INVESTIGATION OF THE CARBON ARC SOURCE AS AN AM0 SOLAR SIMULATOR FOR USE IN CHARACTERIZING MULTI-JUNCTION SOLAR CELLS[1]

Jianzeng Xu and James R. Woodyard
Wayne State University
Detroit, Michigan 48202

ABSTRACT

The operation of multi-junction solar cells used for production of space power is critically dependent on the spectral irradiance of the illuminating light source. Unlike single-junction cells where the spectral irradiance of the simulator and computational techniques may be used to optimized cell designs, optimization of multi-junction solar cell designs requires a solar simulator with a spectral irradiance that closely matches AM0. This is particularly true for multi-junction solar cells designed to be used in radiation environments as well as cells that experience photo-degradation under AM0. The carbon arc source is being investigated to determine its suitability as an AM0 solar simulator for the characterization of multi-junction solar cells. The spectral irradiance of readily available solid and cored carbon rods has been investigated. The spectral irradiance produced by the carbon rods used in these investigations is due to two mechanisms. One is spectral emission from atoms and molecules in the arc that originate from the gaseous atmosphere and the carbon rods. The other mechanism is thermal radiation from the high temperature carbon rods. The spectral irradiances for these two mechanisms are quantified and compared with the WRL AM0 spectrum.

INTRODUCTION

High efficiency two-terminal monolithic multi-junction solar cells are attractive for space applications because they can be designed to convert a larger fraction of AM0 irradiance into electrical power than single-junction cells. The design of multi-junction cells for space applications requires matching the optoelectronic properties of the junctions to the spectral irradiance of the AM0 spectrum. This is the case because the junctions are in series and optical injection and carrier collection in each junction must be critically balanced to optimize cell performance.

Multi-junction solar cells, unlike single junction cells, must be characterized under light-bias conditions with a light source having the spectral irradiance of the source to be used under power-generating conditions. Cells employed for space-power applications must therefore be characterized either using AM0 or a solar simulator that approximates AM0. Since true AM0 measurements can only be made in space, and access to space is limited and costly, there is a need to develop laboratory-based methods for characterizing multi-junction solar cells. The methods include measurements of current-voltage characteristics and quantum efficiencies, as well as determining the accuracy of the solar simulator spectral irradiance required for effective AM0 cell characterization. If laboratory-based AM0 measurements are going to be effectively employed in optimizing multi-junction solar cell designs and fabrication methodologies, the specifications of the spectral irradiance of solar simulators to be used in the characterization of virgin, photo-degraded and irradiated cells must be determined. The goal of this work is to evaluate the carbon arc source for use in the characterization of multi-junction solar cells and to determine the dependence of the accuracy of the spectral irradiance compared to AM0 for effective cell characterization.

---

[1] This work was supported under NASA Grant NAG3-2180.

DESCRIPTION OF CARBON ARC LIGHT SOURCE

Investigations in our laboratory of the carbon arc light source for use as an AM0 solar simulator were carried out with an Aschraft Super-High projection lamp house. The unit is typical of lamp houses used in movie film projectors prior to their replacement with high-pressure xenon arc discharge lamp in the late 1960's. The lamp house used in this work was made available by the Department of Public Works, Dearborn, Michigan. The National Electrical Carbon Company (NECC) in Fostoria, Ohio, was very helpful in providing a manual for the lamp house, showing us how to "burn" carbon rods, and transferring company reports on the development of carbon arc technology. The carbon rods used in these investigations were purchased from NECC.

A diagram of the lamp house is shown in Figure 1. The arc is maintained between two carbon rods; one is maintained at a positive polarity and the other is negative. The horizontal positive rod is rotated and fed into the arc at a rate of about 300 to 600 mm per hour. The negative carbon rod is not rotated; it is fed into the arc at an angle that is about 25 to 30 degrees below the horizontal axis of the positive rod. The feed rate of the negative rod is about one-third that of the positive rod. The rotation of the positive rod and the feed rate of both rods is accomplished with a drive assembly that includes a variable-speed DC motor, gear box and drive chains. The rod holders are designed for positive rods 10 to 11 mm in diameter and negative rods 9 mm in diameter. The positive and negative rods used in this work were about 510 and 230 mm in length, respectively, and the negative rods were copper cladded.

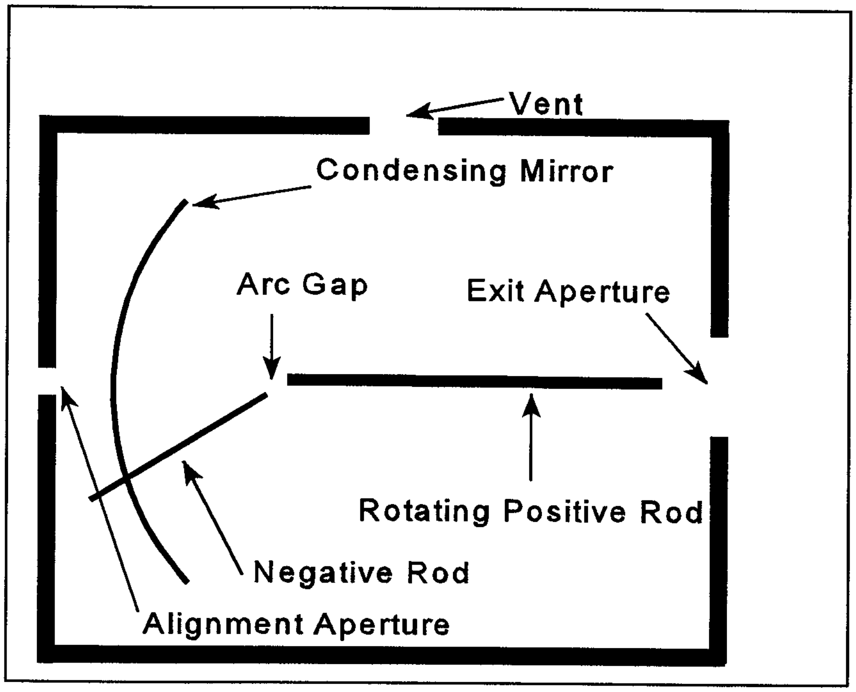

Figure 1. Diagram illustrating the optics of the carbon arc lamp house

Light is produced by sustaining an arc between the positive and negative carbon rods that is powered by a DC power supply. A model 330A/BP Miller welding power supply was used for the initial experiments. However, it was difficult to control the carbon arc current and voltage; the unit was subsequently replaced with a Miller Syncrowave 500 constant current power supply. The feed rate of the rods was controlled to maintain an arc gap of about 10 mm during the experiments. Electrical contact to the rotating positive rod is effectuated with water-cooled silver contact shoes located about 25 mm from the arc gap. Arc currents and voltages were typically 90 to 130 A at 40 to 90 VDC, respectively. The burn time for a positive rod was about one hour. The lamp house also had external mechanical controls for displacing the rod holders to strike the arc and to correct for variations in the feed rate of the rods in order to maintain a good burn. A good burn is one that produces the maximum constant light intensity with minimum arc instabilities. The lamp house was vented to an air handling system that discharged the arc gases to a stack on the roof of the research laboratory.

Figure 1 shows the lamp house with a condensing mirror that focuses the light from the carbon arc on the exit aperture of the lamp house. The mirror was removed from the lamp house to permit the light to pass through the alignment aperture for the spectral irradiance measurements. The modification was made to insure the spectral irradiance of the light produced by the carbon arc was not influenced by the optical properties of the condensing mirror. The spectral irradiance was measured with a computer-interfaced spectral radiometer [1]. The spectral radiometer employs an integrating sphere, order-sorting filters, 275 mm focal length f/3.8 monochromator and silicon photodetector. The spectral response of the photodetector limits the spectral irradiance measurements to the 350 to 1100 nm wavelength range. The wavelength scale of the monochromator was calibrated with a Hg(Ar) pencil light source. The intensity calibration was carried out with a FEL lamp traceable to NIST standards. The entrance port of the spectral radiometer was positioned on the axis of the positive rod and located opposite the alignment aperture at a distance of 43.2 cm from the center of the carbon arc.

RESULTS

The spectral irradiance of NECC L-0106 and NECC TC-190 positive rods was investigated. The L-0106 positive rod has an outer carbon shell filled with a proprietary compound; the rod is referred to as a cored rod. The TC-190 positive rod is a high purity solid carbon rod and referred to as a pure carbon rod in this work. NECC L-1115 negative rods were used with the positive rods. The negative rods were solid carbon with a copper cladding.

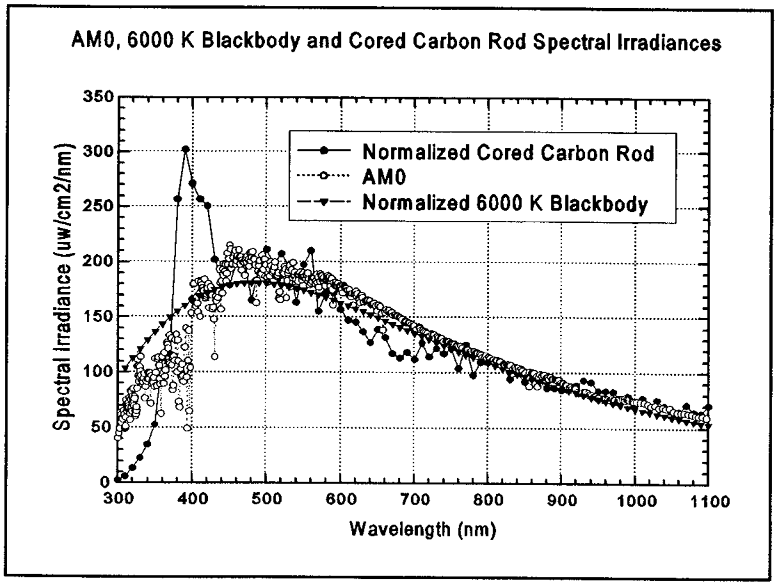

Figure 2. AM0 spectrum and the spectral irradiances of a 6000 K blackbody and cored carbon rod measured with 6.0 nm resolution

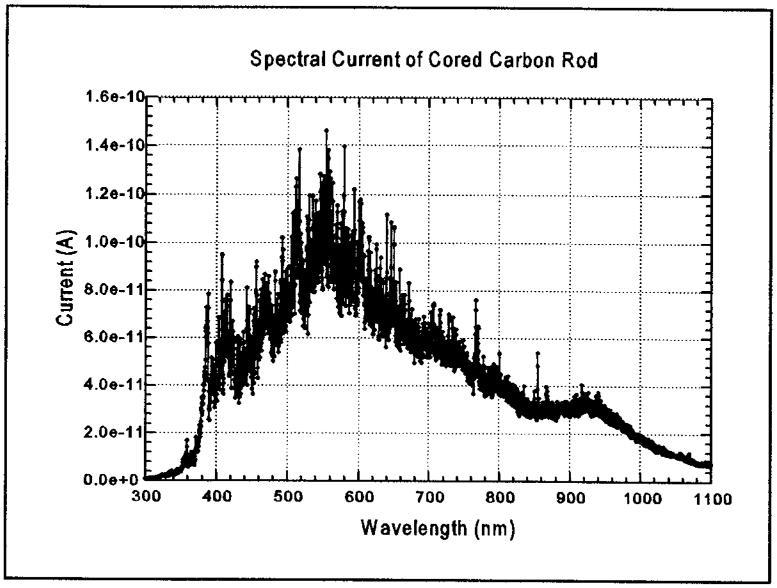

Figure 3. Spectral current of cored carbon rod measured with 0.5 nm resolution

The spectral radiometer was configured with 2 mm slits and measurements made in 10 nm steps; the resolution of the spectral radiometer was about 6 nm for the first set of experiments. The spectral irradiance of a cored carbon rod is shown in Figure 2. The current, voltage and power were unstable during the experiment and were about 100 A, 90 V and 9.0 kW, respectively. For comparison purposes, the spectral irradiance of the World Radiation Laboratory AM0 spectrum and the calculated spectral irradiance of a 6000 K blackbody are shown. The spectral irradiance of the 6000 K blackbody and cored carbon rod were normalized to the AM0 spectrum. The major deviation from the AM0 spectrum occurs in 300 to 440 nm region. The spectral irradiance of the carbon arc is greater than AM0 from 360 to 440 nm and less than AM0 in the 300 to 350 nm range. The existence of a peak at 390 nm, as well as the structure of the peak, suggest that spectral emission contributes to the spectrum. The measurements shown in Figure 2 were complicated by the instability of the arc due to the difficulty in controlling the arc current and voltage with the model 330A/BP Miller power supply. A more stable power supply, namely, a Miller Syncrowave 500 constant current power supply, was installed in the system.

Investigations of the cored carbon rods were then carried out with 0.15 mm slits in the spectral radiometer and a resolution of about 0.5 nm. The wavelength was stepped in intervals of 0.25 nm. The measured spectral current is shown in Figure 3. The arc current, voltage and power were 105.6 ±1.2 A, 52 ± 4 V and 5.5 kW, respectively. The spectral current has a great deal of structure suggesting the spectrum contains a large number of emission lines.

The literature was reviewed to determine if the elements producing the spectral lines could be identified [2,3]. Several elements have emission lines in the wavelength range investigated. The cited references do not specify the measurement conditions under which the spectral lines were measured. Relative values are reported for the intensity of lines resulting from the numerous transitions that are possible in the various elements. At this time we are unable to identify most of the spectral lines in Figure 3.

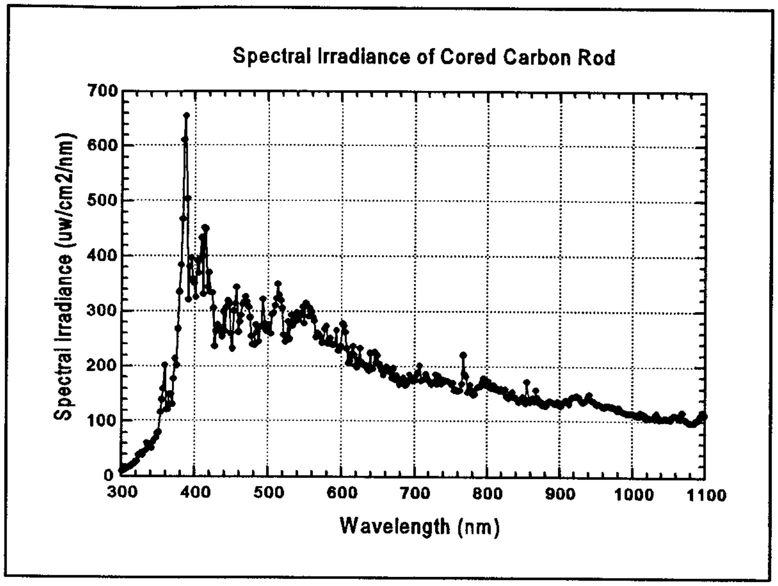

Figure 4. Spectral irradiance of cored carbon rod averaged over 2.0 nm intervals

The spectral irradiance was calculated from the spectral current using the calibration data for the spectral radiometer. The spectral radiometer was calibrated with a resolution of 2.0 nm, the resolution of the data supplied with the calibrated FEL lamp. However, the data in Figure 3 are the spectral current measured in 0.25 nm wavelength intervals. Instead of extrapolating the lamp calibration data to obtain the spectral irradiance in 0.25 nm wavelength intervals, the spectral irradiance was calculated in 2.0 nm intervals by averaging the spectral current over 2.0 nm intervals. The results are shown in Figure 4. The peaks in the 360 to 420 nm range of the spectral irradiance dominate at shorter wavelengths. The literature [4] suggests that these peaks are due to three vibrational bands of the cyanogen molecule, CN. According to the literature, the emission spectrum of these bands can be eliminated by burning the arc in a nitrogen-free atmosphere.

Figure 4 is instructive because the fine structure illustrated in Figure 3 is smoothed by the averaging calculations; only the structure at about 380 nm remains. It points to the role of the optoelectronic properties of a solar cell in determining the specifications of the spectral irradiance for an AM0 simulator. The rate of change of the optical absorption coefficient with respect to wavelength of the solar cell determines the importance of the fine structure in the simulator spectral irradiance. Should the rate of change of the optical absorption coefficient be small over the spectral range where emission lines dominate, then the fit of the averaged spectral power to AM0 over the wavelength range is the determining factor. The spectral-irradiance specifications of an AM0 solar simulator are therefore critically dependent on the wavelength dependence of the optical absorption coefficient of the materials used in the fabrication of multi-junction solar cells.

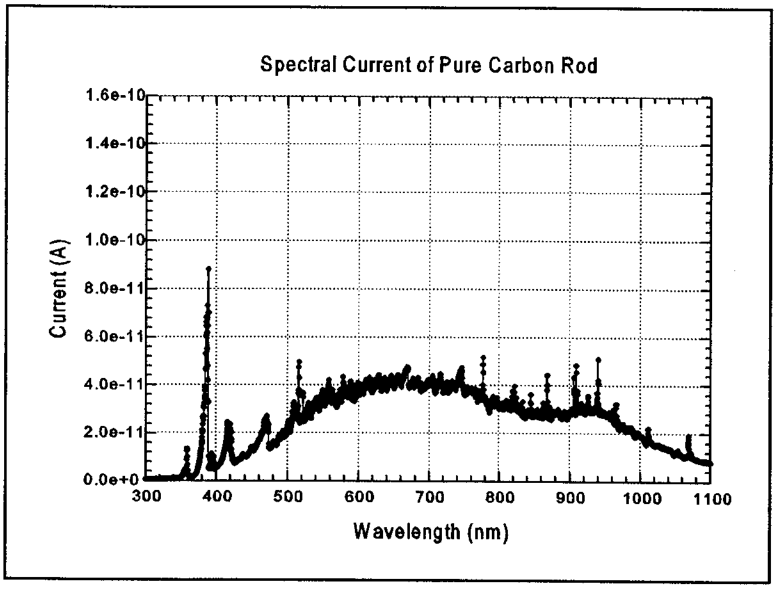

Figure 5. Spectral current of a pure carbon rod measured with a resolution of 0.5 nm

Pure carbon positive rods with 11 mm diameters were investigated to determine the role of the spectral emission of compounds in the cored carbon rods. It was reasoned that black body radiation of the carbon rods, and the emission spectrum of carbon atoms, would dominate the spectral irradiance if only carbon were in the arc. Figure 5 shows the spectral current measured with 0.15 mm slits, 0.25 nm steps and a resolution of about 0.5 nm. The arc current, voltage and power were 104.0 ± 0.4 A, 49 ± 1 V and 5.1 kW, respectively. Note that there is very little structure in the 400 to 800 nm range. A comparison of Figure 5 with Figure 3 suggests that the structure in the 400 to 800 nm range of Figure 3 is due to spectral emission from the compounds in the cored carbon rods.

The spectral current of the pure carbon rod in Figure 5 and the spectral radiometer calibration data were used to calculate the average spectral irradiance over 2.0 nm intervals. The results are shown in Figure 6.

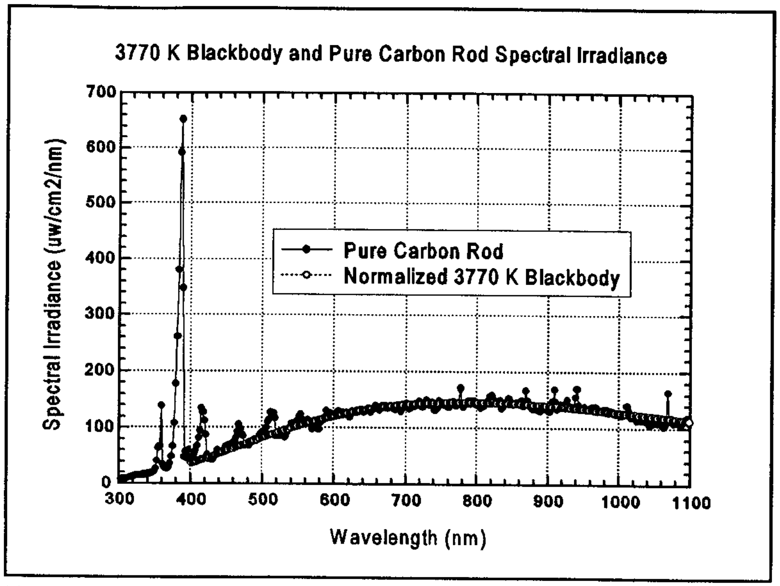

Figure 6. Spectral irradiance of pure carbon rod averaged over 2.0 nm intervals and spectral irradiance of normalized 3770 K blackbody

Comparison of Figure 6 with Figure 4 illustrates the relative power irradiated by an arc with cored carbon rods as compared to pure carbon rods.

A least-squared fit of the spectral irradiance of the pure carbon rod shown in Figure 6 to the spectral irradiance of blackbody at a given temperature was investigated. The spectral lines in shown in the figure were subtracted from the spectral irradiance of the pure carbon rod. The best fit to the data was obtained for a blackbody temperature of 3770 ± 10 K. The temperature compares favorable with the 3752 to 3825 K range of sublimation temperatures for carbon with various types of structures. This suggests that thermal radiation is the main mechanism for radiating power from an arc produced by burning pure carbon rods. The suggestion is is also confirmed by the fact that there is relatively little structure in the spectral current in Figure 5 as compared to Figure 3. The agreement of the spectral irradiance in the 900 to 1100 nm range of Figures 4 and 6 suggests that the cored carbon rods are at approximately the same temperature as the temperature of the pure carbons.

A comparison of the burn rate, input power and radiated power for the pure and cored carbon rods is presented in Table I. The radiated power was determined by numerical integration of the spectral irradiance in the 300 to 1100 nm wavelength range. The table shows that the burn rate of the cored rod is 2.1 times higher than the pure carbon rod; the arc input power is the same to within about 7% for the two types of rod. The radiated power is 93 mW/cm^2 for the pure carbon rod as compared to 150 mW/cm^2 for the cored carbon rod. The radiated power is 1.6 times higher for the cored carbon rods. The difference in the irradiated power for the two rod types, namely, 57 mW/cm^2, appears to be due to power radiated by atomic emission of the elements in the cored carbon rods. While the burn rate for the cored carbon rods is 2.1 times that of the pure carbon rods, it does not appear to be a determining factor in power radiated as long as the input power to the arc is approximately the same for the two types of carbon rods. The AM0 integrated power in the 300 to 1100 nm wavelength range is 99.8 mW/cm^2. Table I shows that 150 mW/cm^2. Is radiated by the cored carbon rods on a surface located at a distance of 43.2 cm from the arc. Therefore the intensity of the light radiated from the carbon arc in this spectral range is more that sufficient for AM0 simulation.

Table I

Rod	Dia. (mm)	Burn Rate (mm/hr)	Input Power (kW)	Radiated Power mW/cm^2
Cored	10	530	5.5	150
Pure	11	250	5.1	93

CONCLUSIONS

The investigations enabled us to quantify the mechanisms for radiation produced by a carbon arc. The best fit to the data was obtained for a blackbody temperature of 3770 ± 10 K. This compares favorable with the 3752 to 3825 K range of sublimation temperatures for carbon with various types of structures. The spectral irradiance produced by the carbon rods used in these investigations is due to two mechanisms. One is spectral emission from atoms and molecules in the arc that originate from the gaseous atmosphere and the carbon rods. The other mechanism is thermal radiation from the high temperature carbon rods. The spectral irradiances for these two mechanisms were quantified; the spectral irradiance from the carbon arc compares favorable with the WRL AM0 spectrum. Future work will include extending the wavelength measurement capability to 1800 nm and modifying the lamp house to permit investigations in inert gases in an effort to reduce the spectral irradiance in the 360 to 440 nm wavelength range.

REFERENCES

1. Laboratory Instrumentation and Techniques for Characterizing Multi-Junction Solar Cells, James R. Woodyard, Proceedings of the XIV Space Photovoltaic Research and Technology Conference 1995, NASA Conference Publication 10180, page 158.
2. Tables of Spectral Lines of Neutral and Ionized Atoms, A. R. Striganov and N. S. Sventitskii, IFI/Plenum Data Corporation, New York, 1968.
3. Tables of Spectral Lines, A. N. Zaidel, V. K. Prokofev, S. M. Raiskii, V. A. Slavnyi and E. Ya. Shreider, IFI/Plenum Data Corporation, New York, 1970.
4. L. H. Ahrens and S. R. Taylor. Spectrochemical Analysis. Reading, MA: Addison-Wesley Publishing Company, 1961, pages 66 and 172.