NOTICE

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GLOBAL CALIBRATION OF TERRESTRIAL REFERENCE CELLS AND ERRORS INVOLVED IN USING DIFFERENT IRRADIANCE MONITORING TECHNIQUES

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National Aeronautics and Space Administration
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Work performed for
U.S. DEPARTMENT OF ENERGY
Energy Technology
Distributed Solar Technology Division

Prepared for
Fourteenth Photovoltaic Specialists Conference
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ABSTRACT

Experiments have shown that global calibration of terrestrial reference cells is feasible provided reasonable constraints on irradiance and incident sun angle are used. There is significantly less dependence of the calibration value on atmospheric composition in the global method compared to the collimated technique. A simple, accurate "secondary" calibration technique based on ratios of test to reference cell currents measured in natural sunlight was developed. Studies and experiments have been performed to determine relative merits and errors involved in using different techniques for monitoring incident irradiance during solar cell performance measurements. The techniques of black-body detectors, calibrated reference cells, and the convolution of spectral response with solar irradiance are considered. The second is the most accurate technique.

INTRODUCTION

Calibrated reference cells have been used to measure and monitor solar irradiance for photovoltaic performance measurements for many years. Reference cells are used in both simulated and natural sunlight for space and terrestrial cell measurements. Because solar cells have a response which is proportional to solar intensity and which varies greatly with wavelength, their output varies with changes in the spectral distribution of incident irradiance. Large variations in calibration number (short-circuit current per unit incident irradiance) occur when the same cell is measured under different light sources relative to a black-body detector. Calibrated reference cells have been used to greatly reduce the effect of these variations (1).

Reference cells must be available and calibrated to be useful as irradiance monitors. Currently, cells are calibrated for space testing by flying them on high altitude balloons or aircraft, and extrapolating short-circuit current data to zero air mass (2,3). Terrestrial cells are calibrated using a normal incidence phyrheliometer and a corresponding collimating tube for the cell. Data are taken at standard levels of atmospheric parameters (turbidity, air mass, water vapor content) or, corrected to those standard level (4).

The recent growth of terrestrial photovoltaic activity has raised two concerns about the calibration of terrestrial reference cells. One involves the desire to use global sunlight for calibration rather than only the direct solar beam. This concern arises because solar cells used in terrestrial applications generally view the entire sky (except in concentrator applications), and not just the direct beam. The second concen involves the complexity of the present calibration technique which involves measurement of atmospheric parameters. Thus, to resolve these issues, as part of the DOE National Photovoltaic Program, the NASA/Lewis Research Center has been investigating the feasibility of the global calibration of terrestrial reference cells. It is the primary purpose of this paper to present the results and conclusion of a year-long experimental study on feasibility of global calibration.

Secondly, although the reference cell technique is the recommended procedure for the total irradiance during photovoltaic performance measurements, several alternative procedures have been used by various laboratories. The two main alternatives are (1) use of a black-body detector such as a thermopile or pyranometer, and (2) the convolution of the measured spectral response of the test cell against the spectral distribution of either space or terrestrial sunlight to obtain cell short-circuit current. The incident irradiance is subsequently adjusted so the cell reads the convoluted short-circuit current and performance measurements are made (5).

At the NASA-Lewis Research Center, experiments and calculations have been performed to examine the relative merits of these three different techniques for irradiance monitoring of simulated and natural sunlight for space and terrestrial applications. The results of this study will be reported here. Additionally, the magnitude of measurement errors in short-circuit current attributed to spectral mismatch for each technique are presented.

APPARATUS FOR GLOBAL CALIBRATION

The basic approach to the global calibration experiment is to expose a variety of terrestrial reference cells having different spectral responses to global sunlight and monitor short circuit-current for an extended period of time, while also measuring the output of a pyranometer. No measurements of atmospheric water vapor content or turbidity were made.

Figure 1 shows the test fixture with three reference cells in place. The cells are tilted to an angle of 37° above the horizontal. This is a few degrees less than the local latitude (41.4°) and is representative of the tilt angles for terrestrial photovoltaic use. There is a horizon shield to block off incident irradiance from below the horizon and the cells are pointed south. A pyranometer having the same orientation and shielding is located adjacent to this test fixture.

Of the three positions for reference cells, one is always occupied by cell Y-229, a stable silicon solar cell. Several other typical silicon cells, a cadmium sulfide cell, a gallium arsenide cell and a silicon cell with low lifetime are rotated among the other two positions. Cell changes are made approximately monthly. The cells are placed outdoors on any reasonable sunny, dry day. Data are taken throughout the day as the sun angle changes.

Voltage drop across a precision 0.1 Ω resistor is used to determine cell short-circuit current. The data are continuously integrated and automatically recorded at 1 hour intervals, along with the pyranometer reading. Temperature of one cell is measured and used to correct all cell currents to 28° C. The air mass and direct beam solar incidence angle are calculated from time of day and day of year.

APPROACH FOR COMPARISON OF DIFFERENT IRRADIANCE MONITORING TECHNIQUES

The basic approach for comparing the three different irradiance monitoring techniques is based on measurement of short-circuit current. It is assumed that short-circuit current (I_{sc}) may be expressed as:

$$I_{sc} = A\int R(\lambda)J(\lambda)\, d\lambda \quad (1)$$

Where A is cell active area, $R(\lambda)$ is cell spectral response and $J(\lambda)$ is the spectral distribution of the incident irradiance. The calibration number is defined as short-circuit current per unit incident irradiance, where incident irradiance is given by $\int J(\lambda)\, d\lambda$ or:

$$\text{Cal. No.} = \frac{A\int R(\lambda)J(\lambda)\, d\lambda}{\int J(\lambda)\, d\lambda} \quad (2)$$

Obviously, I_{sc} and calibration number for any cell will change as the incident irradiance changes. Because a black-body detector measures the total irradiance, errors involved in using this technique may be determined readily by comparing calculated calibration numbers.

For the spectral response convolution technique, error determinations may be made for those cells which have both an absolute spectral response measurement and either a measured terrestrial or space calibration number. Then the calculated calibration number can be readily compared with the actual measured value.

Evaluation of the reference cell technique is slightly more complicated. Spectral response curves for both a test cell (cell to be measured) and the reference cell are needed in addition to the spectral distribution of both the test irradiance and the irradiance of the intended application (space or terrestrial). In the reference cell technique, the test irradiance is measured with the reference cell, which has a spectral response similar to that of the test cell. Then the performance measurements of the test cell are made at that irradiance. Hence, an evaluation of the reference cell technique may be made by comparing the ratio of calibration numbers for the test cell, calculated under the desired simulator and solar spectra, with the same ratio for the reference cell (1).

Figure 2 plots two solar irradiance curves of interest: the outer space AMO curve of Labs + Nickel and the calculated direct beam terrestrial irradiance curve at air mass 1.5 (4). In the terrestrial case, the diffuse component of sunlight is also needed. Figure 3 shows a calculated direct and diffuse beam with the sun at 60° from the zenith (AM2) (6). Figure 4 shows the measured spectral irradiance distributions of four commonly used solar simulators compared to the AM 1.5 distribution. They are: (1) short arc filtered xenon; (2) long arc pulsed unfiltered xenon, (3) 3400 K tungsten filament quartz halogen lamps; and (4) the dichroic filtered quartz halogen lamps (ELH type).

Figure 5 shows a spectral response curve for four typical cells: silicon, gallium arsenide, cadmium sulfide and a low-lifetime silicon cell.

RESULTS AND DISCUSSION

Global Calibration

Figure 6 shows the variation of global calibration number with irradiance for cell Y-229 which was always part of the experiment. The data are for all zenith angles and for measured irradiance values (pyranometer) between 20 and 90 mW/cm^2. Each data point represents 1 hour of integrated data. Nearly one year of data are reflected in the curve. Note that there is considerable spread in the data, especially at the lower irradiance levels. The average calibration number is 1.280 mA/(mW/cm^2) with a standard deviation of 2.48%.

The spread at lower irradiance levels can be caused by either spectral irradiance changes or change in cell response with incident angle. Calculations indicate that spectral differences can result in a maximum decrease of only 9% to 10% in calibration number as the spectral irradiance changes from entirely direct beam to entirely diffuse beam using the data in Fig. 3. Hence, the bulk of the spread in Y-229 calibration number must be attributed to reflection effects arising from the different incident angles of the incoming irradiance. The quartz covered cell and the pyranometer are known to differ in their response as incidence angle changes.

Data spread from this source can be substantially reduced by only considering data where the zenith angle of the direct beam is within 40^o of normal to the cell and the total irradiance is greater than 60 mW/cm^2. Figure 7 shows the trend of Y-229 calibration number with irradiance under these circumstances. The average calibration number is changed only slightly (1.271 compared to 1.280 mA/(mW/cm^2) while the standard deviation is reduced from 2.48% to 1.13%. Thus, restricting direct beam incidence angle yields a reasonably constant global calibration number that appears to be independent of atmospheric water vapor content and turbidity. Table I shows the average global calibration number, its standard deviation, and the normal incidence calibration number (when available) for all the cells measured during this investigation. The data for the first six cells cover nearly a one-year period. These cells are typical terrestrial silicon cells. The gallium arsenide, cadmium sulfide and low lifetime silicon cells have been measured for several months.

Note that the first six cells all have standard deviations near 1%. The global calibration number and the normal incidence numbers agree within about 2%, with the global value consistently lower than the normal incidence value. This trend is expected from calculations made on cell response to both the direct and diffuse components noted earlier. For the other three cells, the data spreads, as indicated by the standard deviation, are somewhat higher. For the low lifetime silicon (low red spectral response) and the gallium arsenide cells, the standard deviations are only slightly higher than the terrestrial silicon cell values. However, for the cadmium sulfide cell, the standard deviation is much larger (2.54%). This cell, however, exhibits unstable behavior under constant illumination. Simulator tests indicate a change in short-circuit current of about 3% to 4% over a period of a few hours under constant irradiance that may account for this increase.

Short-Circuit Current Ratio Measurements

Since cell Y-229 was always on test, we can calculate ratios of short-circuit currents of any cell to Y-229. Figure 8 shows the short-circuit current ratio for four cells as a function of measured irradiance. The zenith angle is less than 40^o. The four cells are terrestrial silicon, gallium arsenide, low lifetime silicon and cadmium sulfide. Table II gives a data summary of average ratio, standard deviation and spread for all eight cells. Nearly constant ratios are obtained. For the terrestrial silicon cells, which have the closest spectral response to Y-229, the standard deviations of the mean ratio vary from about 0.5% to 0.8%. The other three cells exhibit more spread in the ratio, with the low lifetime silicon and gallium arsenide having standard devistions of 1.1% to 1.4%. This is about twice the values for the five terrestrial silicon cells and can be explained by the larger differences in spectral response curves when compared to Y-229. The cadmium sulfide cell is again much higher, probably due both to the unstable nature of the cell, and the difference in spectral response between Y-229 and the cadmium sulfide cell.

Comparison of Irradiance Monitoring Techniques

Convolutions of the measured spectral response of more than thirty cells were made with the spectral irradiance curves of Figs. 2 to 4. The cells were primarily silicon (terrestrial and space) supplemented with a few gallium arsenide, cadmium sulfide and low lifetime silicon cells. Twenty of the cells also have an actual calibration number for either space or terrestrial use. Table III shows results of the convolutions for five typical cells. The table contains the calibration numbers calculated using Eq. (2) under the various spectral irradiance distributions. Because the irradiance in the denominator of this calculation is an integral over the entire solar spectrum, it is equal to the total irradiance measured by a black-body detector. Therefore, the black-body irradiance monitoring technique can be evaluated simply by comparing the column of calibration numbers for any cell for the different simulators. Table IV shows a number of ratios of calibration numbers calculated with a simulator spectrum and a solar spectrum. Accuracy of the black-body technique for any simulator can be determined directly from this table. Perfect agreement produces a ratio of unity.

Inspection of the ratios in Table IV and for all the other 25 cells indicate that errors in short-circuit current measurement as high as 50% can occur with an unfiltered tungsten light source when a black-body is used to set intensity. The errors similarly are as high as 10% when filtered tungsten (ELH) lamps are used as a terrestrial simulator but 30% when they are used as an AMO simulator. For the short-arc xenon simulator, the errors are about 3% to 5% for space and can be as high as 15% for terrestrial measurements. It must be noted that the simulator spectra used in these calculations are a single measurement of one simulator. Other simulators may differ somewhat and the spectral distribution of most simulators changes with time. So the errors calculated here are to be taken as general indications and not quantitative values.

Twenty cells, which had both a spectral response measurement and either a space (9) or terrestrial calibration number (11) were used to study the convolution technique of irradiance monitoring. Convolutions of the spectral response with the appropriate solar irradiance curves resulted in calculated calibration numbers from 3% to 9% lower than the actual measured values. These differences, which also are representative of the errors in the convolution technique of irradiance monitoring, arise from two sources. Both errors in the measurement of absolute spectral response and uncertainties in the knowledge of the solar spectral irradiance, contribute to the above differences.

In the reference cell technique, the simulator irradiance is measured using a reference cell and then the test cell data are taken. Therefore the error due to spectral mismatch is determined by comparing the calibration number ratios for the test cell and reference cell calculated for the desired simulator and solar spectra. The error is equal to the percentage difference between the two calibration number ratios. Table V summarizes the range of short-circuit current errors, obtained both by calculations and measurements, for the four simulators. Data are limited to these cases where the spectral response curves of the test and reference cells match, as determined by visual inspection of their shapes. Both space and terrestrial results are shown.

The data in Table V indicate the reference cell technique can result in small errors, depending on the simulator used. Errors of well under 2% occur when a short arc xenon lamp simulator is used in either space or terrestrial testing. The pulsed long arc xenon source is also an acceptable simulator for both space and terrestrial measurements. However, maximum error is slightly higher for terrestrial measurements. The dichoric filtered tungsten source provides a good simulator for terrestrial testing only, because it lacks UV and blue irradiance. The unfiltered tungsten produces unacceptably large errors for both spectra.

CONCLUSIONS

Four main conclusions may be drawn from the data presented here. They are:

1. Global calibration of terrestrial reference cells is feasible under a broad set of incident irradiance conditions. These conditions are: total intensity between 60 and 90 mW/cm^2, solar incidence angle less than 40^o and elimination of irradiance from below the horizon. The conditions utilized by Trebie (7) are similar. No measurements of atmospheric parameters are required.

2. It is feasible to obtain a secondary calibration of terrestrial reference cells by measuring the ratio of the short-circuit currents of the cell to be calibrated and a previously calibrated cell, when both cells are exposed to global irradiance. The spectral response matching is not critical, only requiring that the two cells be made from the same material.

3. The methods for monitoring irradiance during photovoltaic measurements may be ranked according to expected levels of spectral mismatch error in short-circuit current. The rank is (a) reference cell technique, (b) spectral response convolution with the solar spectrum; and (c) black-body detectors.

4. An acceptable list of solar simulators may be developed based on expected spectral mismatch error in the reference cell technique. The short arc xenon source is best followed closely by the pulsed long arc xenon simulator. Both are acceptable for space and terrestrial testing. The dichroic filtered tungsten simulator is acceptable for terrestrial measurements only. The unfiltered tungsten source is unacceptable as a simulator for both space and terrestrial use.

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TABLE I. - CALIBRATION NUMBERS* (GLOBAL AND DIRECT BEAM) FOR SEVERAL CELLS

Cell	Type	Global cal. no.	Standard deviation, %	Direct cal. no.
Y-229	Silicon	1.271	1.13	-----
Y-16	↓	1.333	1.14	-----
Y-111	↓	1.120	.96	-----
Y-135	↓	1.306	.75	1.326
Y-259	↓	1.040	1.05	1.067
Y-274	↓	1.251	.84	1.265
Y-137	Low lifetime silicon	1.082	1.41	
Y-138	Cadmium sulfide	.703	2.54	
Y-139	Gallium arsenide	1.071	1.36	

*Calibration numbers in mA/(mW/cm^2)

TABLE II. - RATIOS OF I_{sc} OF TEST CELL TO CELL Y-229. GLOBAL VIEWING

Test cell	Type	Ratio	Standard deviation, %	Spread	
				Min.	Max.
Y-16	Silicon	1.053	0.79	1.029	1.073
Y-111	↓	.873	.73	.849	.888
Y-135	↓	1.016	.53	1.001	1.028
Y-259	↓	.821	.65	.809	.842
Y-274	↓	.986	.78	.967	1.006
Y-137	Low lifetime silicon	.855	1.35	.833	.875
Y-138	Cadmium sulfide	.547	2.33	.524	.586
Y-139	Gallium arsenide	.843	1.12	.823	.857

TABLE III. - CALIBRATION NUMBERS* FOR SEVERAL CELLS UNDER DIFFERENT SPECTRAL IRRADIANCE DISTRIBUTIONS

Irradiance spectrum	Silicon	Silicon	Low lifetime silicon	Gallium arsenide	Cadmium sulfide
AMO	1.120	1.173	0.659	0.824	0.590
AM 1.5	1.280	1.338	.766	.987	.666
Direct	1.314	1.377	.777	.996	.683
Diffuse	1.276	1.318	.787	.956	.674
Xenon	1.156	1.211	.684	.851	.608
Flash xenon	1.048	1.101	.595	.725	.566
ELH	1.250	1.290	.811	1.086	.653
Tungsten	.725	.789	.343	.443	.380

*Calibration numbers in mA/(mW/cm^2)

TABLE IV. - COMPARISON RATIOS OF CALIBRATION NUMBERS FOR SEVERAL CELLS OBTAINED FOR DIFFERENT SIMULATOR, SOLAR SPECTRUM COMBINATIONS

Simulator/solar	Silicon	Silicon	Low life-time silicon	Gallium arsenide	Cadmium sulfide
Xenon/AM 1.5	0.903	0.906	0.892	0.862	0.913
Flash/AM 1.5	.818	.823	.776	.735	.849
ELH/AM 1.5	.976	.964	1.058	1.100	.980
Tungsten/AM 1.5	.566	.590	.448	.449	.570
Xenon/AMO	1.033	1.033	1.037	1.032	1.030
Flash/AMO	.936	.939	.902	.880	.958
ELH/AMO	1.116	1.100	1.230	1.317	1.106
Tungsten/AMO	.647	.673	.520	.537	.644

TABLE V. - ERRORS IN I_{sc} USING REFERENCE CELL TECHNIQUE FOR IRRADIANCE MONITORING

Simulator	Space, %	Terrestrial, %
Short arc xenon	1/2-1	1-1 1/2
Pulsed long arc xenon	1-2	1-3
Dichoric filtered tungsten (ECH)	2-5	1-2
Unfiltered tungsten	5-8	5-8

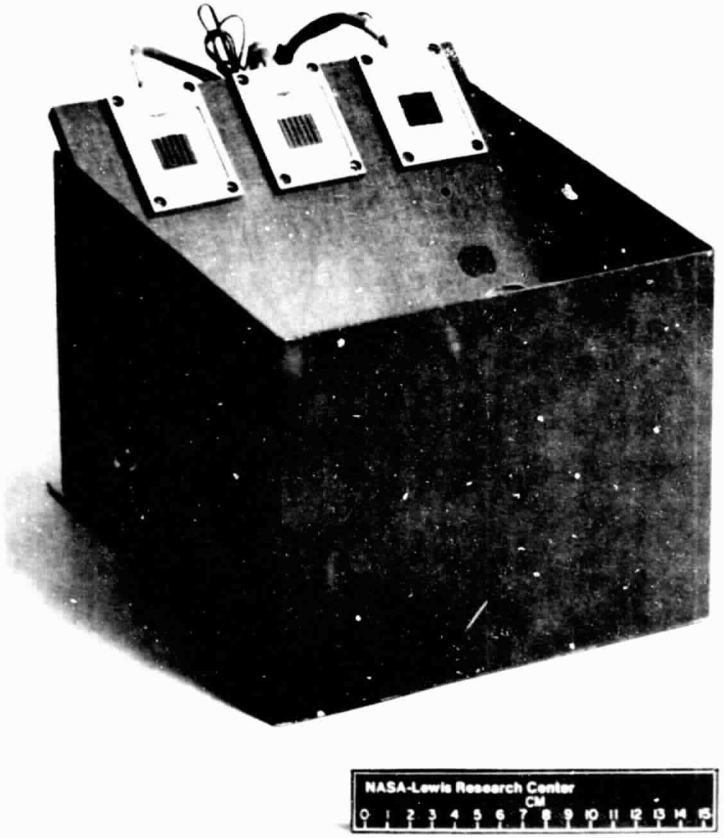


Figure 1. - Test fixture for global calibration experiment.

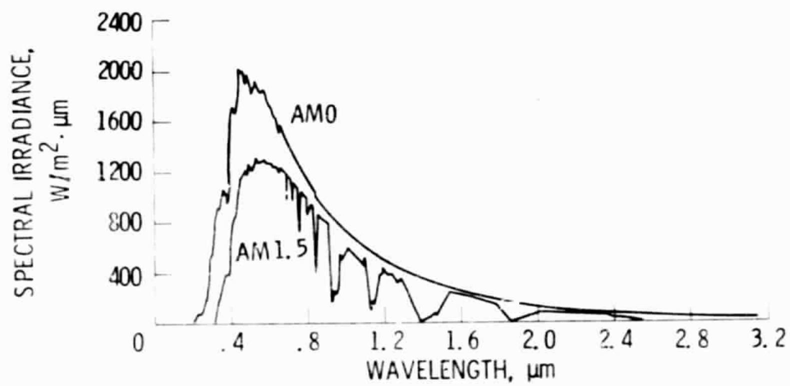
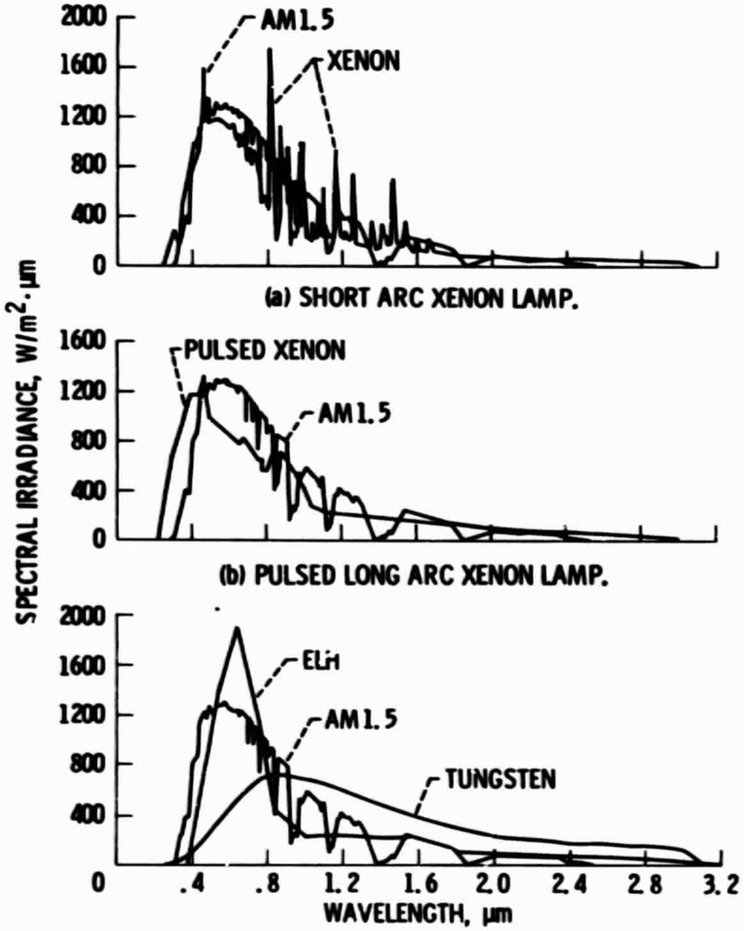


Figure 2. - Spectral distribution of space (AM0) and terrestrial (AM1.5) sunlight.



(a) SHORT ARC XENON LAMP.

(b) PULSED LONG ARC XENON LAMP.

(c) ELH AND PLAIN TUNGSTEN LAMPS.

Figure 3. - Spectral distribution of various solar simulators plotted with terrestrial sunlight.

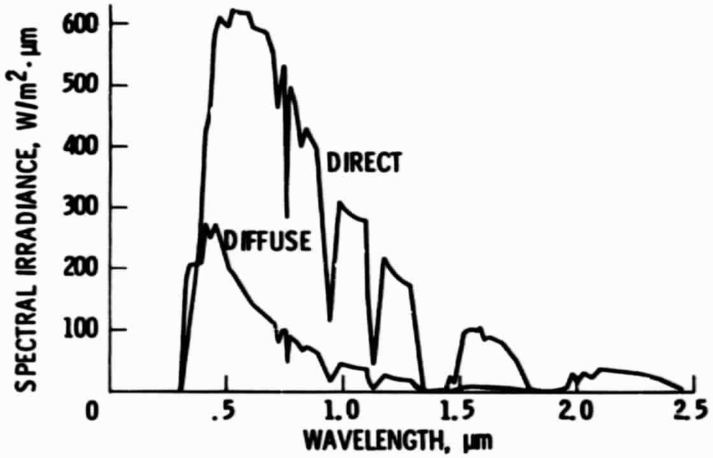


Figure 4. - Spectral distribution of direct and diffuse sunlight at AM2 on a horizontal plate.

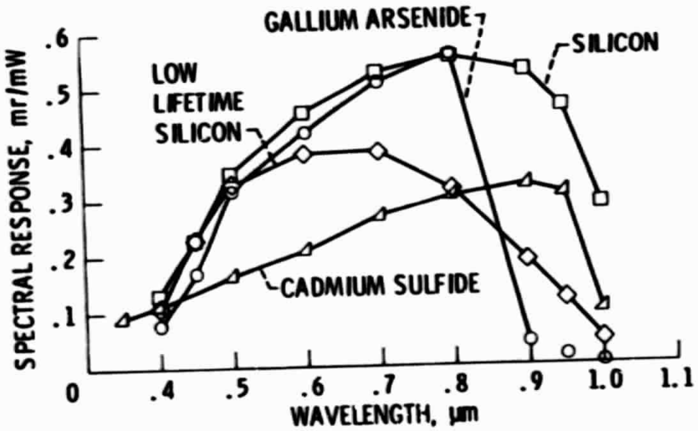


Figure 5. - Spectral response of four typical solar cells.

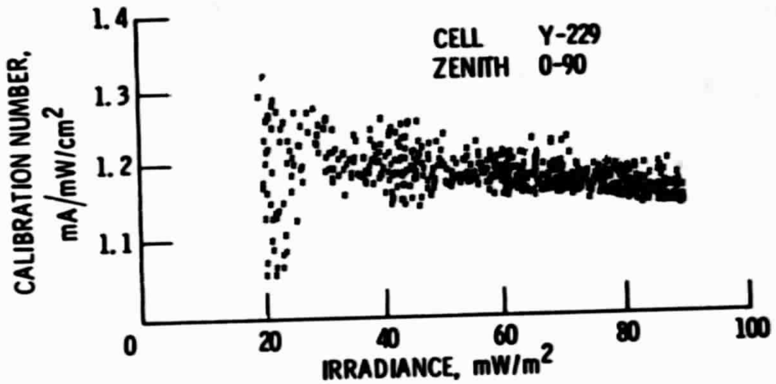


Figure 6. - Change in global calibration number with irradiance.

Figure 7. - Change in global calibration number for cell Y-229 with irradiance.

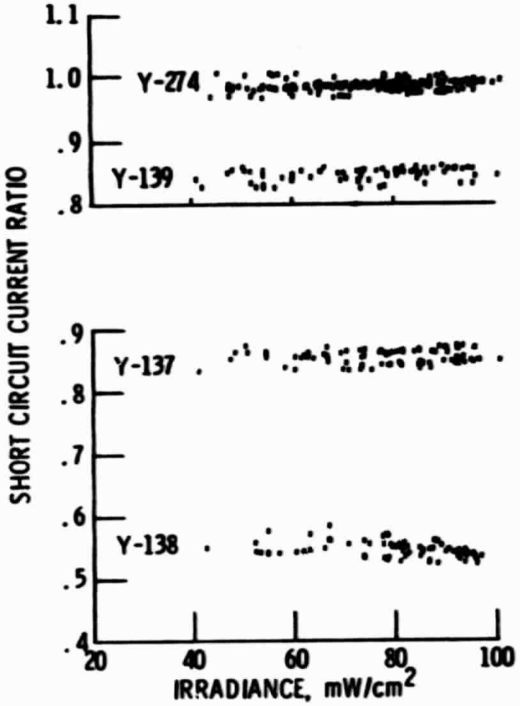


Figure 8. - Variation of ratios of cell current to cell Y-229 with irradiance.

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