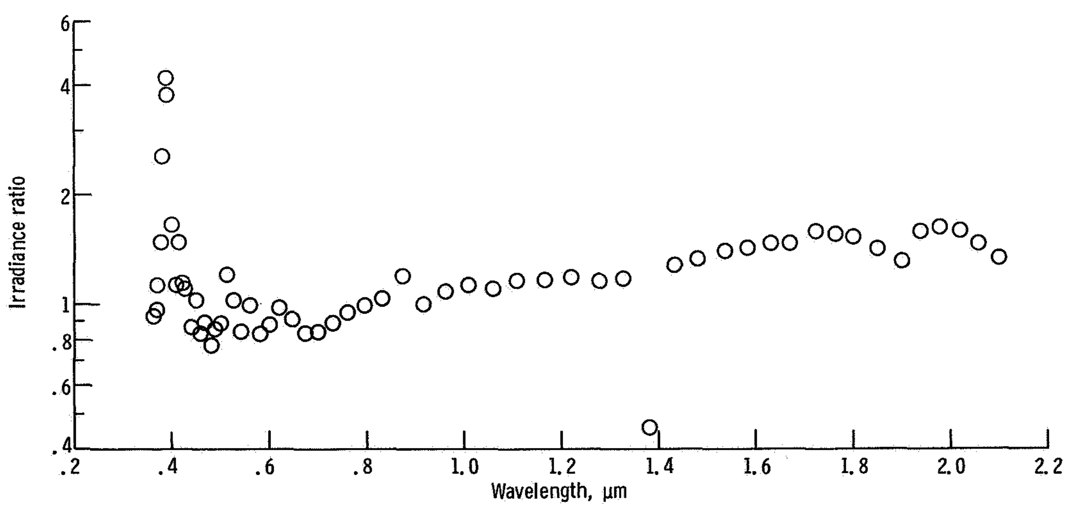


Figure 6. - Ratio of carbon arc irradiance to solar spectrum irradiance (carbon negative).

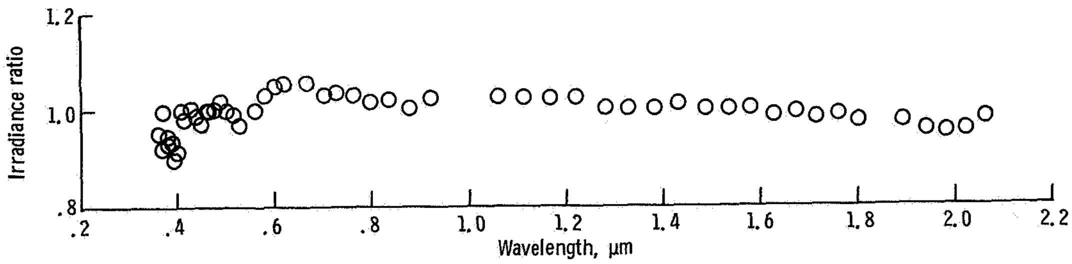


Figure 7. - Ratio of carbon arc lamp irradiance with screens to irradiance without screens.

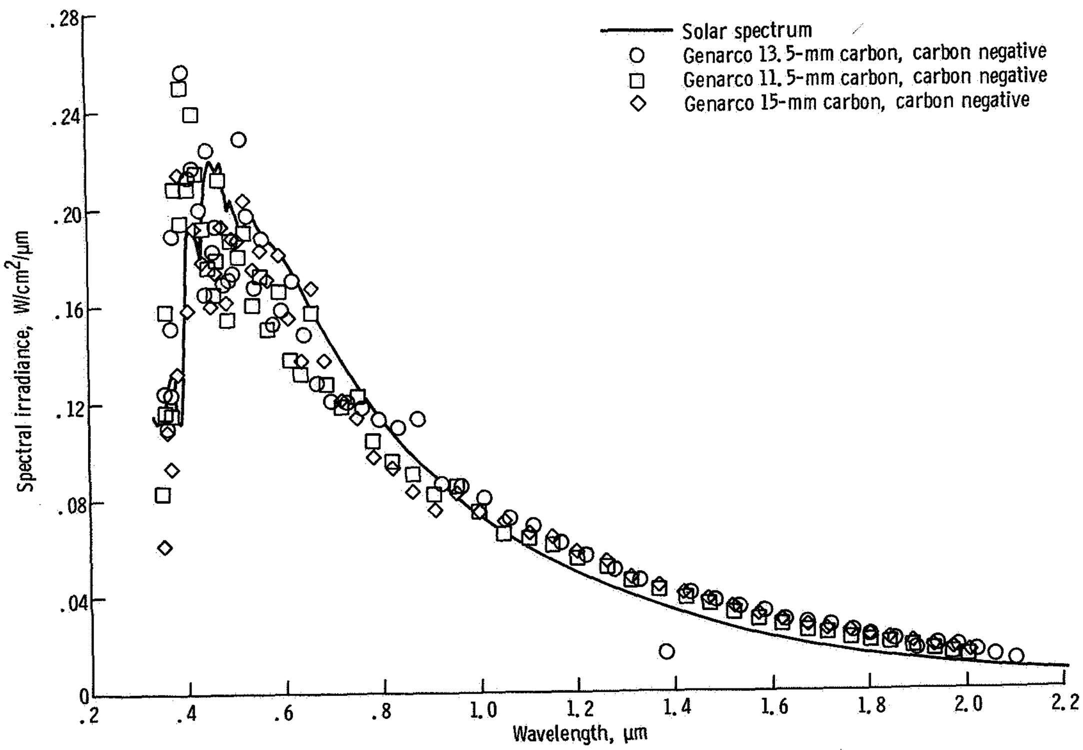


Figure 8. - Spectral irradiance of various carbon arc solar simulators.

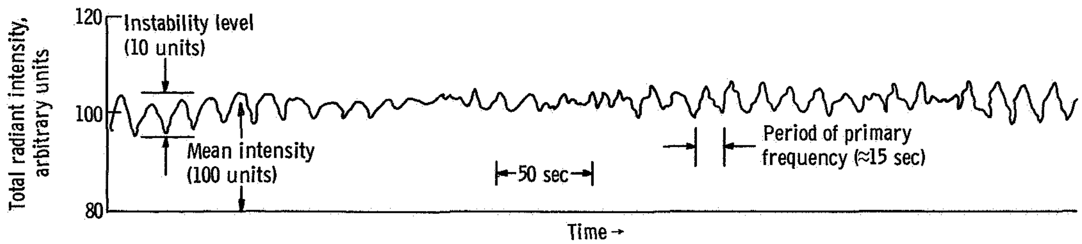


Figure 9. - Typical initial stability of carbon arc solar simulator (tungsten negative electrode).

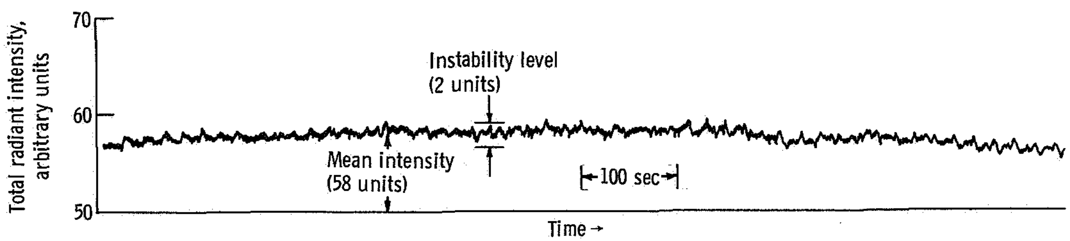
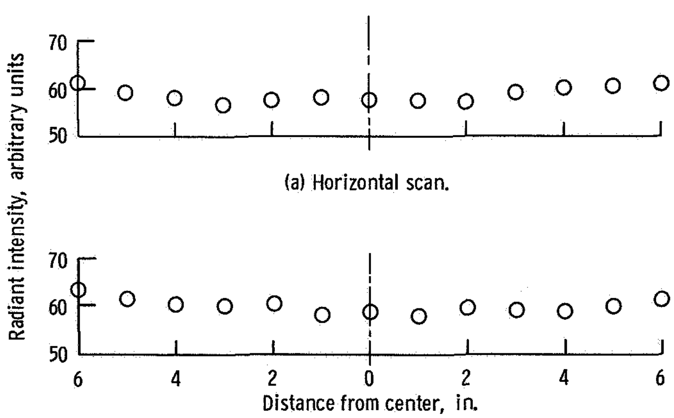


Figure 10. - Acceptable stability level of carbon arc solar simulator.



(b) Vertical scan.

Figure 11. - Radiant intensity profile along major horizontal and vertical axes.

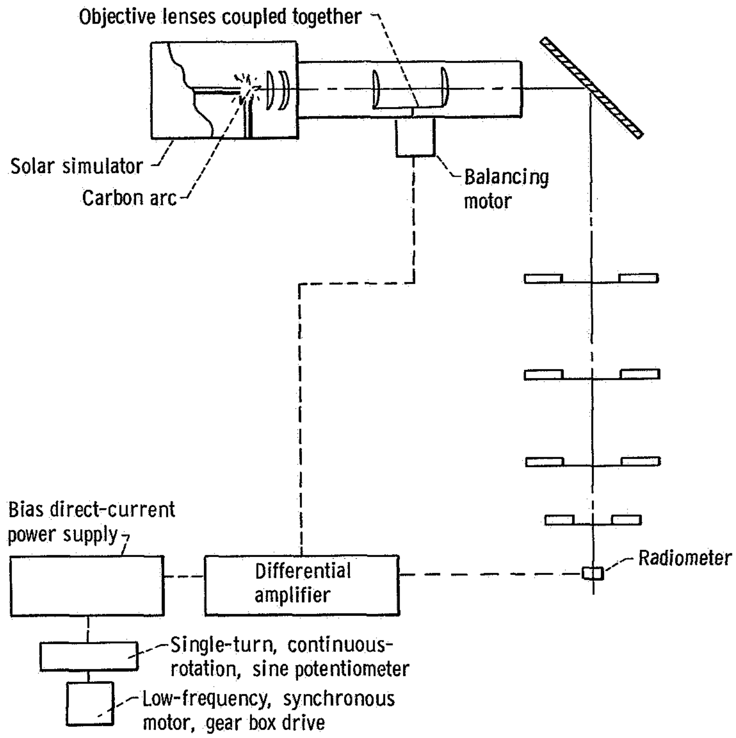
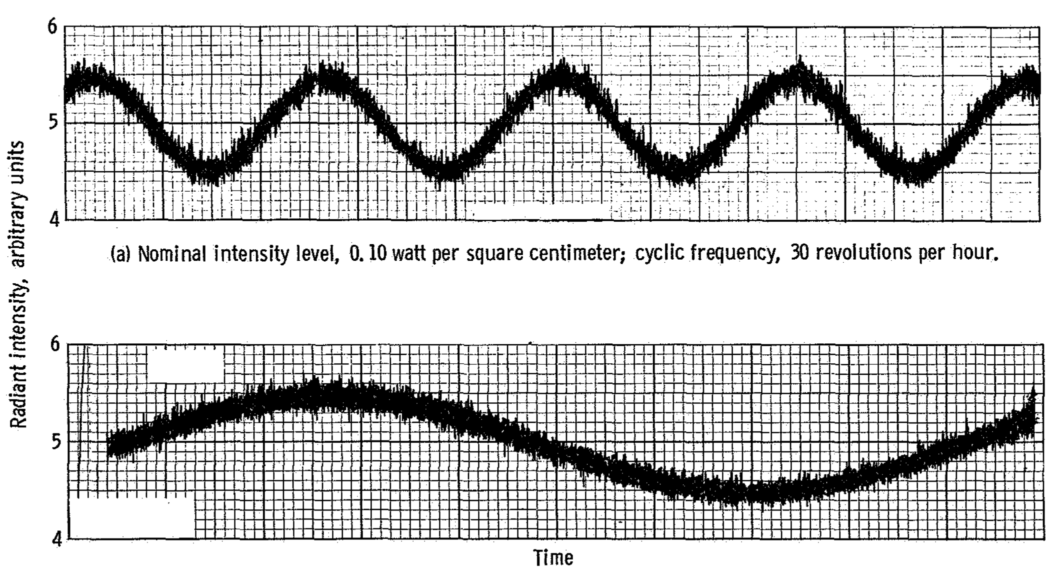


Figure 12. - Schematic drawing of control system for radiant intensity.



(a) Nominal intensity level, 0.10 watt per square centimeter; cyclic frequency, 30 revolutions per hour.

(b) Nominal intensity level, 0.003 watt per square centimeter; cyclic frequency, 4 revolutions per hour.

Figure 13. - Sinusoidal perturbation of radiant intensity.

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