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U.S. TERRESTRIAL SOLAR CELL CALIBRATION AND MEASUREMENT PROCEDURES

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Summary

In the fall of 1976, a workshop was held to evaluate and revise interim terrestrial solar cell calibration and measurement procedures. This paper describes the revisions made to the interim testing procedures. The calibration of reference cells and the design of their holders is covered. Considerations include view angle and optical and thermal matching. The atmospheric factors which affect the calibration and performance of solar cells are discussed. The most critical atmospheric parameter appears to be water vapor. Techniques for matching reference cells to cells or arrays under test are described. Data showing errors in performance under artificial sunlight simulators due to mismatch of reference and test cells is presented. Finally, measurement procedures and data transformations needed to obtain the performance of solar cells and arrays in outdoor natural sunlight are described.

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1. INTRODUCTION

As a part of the U.S. Energy Research and Development Administration's (ERDA) National Photovoltaic Conversion Program, the NASA-Lewis Research Center has the following responsibilities:

- 1) Operate a national measurements laboratory
- 2) Develop methodology for determining terrestrial solar cell performance
- 3) Calibrate and distribute reference cells to ERDA investigators
- 4) Conduct measurement procedures workshops and issue manuals.

These activities are strongly interrelated. It is the purpose of this paper to outline the changes in measurement procedures that resulted from the most recent workshop and to detail calibration and measurement methodologies for terrestrial solar cells.

2. SECOND ERDA/NASA TERRESTRIAL SOLAR CELL MEASUREMENT PROCEDURES WORKSHOP

This workshop was held at Baton Rouge, Louisiana in November 1976 with a total of 54 attendees (6 from outside the U.S.A.). Topics covered included solar irradiance measurement, effects of terrestrial sunlight on solar cell performance, terrestrial sunlight simulation, reference cell calibration, cell measurement procedures and cell characterization and diagnostics. As a result of this meeting revisions were made to the interim measurement procedures (1).

The basic measurement procedure uses reference cells, calibrated under collimated conditions against a normal incidence pyrheliometer, to set or determine light levels of xenon arc lamps or natural sunlight. The use of a pyranometer or pyrheliometer as an insolation monitor for outdoor solar cell performance measurements was discouraged. Three light sources are now acceptable: xenon short arc, pulsed xenon, and dichroic-modified 3400 K tungsten. A standard atmosphere was defined (air mass = 1.5, water content = 2 cm, turbidity = 0.5) and all reference cell calibrations are to be reported for this one condition.

The absolute scale of irradiance (PACRAD III) is to be used as soon as possible as a basis for determining the cell calibration factor (short-circuit current divided by irradiance). The primary method for cell calibration using collimated sunlight was not changed. Direct beam intensity is to be $750-900 \text{ W/m}^2$. Evaluation of global calibration procedures was recommended. Measurement procedures for concentrator solar cells were de-

fined. The workshop proceedings (2) and a revised measurement procedures manual (3) incorporating these changes have been published. The reader is referred to these sources (1-3) for more complete information.

3. REFERENCE CELLS

Design: Key considerations in the design of a reference cell together with its holder are view angle, optical coupling, temperature control and ruggedness (4). While view angle is not critical for cells used or calibrated in collimated sunlight, it is a significant factor for cells designed for use under global illumination. Figure 1 shows the measured effect of sidewall shadowing on cell short-circuit current for two different types of cells. Texturized cells are more sensitive to sidewall shadowing, especially under conditions of high turbidity (B). A design angle for the reference cell holder of 7° was selected as being reasonable. Thus, even under extreme turbidity conditions, sidewall shadowing amounts to less than 0.2%.

The second important factor is optical coupling. Cells with no optical coupling agents (e.g. silicone) reflect a greater percentage of the low incidence angle diffuse radiation than do reference cells encapsulated in clear silicone. The calibration factors determined under collimated and global conditions differ by about 5% for a cell with no optical coupling (4). With clear silicone, the factors agree within 1%. Thus the reference cell holder selected includes a clear silicone adhesive between the cell and a protective fused quartz window.

The reference cell holder resulting from these studies is shown in figure 2. Temperature of the reference cell is monitored by a thermocouple attached to the front contact. Integral cooling is not included. Tests show a 1° C temperature differential between the cell surface and the cooled test plate upon which the cell holder was placed. The holder is machined from brass. The resulting holder is rugged and convenient to use.

Calibration: The spectral distribution of terrestrial sunlight is strongly affected by atmospheric variables such as water vapor, particulates, air mass, ozone and other gasses. Of these factors, water vapor has the greatest influence on the cell calibration factor measured under collimated conditions (4). Variation of the calibration factor of a typical reference cell with water vapor is shown in figure 3 taken from (5). The product of water vapor and air mass is used as the abscissa to give a measure of the total amount of water vapor between cell and sun. A varia-

tion of about 5% in calibration factor between winter (0.5 cm) and summer (3 cm) conditions is indicated.

Typical annual variation of clear day water vapor content measured with a Volz sunphotometer is shown in figure 4, taken from (5). Figure 5, taken from (6) shows that the effect of water vapor on calibration factor is not location dependent. The data obtained at diverse locations in the U.S. agree well with data obtained only at Cleveland.

Thus the need to specify the calibration factor for a fixed value of water vapor content and air mass is clear. A water vapor value of 2 cm and an air mass of 1.5 were adopted at the Baton Rouge Workshop as part of the standard reference conditions. It should be stressed that the foregoing conclusions apply only to cells calibrated under collimated conditions. For cells calibrated under global conditions, sensitivity to these parameters will differ.

Matching of Reference Cell to Test Cell or Modules: The spectral distribution of terrestrial irradiance constantly changes; moreover, simulators do not duplicate any terrestrial spectrum. Exact measurement of cell performance for standard conditions can occur when either the spectral distribution of the light source exactly duplicates the "standard atmosphere" spectral distribution, or when the spectral response of the reference cell and the test cell is identical (7). In actual practice, the latter condition is easier to accomplish.

A simple procedure for matching device spectral responses has been outlined (4). The procedure utilizes two broad band glass filters whose optical transmission characteristics are shown in figure 6. From measurement of the currents produced under the red and blue filters, a cell or module to be tested can be characterized. Then a matching reference cell can be selected from a previously characterized stock of references.

The procedure for obtaining the red/blue information is outlined in figure 7. A pulsed simulator is used so that modules as well as cells can be characterized.

Reference cells and test articles are matched on the basis of red/blue ratio and red current. Figure 8 is an example of the plots used and illustrates how cells of different spectral response are separated. This procedure has also been used to characterize sunlight simulators (8).

4. OUTDOOR MEASUREMENT

Reproducible measurement of the I-V characteristic of a solar cell under terrestrial sunlight is complex. The techniques and methodology for performing such measurements have been outlined by Curtis (9). In general, irradiance and module temperature do not correspond to standard conditions (1000 W/m^2 , 28° C). Hence the measured curve must be translated to standard conditions. In order to make these transformations several module or cell parameters must be known. These include the current and voltage temperature coefficients (α and β) commonly used, and also the series resistances (R_s) and a curve shape correction factor (K).

Figure 9 shows results obtained for a module measured outdoors and translated to standard conditions (but without curve shape correction) compared to the module as measured under a pulsed xenon light source. Agreement between short-circuit current and open-circuit voltage is within 1%; however the maximum power for the outdoor data is 3% less than simulator results. Using the K factor from reference (10) resulted in agreement of power within 1%. Thus both series resistance and K factor correction terms are needed in addition to the current and voltage temperature coefficients for most accurate measurements.

Summary of Results

The methods for accurate and reproducible measurement of terrestrial solar cell performance are being improved. Modifications to the U.S. procedures were adopted at the Baton Rouge Workshop held in November 1976. The main features of the current procedures are that 1) outdoor measurements of cell performance based on pyranometer or pyrheliometer determination of intensity are discouraged, 2) the absolute scale of irradiance was to be adopted as soon as possible, 3) the standard atmosphere conditions are 1000 W/m^2 irradiance, temperature 28° C , air mass 1.5 and precipitable water vapor content of 2 cm, and 4) the allowable light sources for solar simulation are short arc xenon lamps, pulsed xenon lamps and dichroic filtered tungsten lamps.

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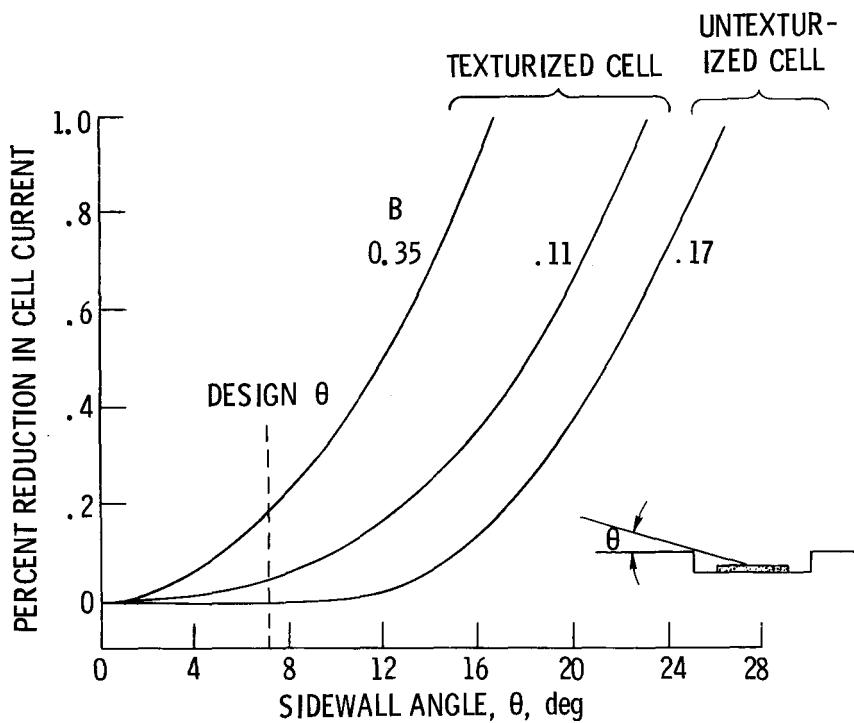


Figure 1. - Reduction in cell current due to sidewall shadowing.

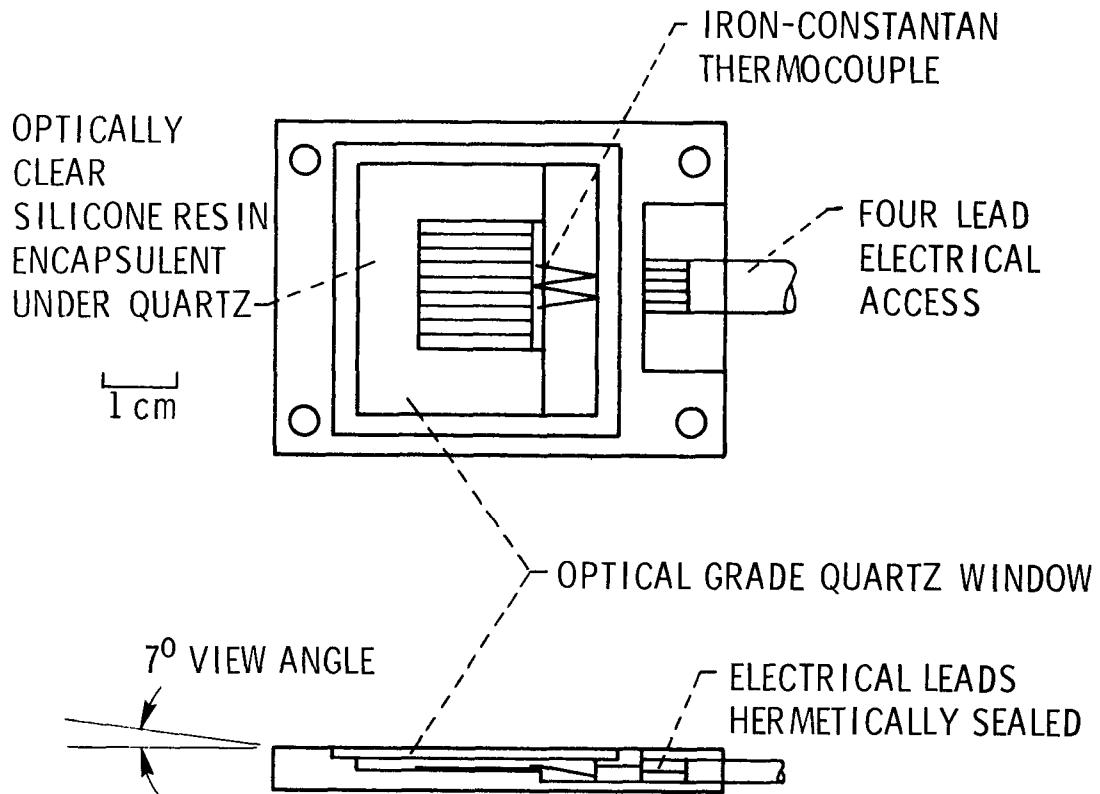


Figure 2. - Intermediate reference cell.

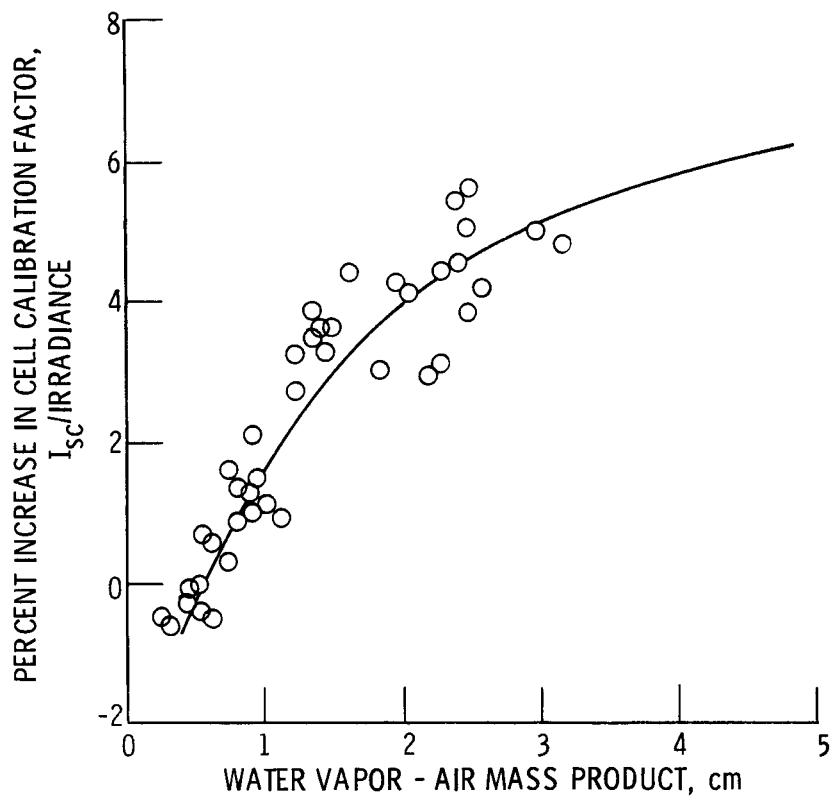


Figure 3. - Effect of water vapor content on calibration factor of silicon standard cell.

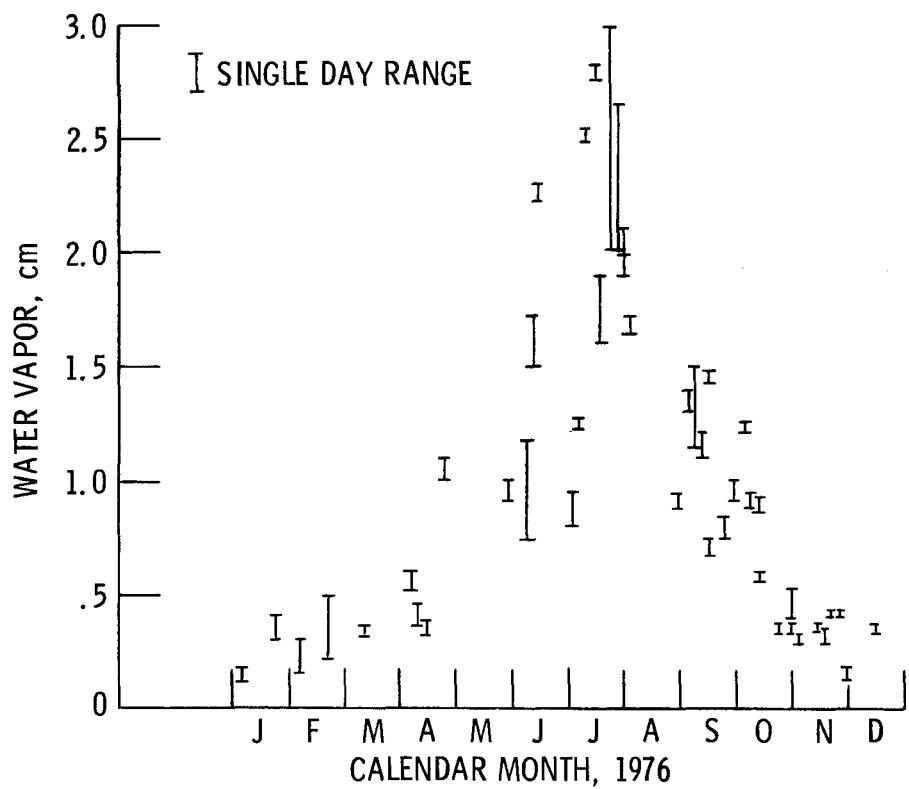


Figure 4. - Clear day precipitable water vapor measurements - Cleveland, Ohio, 1976.

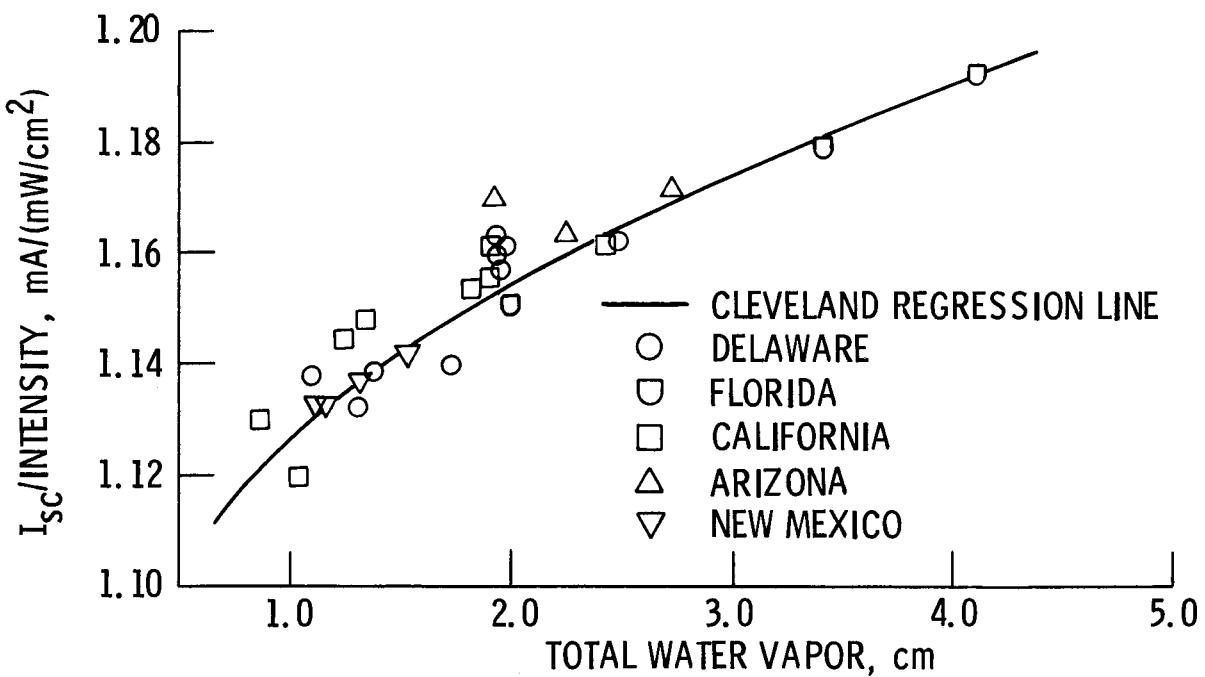


Figure 5. - Sensitivity of solar cell calibration factor to atmospheric water vapor.

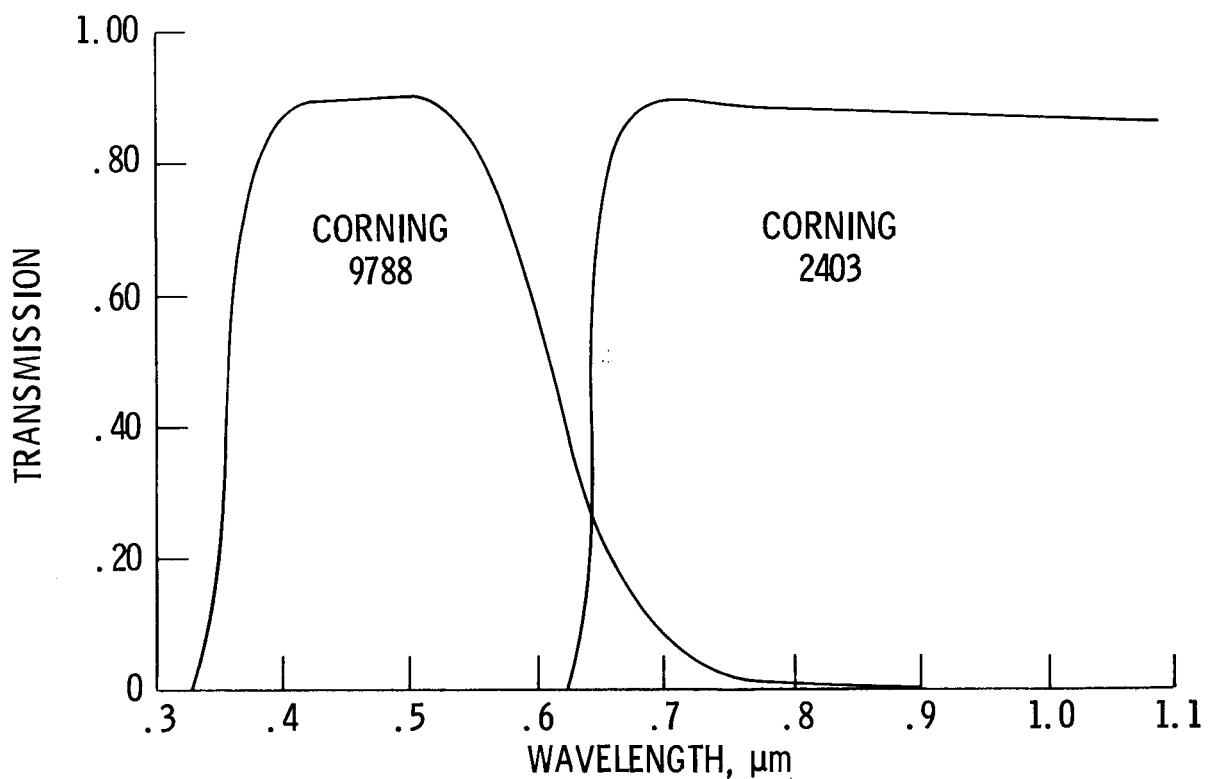


Figure 6. - Transmission curves for broadband filters.

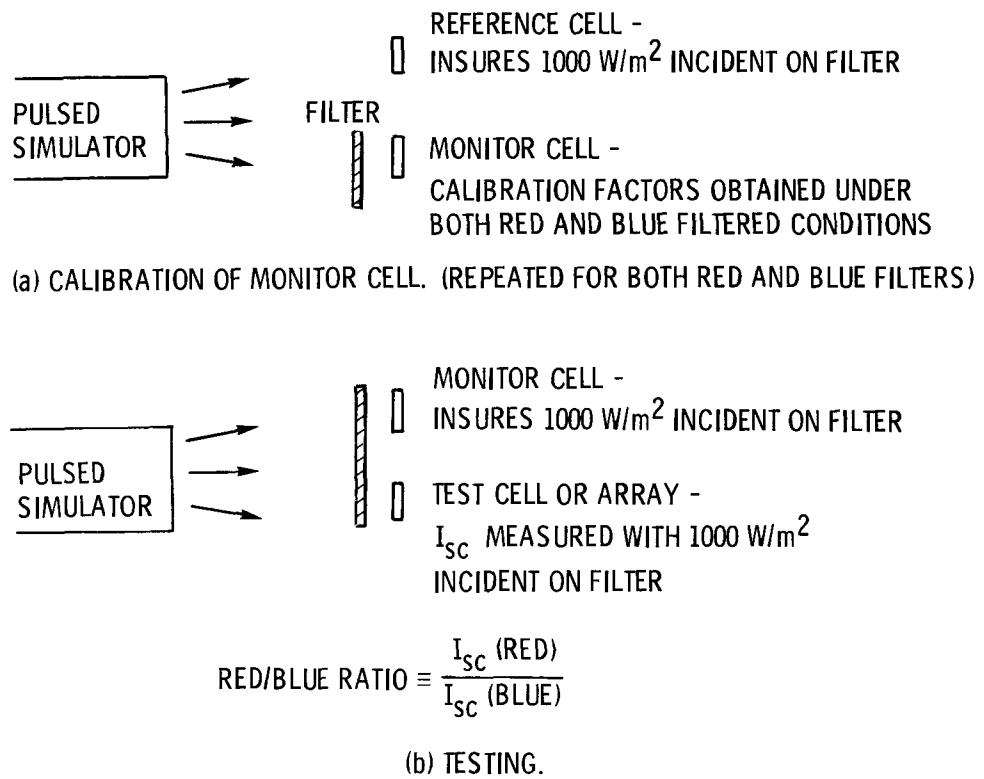


Figure 7. - Schematic diagram illustrating the red/blue ratio measurement technique.

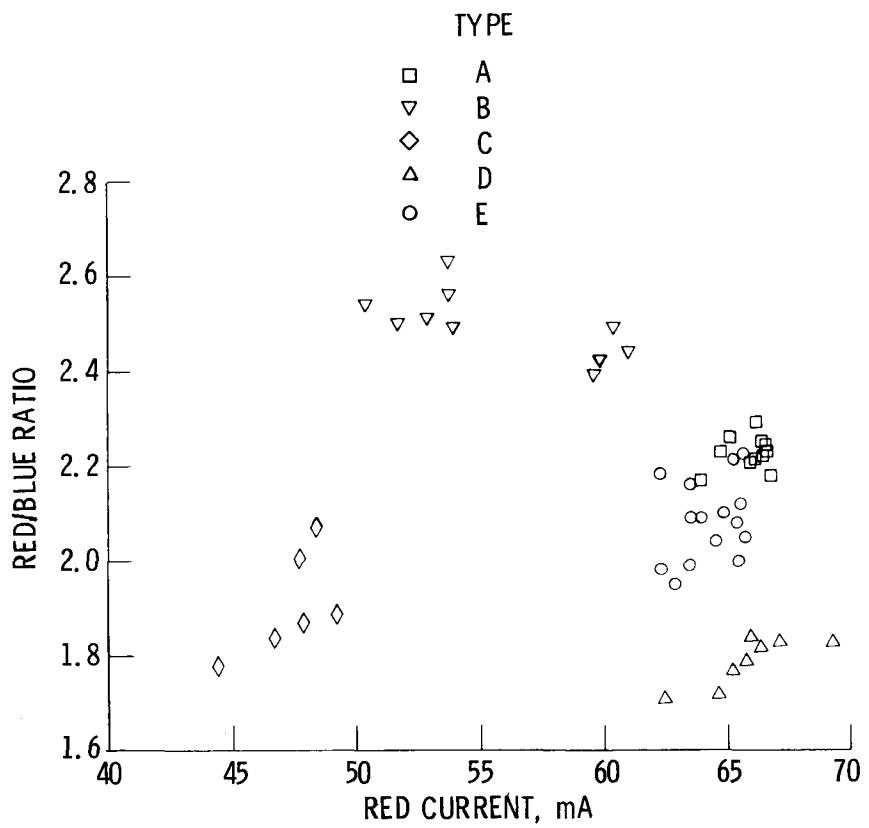


Figure 8. - Distribution of red/blue ratios of typical cells.

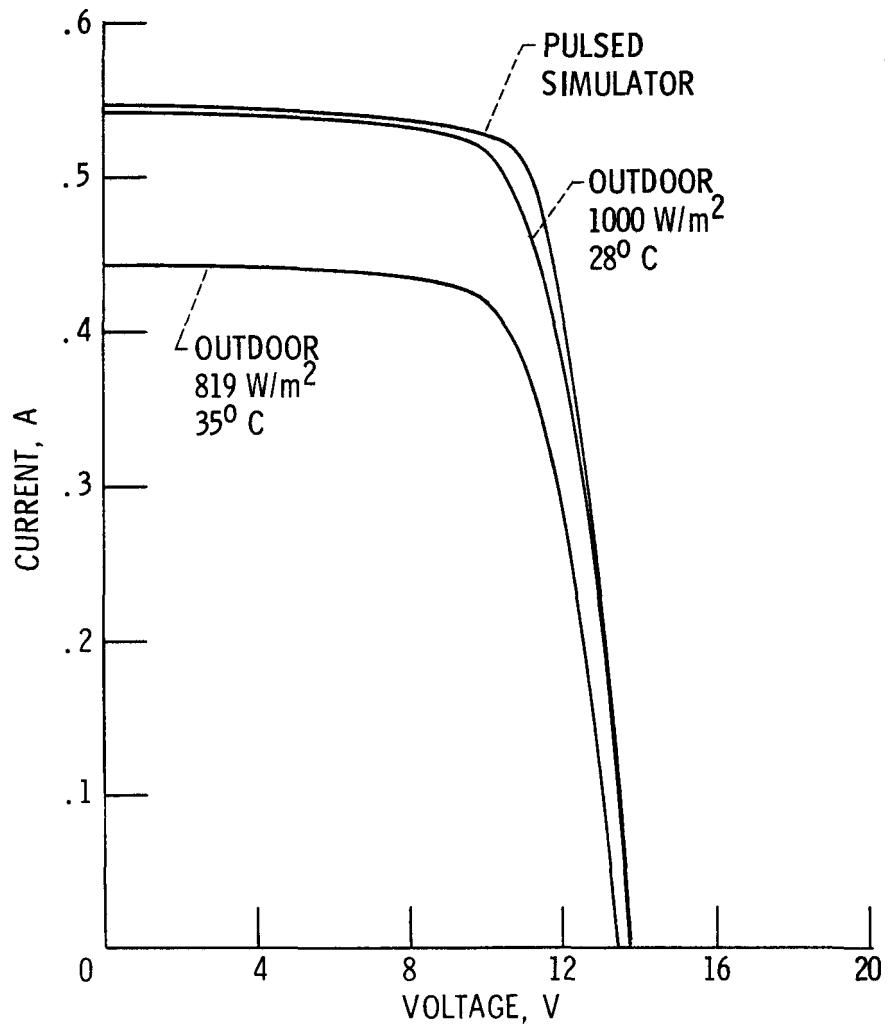


Figure 9. - Comparison of indoors-outdoors I-V measurements.