ERDA/NASA 1022/76/4
NASA CP-2010
Technical Report II-4

CONSIDERATION OF DESIGN AND CALIBRATION OF TERRESTRIAL REFERENCE SOLAR CELLS

V. G. Weizer
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

JUL 1977
RECEIVED
NASA STI FACILITY
INPUT BRANCH

Prepared for
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Office of the Assistant Administrator for
Solar, Geothermal, and Advanced Energy Systems
Division of Solar Energy
Under Interagency Agreement E(49-26)-1022

Presented at Second Annual Photovoltaic Measurements Workshop
Baton Rouge, Louisiana, November 10-12, 1976

(NASA-CP-2010) CONSIDERATION OF DESIGN AND CALIBRATION OF TERRESTRIAL REFERENCE SOLAR CELLS (NASA) 28 p HC A03/MF A01 CSCL 10A
N77-26621
Unclas
H1/44 35424

CONSIDERATION OF DESIGN AND CALIBRATION OF TERRESTRIAL REFERENCE SOLAR CELLS

by V. G. Weizer

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

ABSTRACT

The function of a reference solar cell is the accurate measurement of the power incident on a test plane from either the sun or a solar simulator. The reference cell must be capable of monitoring at least the direct component of the insolation. It is desirable, however, that it also be capable of measuring the total flux. A discussion of the problems encountered in the attempt to design a reference cell that meets these criteria is presented, starting with basic design considerations, and proceeding with the precautions taken to ensure a global monitoring capability. The effects of the variations in atmospheric conditions on the calibration and use of reference cells are presented along with a discussion of the simplifications brought about by the use of spectrally matched test and reference cells. Finally, a method of matching test modules and arrays to reference cells by a red/blue response ratio technique is described.

INTRODUCTION

It is essential to establish reference conditions and measurement methods which will ensure the reproducibility and comparability of data taken by the many investigators in the field of photovoltaic energy conversion. To this end a system of standardized reference cells which have been calibrated under controlled conditions is being established. Many difficulties arise, however, when one attempts to design a reference solar cell package for use in the terrestrial environment. The purpose of this paper is threefold: (1) to present the design of a reference cell package which is capable of measuring either the direct or the total insolation, (2) to point out the considerable simplification in calibration and testing procedures that can be effected through the use of references that are spectrally matched to the modules being tested, and (3) to show how the red/blue response ratio can be used to match reference cells and test modules and arrays.

REFERENCE CELL DESIGN

Interim Reference Cell - In November, 1975, distribution of an interim reference cell was begun. The essential features of the interim cell are shown in figure 1. The package consists of a chrome-plated brass base fitted with a 1/16"-thick optical grade quartz window. The cell is hermetically sealed in an atmosphere of dry inert gas. An iron-constantan thermocouple monitors the temperature of the top surface of the cell. Electrical access consists of a four-point contact system. Mounting holes are provided so that the unit may be bolted to a heat exchanger if desired.

It was clear when the interim reference cell holder was being designed that considerable work would have to be done before a reference cell suitable for global use could be developed. A deep well design was adopted, therefore, to discourage use of the interim reference cell as a global measurement device.

A data package was issued with each of the reference cells which consisted of (1) the calibration factor (sensitivity) obtained under collimated (10:1) conditions in natural sunlight with a solar intensity between 80 and 100 mW/cm^2, and a cell temperature of 28 ±2°C, (2) a nine-point spectral response curve, (3) the illuminated current-voltage characteristic at 100 mW/cm^2 solar intensity, and (4) the value of the atmospheric water vapor content at the time of calibration.

Global Measurement Capability

It is desirable that a reference cell have the capability of measuring the total insolation as well as the direct component. Two factors influence the design of a holder with global sensitivity: shadowing and reflectivity.

To determine the influence of shadowing, a variable geometry cell enclosure was mounted on a solar tracker. The cell enclosure was geometrically similar to the interim reference cell holder with the added capability of continuous wall height variation. In this way the view angle, θ, (as defined in figure 2) could be varied and the reduction in cell current due to the loss of low angle illumination could be monitored. Since it was suspected that cell surface texturization would increase cell sensitivity to the diffuse component, both texturized and planar surfaced cells were investigated.

Measurements were made in natural sunshine under conditions ranging from clear (B=0.1) to very turbid (B= 0.35), where B is the Schüepp turbidity coefficient(1). Some typical results are shown in figure 2 where the percent reduction in cell current due to side wall shadowing is plotted against view angle. As suspected, the texturized cells were more sensitive to the diffuse component than were the planar-surfaced cells. The curves also show the significant effect that turbidity has on cell output.

As a compromise between shadowing and ease of fabrication, a view angle of 7° was selected to be incorporated in an advanced ("intermediate") reference cell holder design. As indicated in the figure, this design introduces a maximum error of only a few tenths of a percent, even under extremely turbid conditions. For the interim cell, on the other hand, with a view angle of 23°, errors of several percent are indicated.

The fact that side wall shadowing is negligible does not, by itself, validate the use of a reference cell as a global measurement device. It must also be shown that the cell does not preferentially reflect a significant portion of the low angle diffuse component. To do this, the sensitivity (cell current per unit incident power density) was measured under both collimated and uncollimated conditions. As can be seen in figure 3, the ratio of the uncollimated sensitivity to the collimated sensitivity for cell Y-1 in a holder with a view angle of 7° is 0.95. This indicates that the cell is selectively reflecting a significant amount of shallow angle light. In an attempt to improve the optical coupling, a number of cells in identical holders were encapsulated in a silicone resin with an intermediate index of refraction ($n = 1.43$).

The results of the double calibration of a resin encapsulated cell, Y-65, are shown in figure 3. As seen in the figure, the two sensitivities now agree to within one percent, indicating that the encapsulated cell does not preferentially reflect. Cell Y-65, in fact, now appears to be a preferential absorber of shallow angle light. This, of course, cannot be so, the excess current being due to spectral differences between the direct and the total insolation.

It can be concluded, therefore, that the improvement in optical coupling afforded by silicone resin encapsulation is sufficient to remove restrictions to the use of the flat solar cell as a global radiation monitor.

Intermediate Reference Cell

The above features have been incorporated into the design of an updated "intermediate" reference cell holder(figure 4). As seen in the figure the new design incorporates many of the features of the interim design. There are, however, two basic differences: (1) the view angle is reduced from 23° in the interim holder to 7°, (2) the cell is encapsulated in an optically clear silicone resin. These changes enable the intermediate reference cell to be used to measure both direct and total insolation.

REFERENCE CELL CALIBRATION

Effect of Atmospheric Variables

The primary function of a reference cell is the measurement of solar intensity. To perform this measurement accurately, the output of the cell must be proportional to the incident power. Changes in the spectral distribution of the incident illumination, however, can produce changes in cell output that are not proportional to the incident power. To avoid error in solar intensity measurements, therefore, the reference cell should always be used under the same spectral conditions under which it was calibrated.

Changes in the terrestrial solar spectrum are brought about by variations in any one of a number of atmospheric parameters: water vapor, ozone, particulates, air mass, oxygen, carbon dioxide, etc. Of these, water vapor has the most influence on solar cell measurements. The variation in calibration factor or sensitivity with atmospheric water vapor content for a typical silicon reference cell is shown in figure 5. A variation of 5 percent is seen as the water vapor content changes from winter conditions (0.5 cm) to summer conditions (3.0 cm) in the midwest. These large variations make it clear that considerable error may be incurred unless care is taken to ensure that the reference cell employed was calibrated under conditions that correspond to the test conditions at hand. The user, therefore, must continuously monitor atmospheric conditions and make timely changes in the reference cell calibration factor (sensitivity). Although, if used properly, this system would provide highly accurate data, it is clear that a simpler method of measuring array efficiency is desirable. Such a method, requiring the use of spectrally matched test and reference cells, is described next.

The Need for Spectral Response Matching

Measurement procedures can be simplified considerably by using reference cells that are spectrally matched to the cells being tested. Two cells are spectrally matched if their spectral response curves are in the same proportion to each other at all wavelengths. If the spectral responses of two cells are proportional, the same proportionality holds for their sensitivities as long as they are both illuminated with the same spectrum. As mentioned previously, the sensitivity of a cell depends upon the spectral distribution of the light with which it is illuminated. A change in this distribution will cause a change in the sensitivity. Two cells that are spectrally matched will experience changes in sensitivity with spectrum change, but their sensitivities will always remain in the same proportion to each other. In other words, the ratio of the sensitivities of two matched cells will remain constant regardless of how the spectrum of the incident illumination changes.

To determine the sensitivity of a test cell by means of a matched reference cell, all that must be known is the constant of proportionality between the sensitivities of the two cells. Since this constant remains unchanged regardless of spectral changes, the appropriate measurements can be made under an arbitrary light source. The required test cell sensitivity can then be computed using this factor and the reference cell sensitivity.

In the special case where the reference and test cells are perfectly matched, i.e., unit proportionality constant, no measurement is needed. In this case, since the two cells are identical, the sensitivity of the test cell is equal to the sensitivity (calibration factor) of the reference cell.

In the more general case where the cells are spectrally matched but not identical, the constant of proportionality between the sensitivities must be found by measurement. The product of this constant with the reference cell sensitivity (calibration factor) will then yield the

Let us consider, for example, two spectrally matched cells, one of which has been calibrated against a black body under atmospheric conditions, A. The proportionality constant between the reference and the test cell sensitivities can be found by measuring the short circuit currents of both cells under an arbitrary set of atmospheric conditions, B. If I_R and I_T are the reference and test cell short circuit currents and P is the solar intensity, all under atmospheric conditions, B, then the sensitivities of the test and reference cells are, respectively, I_T/P and I_R/P. Taking the ratio of these senstivities we find that the proportionality factor is I_T/I_R, the ratio of the short circuit currents. The product of this factor, then, with the reference cell sensitivity yields the test cell sensitivity under atmospheric conditions, A.

Thus, the use of spectrally matched cells permits sensitivity measurements to be made without regard to the solar spectrum or concern about the selection of a calibration factor to match spectral conditions.

Although the measurements described here are simple and straightforward, they are based on the assumption that the reference and test cells are spectrally matched. In reality, however, matching may not be completely achieved. To get a rough indication of the error introduced by the use of a reference cell that is not spectrally matched to the cell being tested, a computer analysis was performed on three cells, the spectral responses of which are shown in figure 6. As seen in the figure there is some mismatch in the spectral responses of these cells. If the sensitivity ratios between these cells were established under one set of atmospheric conditions, say AM1, then any deviation in the solar spectrum from AM1 conditions should cause a deviation in the ratios such that if one of the cells were used as a reference to provide measurements on the other two, errors in the measured sensitivities for the two test cells would result. To quantize these errors, the sensitivities of the three cells were calculated under both AM1 and AM3 conditions using insolation data computed from the extraterrestrial spectrum.(2) The atmospheric conditions assumed in the calculations were: water vapor, 2 cm; ozone, 0.34 cm; turbidity parameters, $\alpha = 1.3$, $B = 0.04$. If the cells were spectrally matched they should respond identically to the spectral changes incurred in going from AM1 to AM3, i.e., the ratio of sensitivities at AM3 should be the same as that at AM1. Because the cells are not matched, however, we should find deviations in the sensitivity ratios. These deviations can be interpreted directly as a measurement error if one of the cells were used as a reference to provide sensitivity measurements on the others.

Before discussing the results of the calculations, it would be appropriate to devise a convenient way of indicating the degree of mismatch in the spectral response curves. One way to do this is to calculate the average fractional difference (AFD) between the curves. This factor can be arrived at as follows. First, each of the two sets of spectral response data to be compared is normalized to an arbitrary data point in the set, such as the 0.7μm response point. This normalization removes any absolute differences in the curves. Next, the two normalized data sets are compared with each other, point for point, and the fractional difference found for each point. The absolute values of the fractional differences are then averaged over the nine points. The resulting factor (AFD) can then be used to characterize the closeness of the spectral match.

Let us return now to the results of the sensitivity calculations. The results are shown in figure 7 where deviations in the sensitivity ratio, i.e., measurement error , are compared with the corresponding mismatch parameter, the AFD. In comparing cell 1 with cell 2 (AFD = 0.1) we find that a measurement error of 0.4% is expected. A comparison of cells 1 and 3 with a larger mismatch (AFD = 0.24) indicates a 1% error for the same spectral change. Bearing in mind that these calculations are merely illustrative and reflect the conditions of this particular example, we see that in this case the AFD must be kept below about 0.12 if measurement error is to be less than 0.5% for an AM1 to AM3 spectral change.

SPECTRAL RESPONSE MATCHING

The Red/Blue Ratio Technique

The requirement that there be a close spectral response match between the reference cell and the solar panels being tested has been established. Since the spectral response of a module or other large area device cannot be measured by conventional methods, an alternate technique must be used. To this end, a technique making use of a large area pulsed simulator and a pair of optical filters is being used. The filters were chosen to examine cell response to both the red and blue ends of the spectrum. Transmission curves for the filters used at this laboratory are shown in figure 8. The test cell short circuit current is measured under both red and blue filtered conditions. The ratio I_{sc} (red)/I_{sc} (blue) is then used to characterize the cell spectrally.

The details of the technique can be explained with the aid of figure 9. The first step is the calibration of a monitor cell with a standard reference cell (figure 9a). The two cells are placed on the test plane of the pulsed simulator. One of the filters is placed over the monitor cell and the cells are illuminated, the reference cell ensuring an intensity of 100 mW/cm^2 incident on the filter. The monitor cell is then used as in figure 9b to ensure 100 mW/cm^2 on the face of the filter when both the monitor and the test cell or array are exposed to filtered light. The process is repeated for both filters.

The ratio of test cell short circuit current under red filtered conditions to that under blue filtering, termed the red/blue (R/B) ratio, is then used as the basis for spectral comparison.

The relationship of the R/B ratio of an entire module to the R/B ratios of the cells in that module is presented schematically in figure 10. The R/B ratio of each of the cells in the module was measured along with that of the module itself. As indicated in the figure, the R/B ratio of the entire module is very close to the average cell R/B ratio.

Comparison with Multipoint Spectral Response Data

The question that presents itself at this point is whether or not the two point R/B ratio technique can be used to replace the nine point spectral response method without a significant loss of spectral information.

If such a substitution were possible, we should be able to show that, when two cells or modules are compared and found to be spectrally matched on the basis of their R/B ratios, agreement will be found also in the nine-point spectral response data. Since there are many different spectral response curve shapes that will yield the same R/B ratio,agreement between the two systems is not assured. We must rely, unfortunately, on empirical information gained from measurements on real cells.

To evaluate the degree of correlation that exists between the two methods, both R/B ratio and multipoint spectral response measurements were performed on a group of 100 cells, 25 from each of four manufacturers. For each set a reference cell was chosen and each of the other cells in the set compared to it. Plots of the AFD vs the fractional difference in the R/B ratio are given in figures 11 to 14. While there is some scatter in the data, there appears to be a reasonable correlation in each case. Extrapolating the data to zero R/B ratio mismatch, it can be seen that a maximum AFD of about 0.04 is expected for the cases considered here. According to figure 7 , an AFD of 0.04 would result in a measurement error of only a few tenths of a percent for an AM1 to AM3 spectrum change.

If we now consider cross-manufacturer comparisons, problems arise. The results of comparing the set of Sensor Technology cells with a Solarex reference cell are shown in figure 15, where the curves from figures 11 to 14 are included for reference. As indicated by the extrapolation to zero R/B ratio mismatch, an AFD of 0.2 is expected. Referring again to figure 7, we see that in this case, even with perfect R/B ratio matching, a measurement error approaching 1% is to be expected.

The conclusion that can be drawn from these limited data, therefore, is that the R/B ratio technique may be used to match cells and arrays if one is comparing devices from the same manufacturer. Cross-company comparisons, on the other hand, may lead to significant error.

SUMMARY OF RESULTS

The results of the preceding paragraphs can be summarized as follows:

(1) It was shown that both the geometry of the cell holder and the optical coupling between the cell and its environment are critical in determining the feasibility of using the flat solar cell as a global insolation measurement device. The design of a reference cell holder that can be used to measure total insolation is presented.

(2) Reference cell calibration was shown to be very sensitive to the spectral variations caused by water vapor and other atmospheric constituents. This sensitivity introduces severe complications into solar cell array testing procedures. The procedures can be greatly simplified if the spectral response of the reference cell used is

closely matched to the spectral response of the array being tested.

(3) A technique is described whereby spectral information is obtained from large area arrays enabling them to be spectrally matched to reference solar cells. The technique involves the use of two broadband optical filters and a large area pulsed simulator. The results of measurements on a large number of cells and arrays indicate that as long as spectral comparisons are restricted to devices produced by the same manufacturer, the technique provides valid spectral characterization. Intercompany comparisons, however, have been shown to introduce error.

REFERENCES

1. Schuepp, W.: Arc. Meteor. Geophys. Bioklim. B1 257 (1949).
2. Thekaekara, M. P.: Conference Proceedings, COMPLES, Dahran, Saudi Arabia, Nov. 1975.

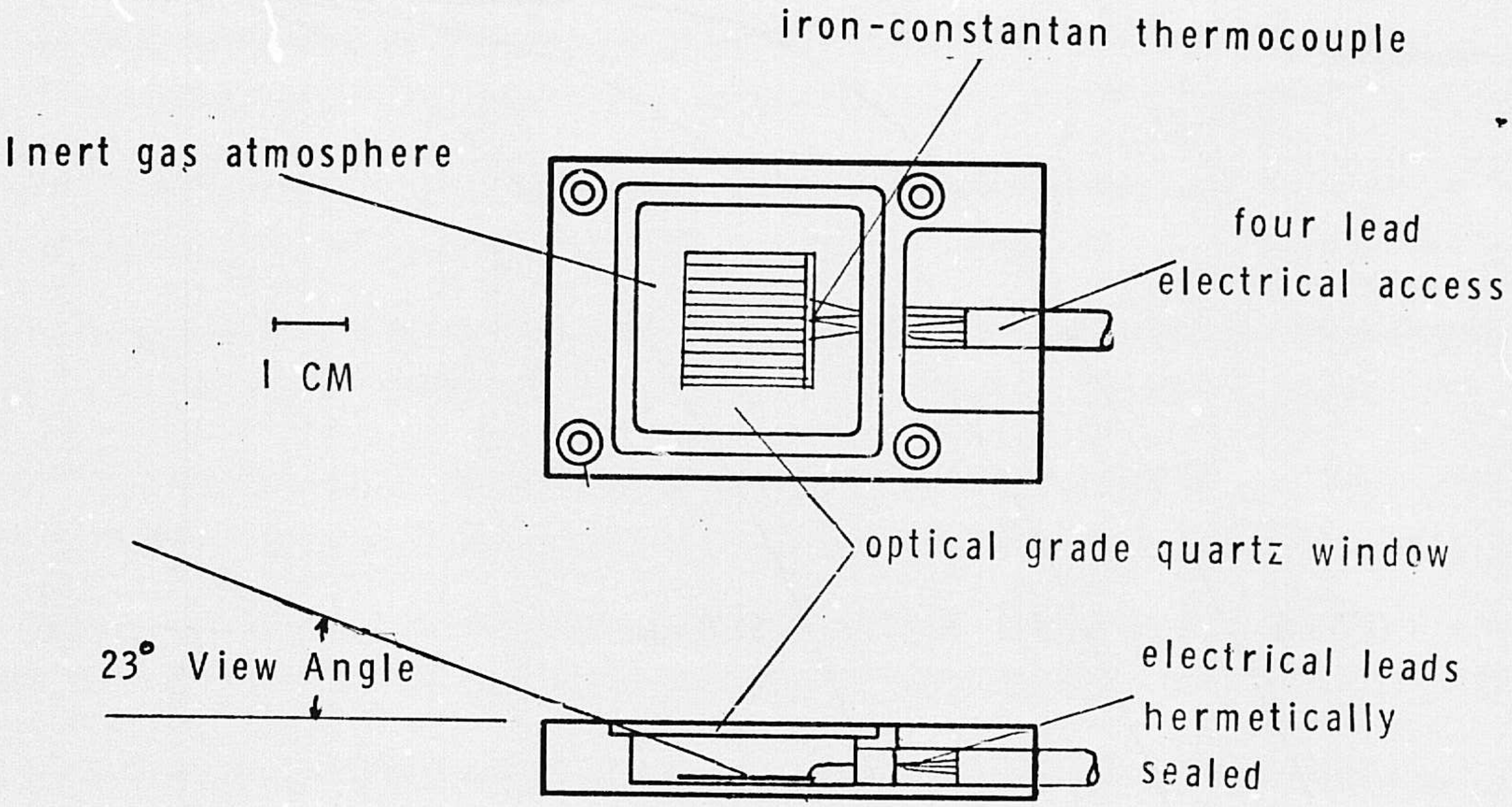


Figure 1. - Interim reference cell

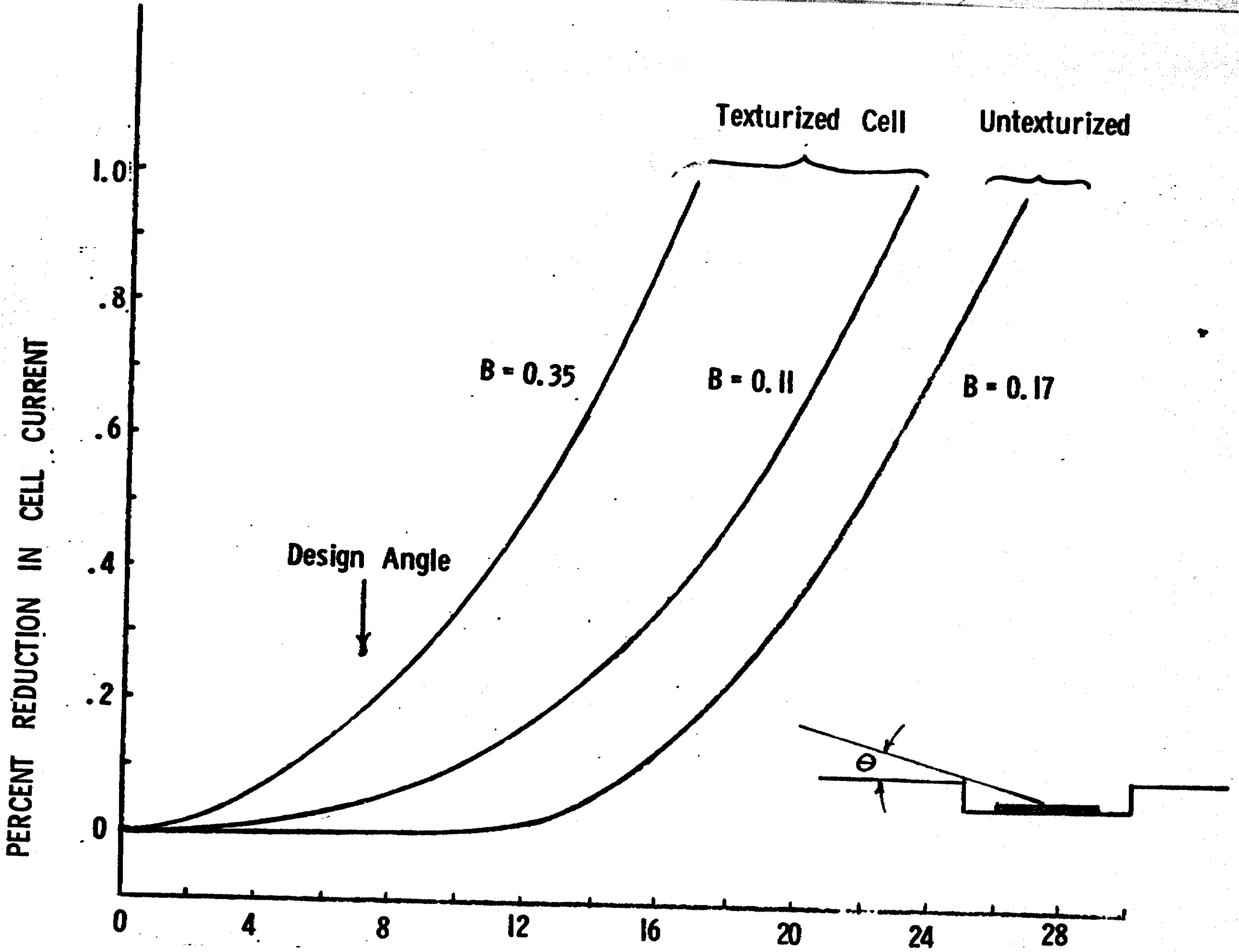


Figure 2. - Reduction in cell current due to side-wall shadowing

	UNCOLLIMATED CAL. FACTOR*	COLLIMATED CAL. FACTOR*	$\frac{\text{UNCOLLIMATED C. F.}}{\text{COLLIMATED C. F.}}$
CELL Y1 INERT GAS	1.031	1.090	.95
CELL Y-56 SILICONE RESIN	1.202	1.185	1.01

* $\frac{\text{MA}}{\text{MW/CM}^2}$

Figure 3. - Comparison of calibration factor measured under collimated and uncollimated conditions

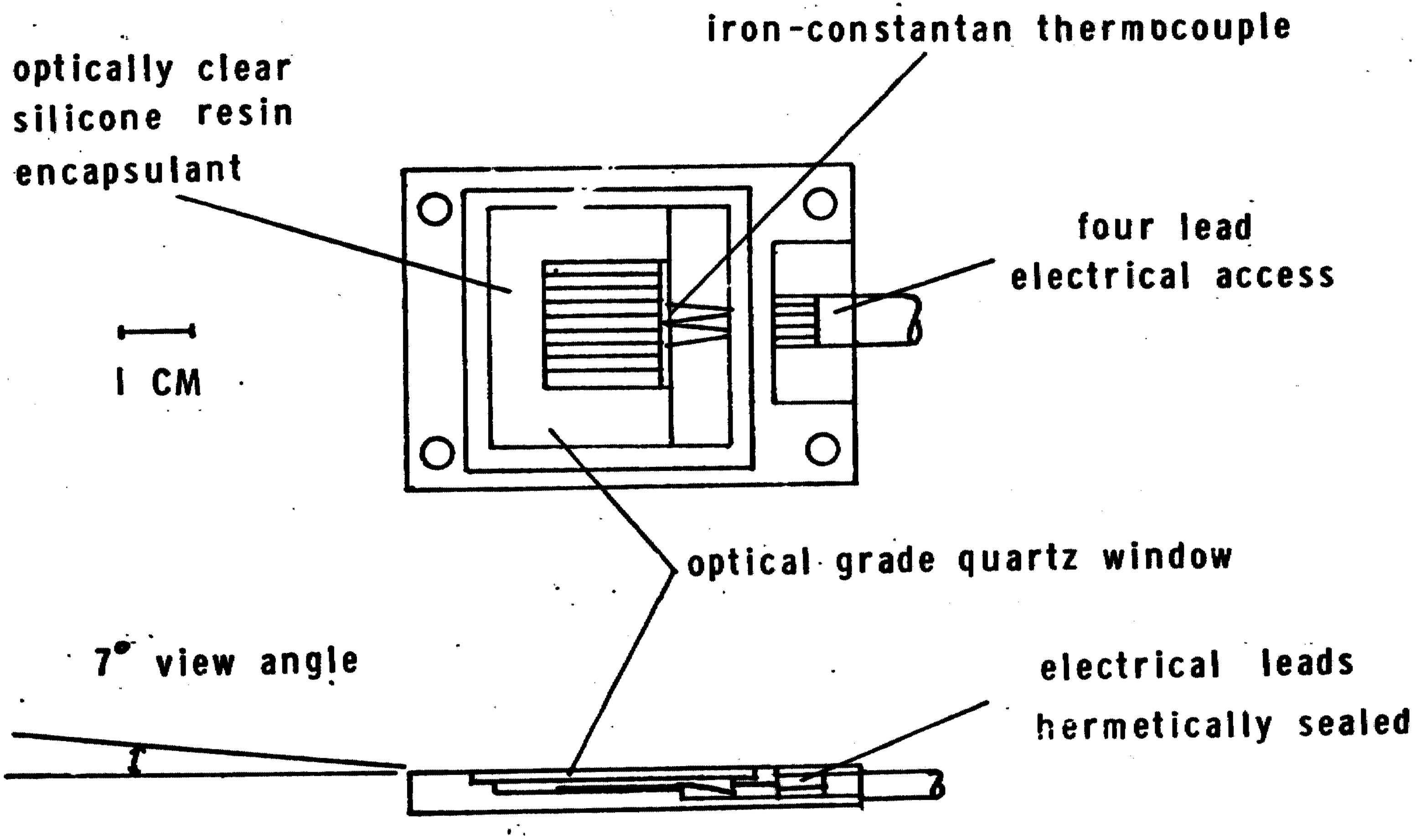


Figure 4. - Intermediate reference cell

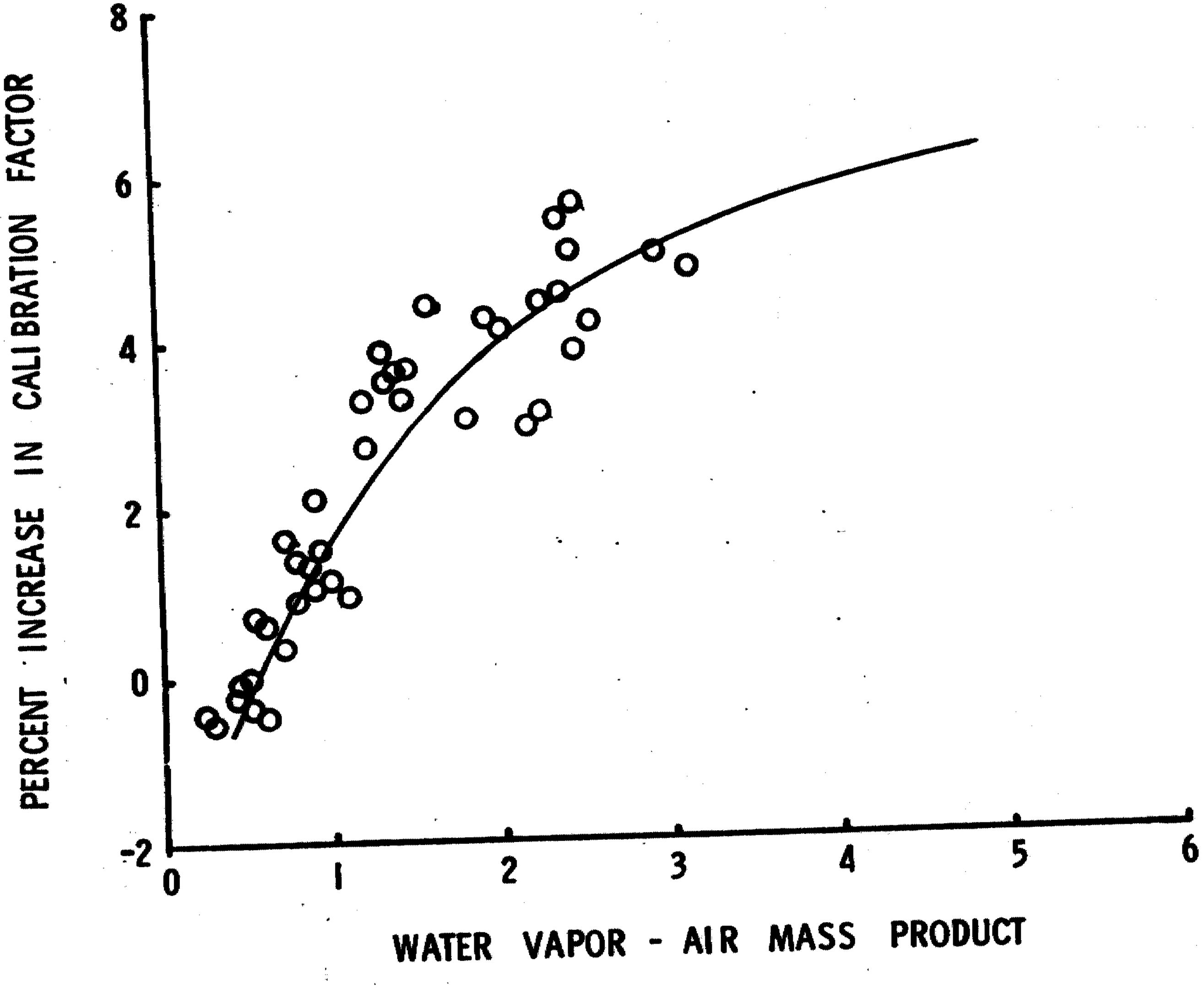


Figure 5. - Effect of water vapor on the calibration factor.

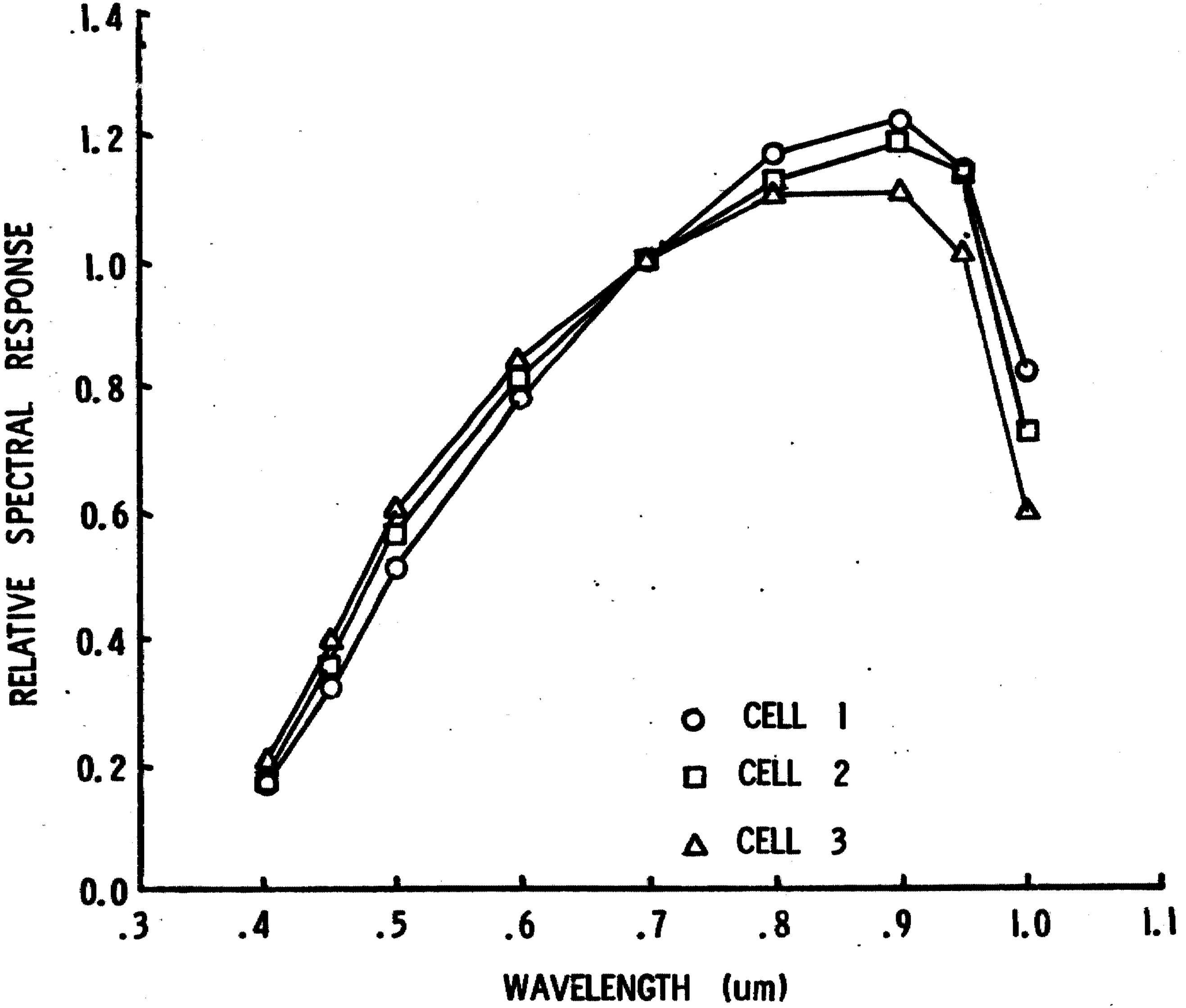


Figure 6. - Relative spectral responses of unmatched cells

REFERENCE CELL	TEST CELL	AFD	MEASUREMENT ERROR AMI --> AM3
1	2	0.10	0.4%
1	3	0.24	1.0%

Figure 7. - Measurement errors due to spectral mismatch

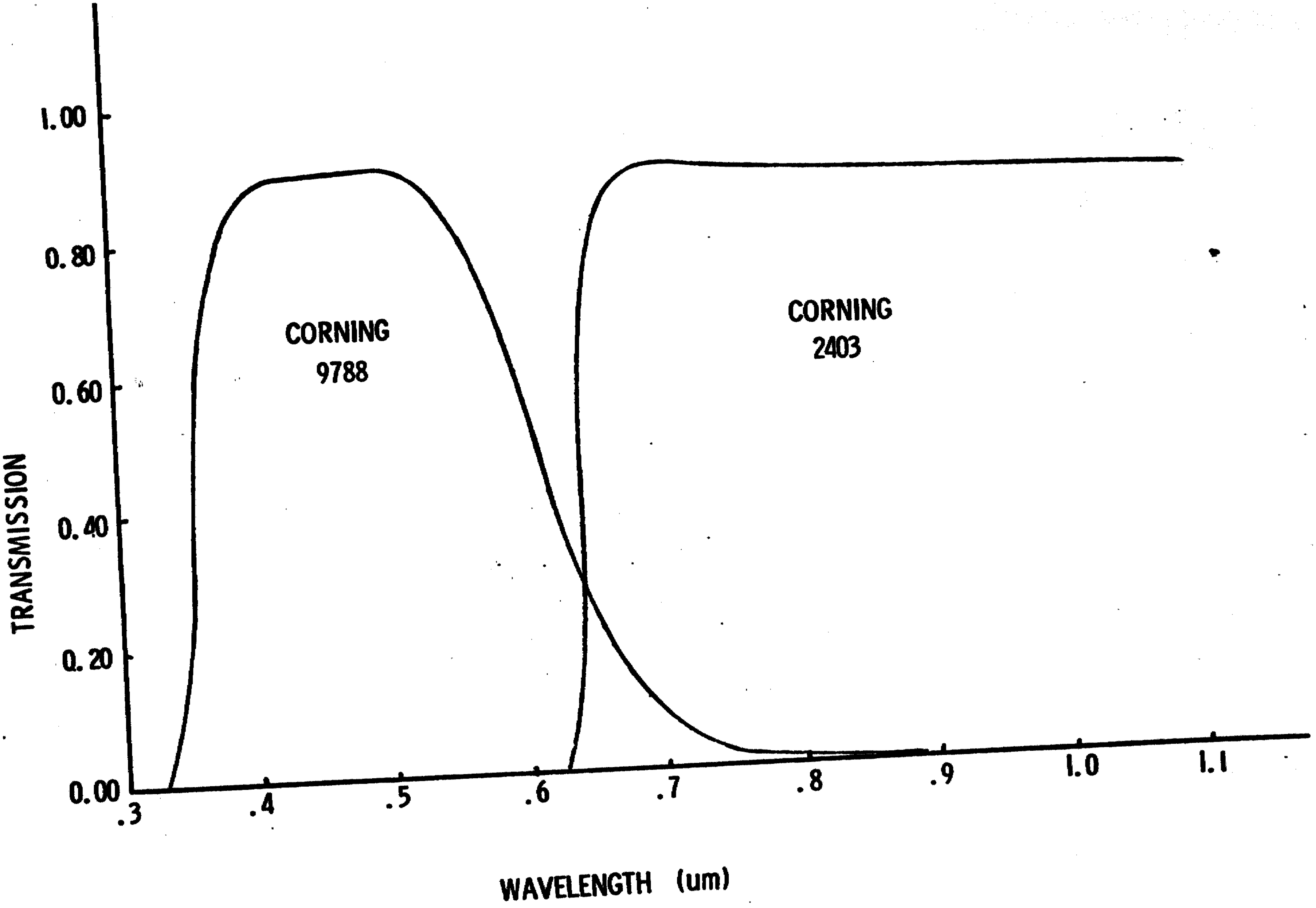


Figure 8. - Transmission curves for broad-band filters

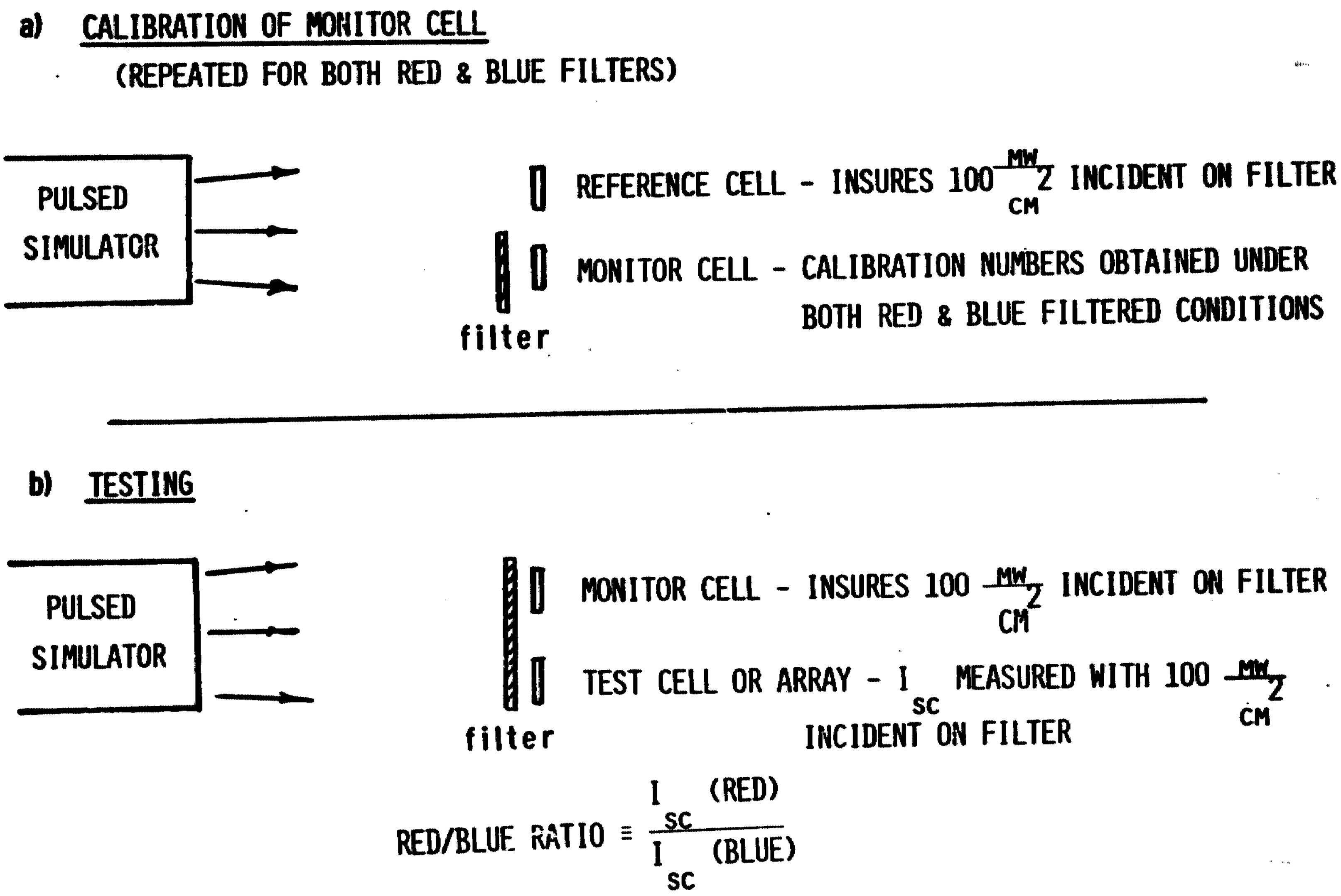
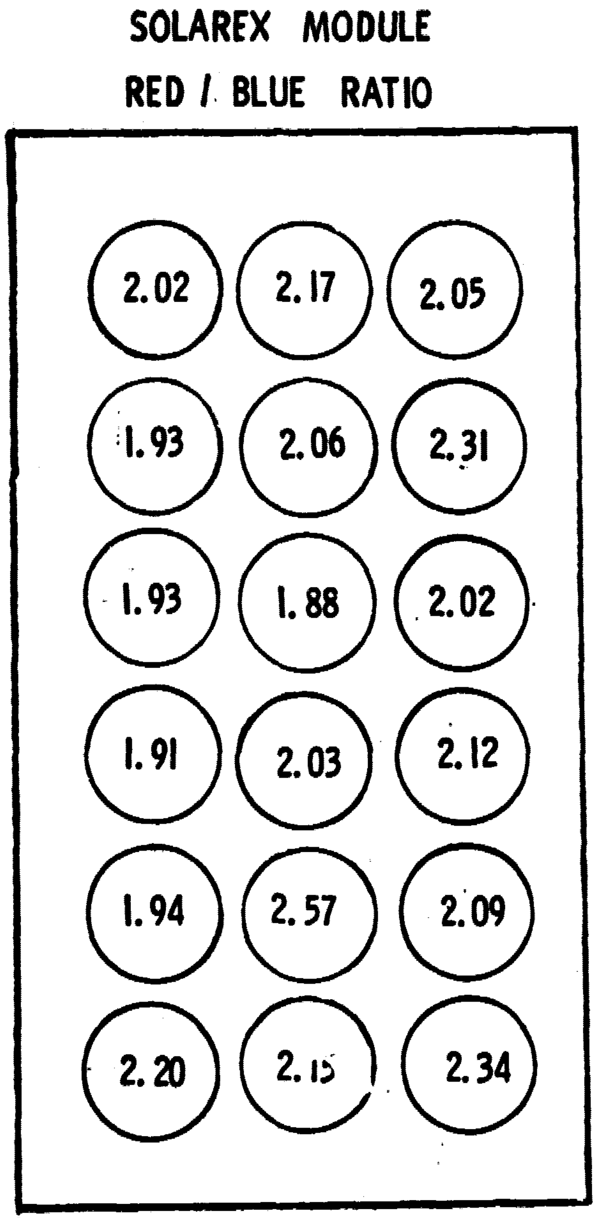


Figure 9. - Schematic diagram illustrating the red/blue ratio measurement technique



AVG. R/B RATIO = 2.10

MODULE R/B RATIO = 2.06

Figure 10. - Red/blue ratios of individual cells in a module

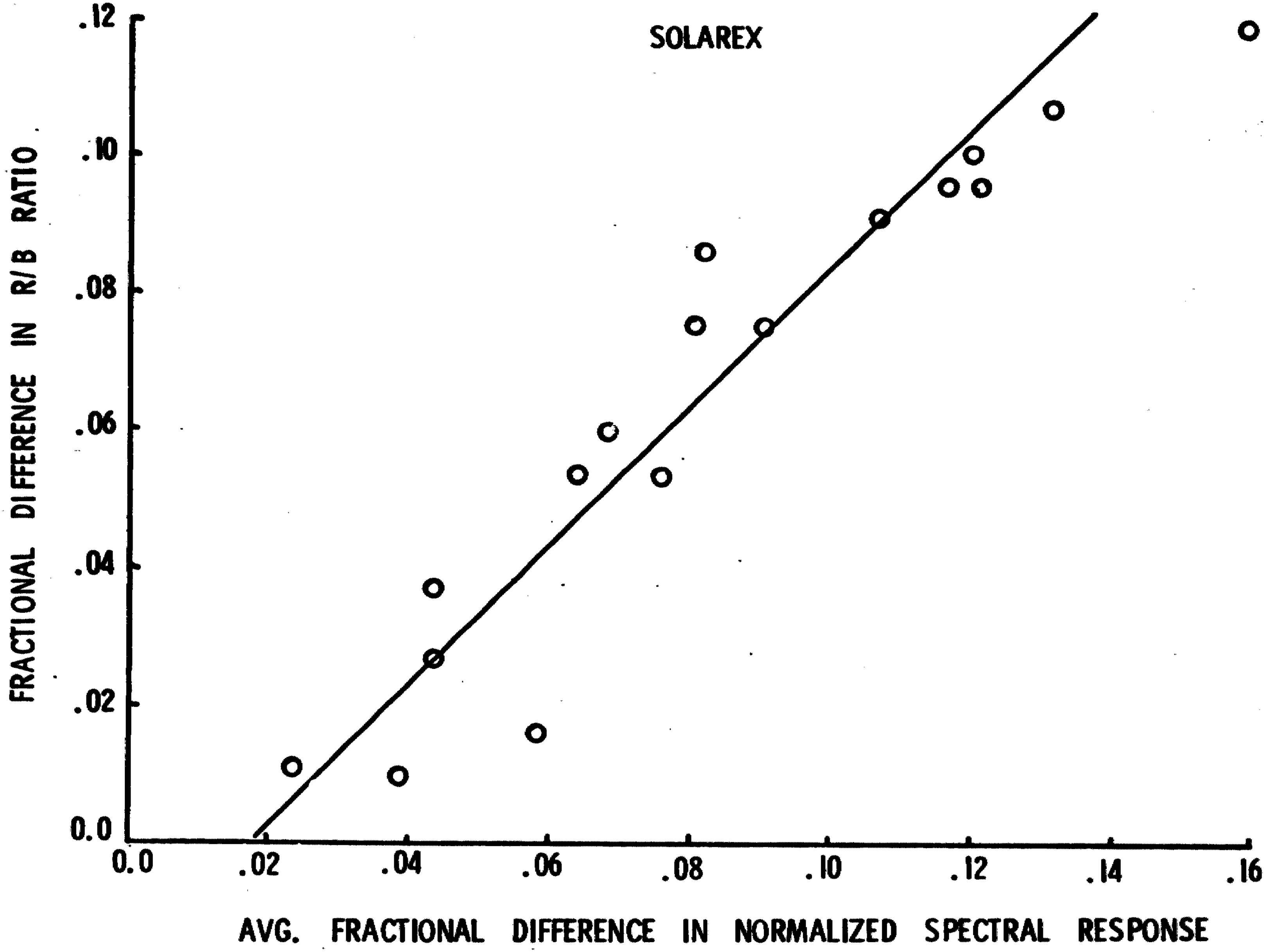


Figure 11. - Red/blue ratio, spectral response correlation for Solarex cells

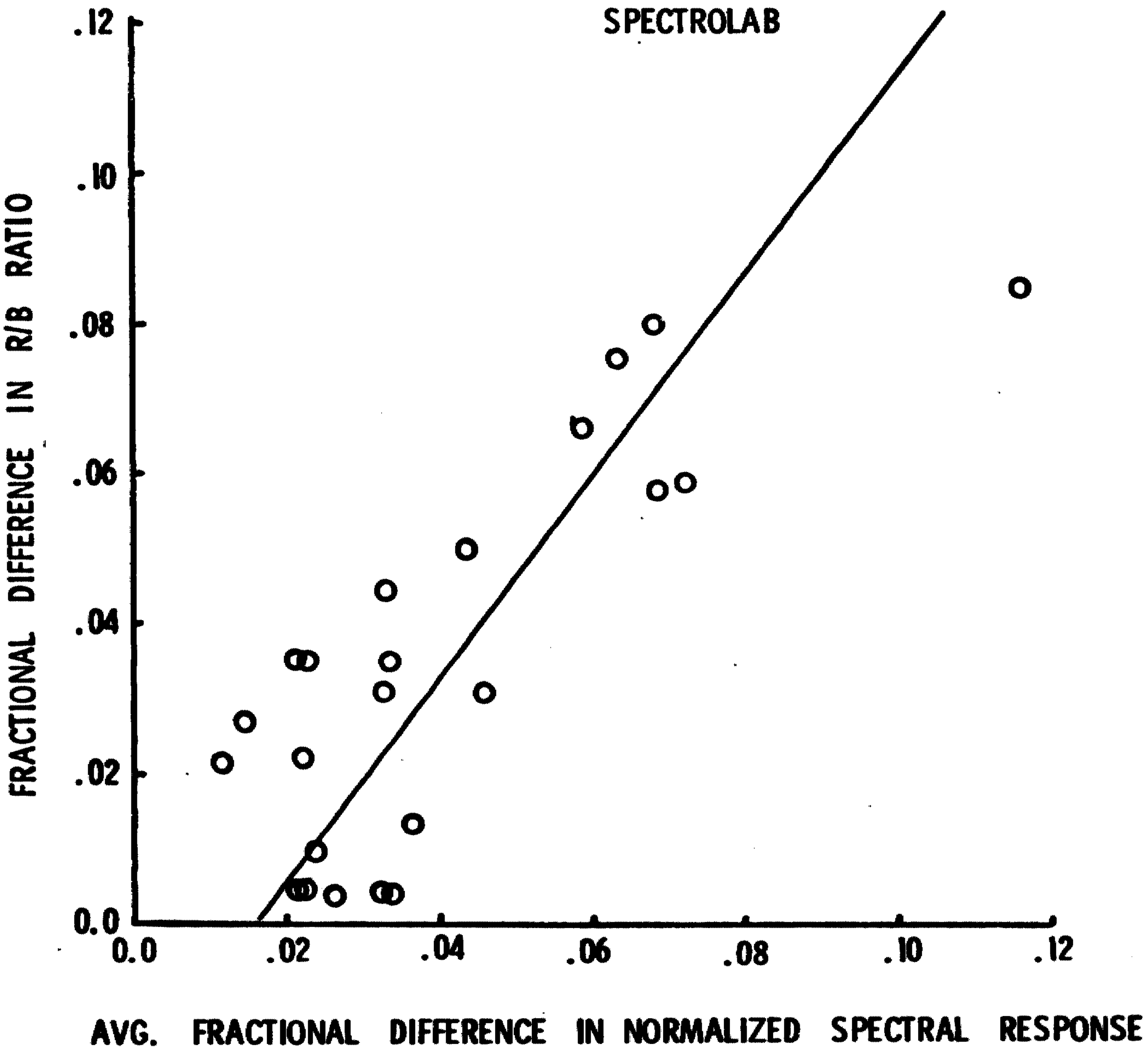


Figure 12. - Red/blue ratio, spectral response correlation for Spectrolab cells

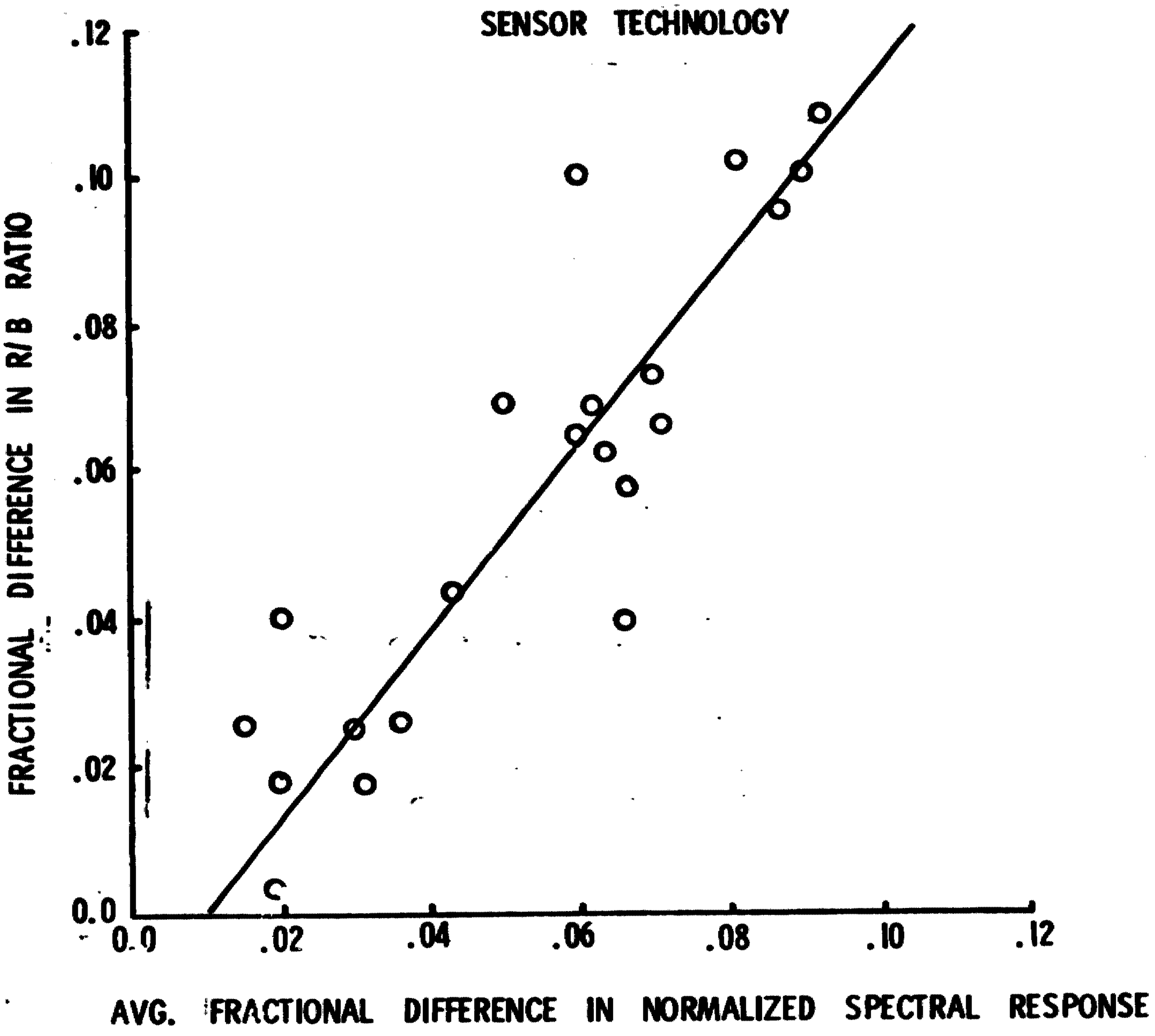


Figure 13. - Red/blue ratio, spectral response correlation for Sensor Technology cells

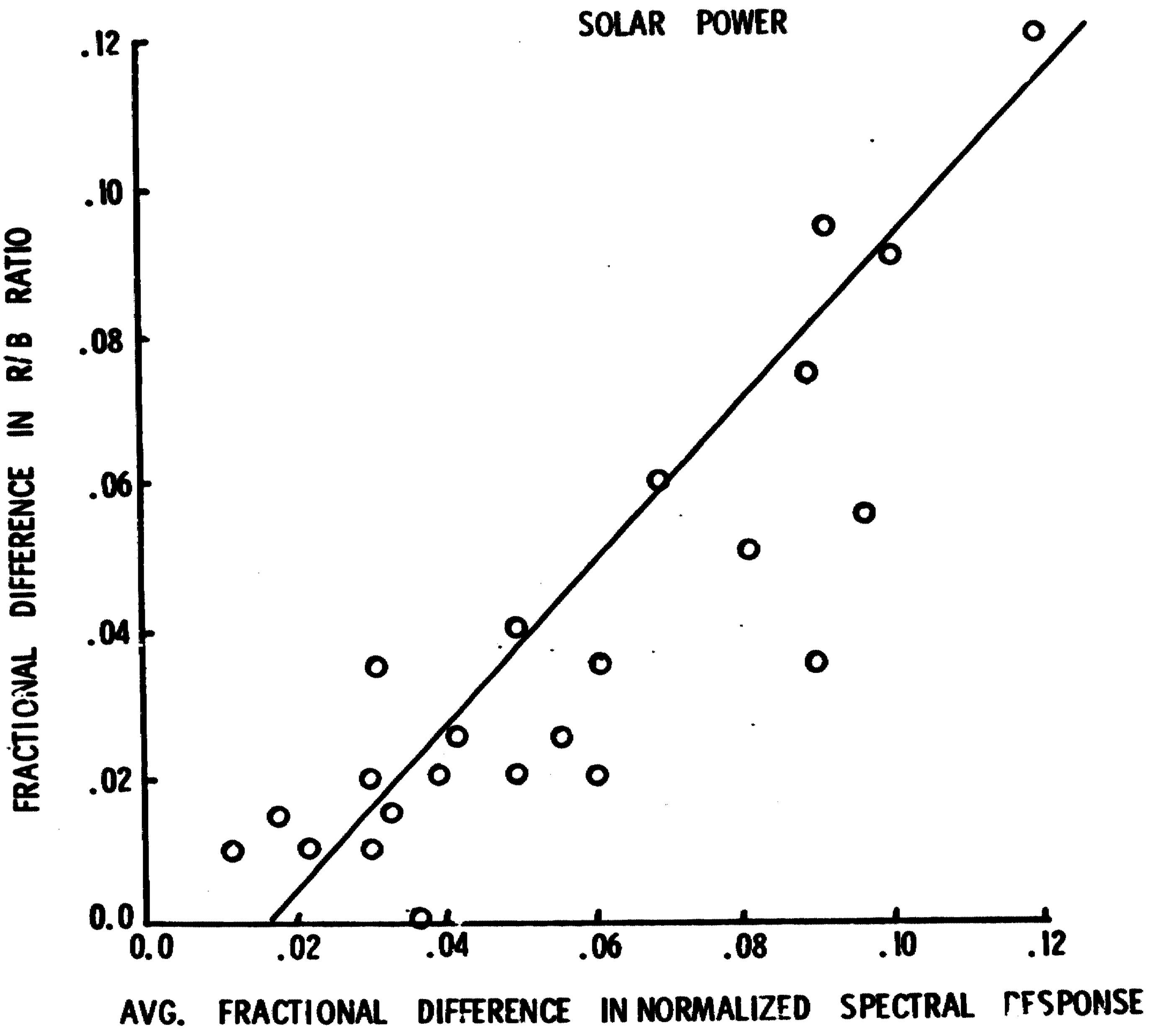


Figure 14. - Red / blue ratio, spectral response correlation for Solar Power cells

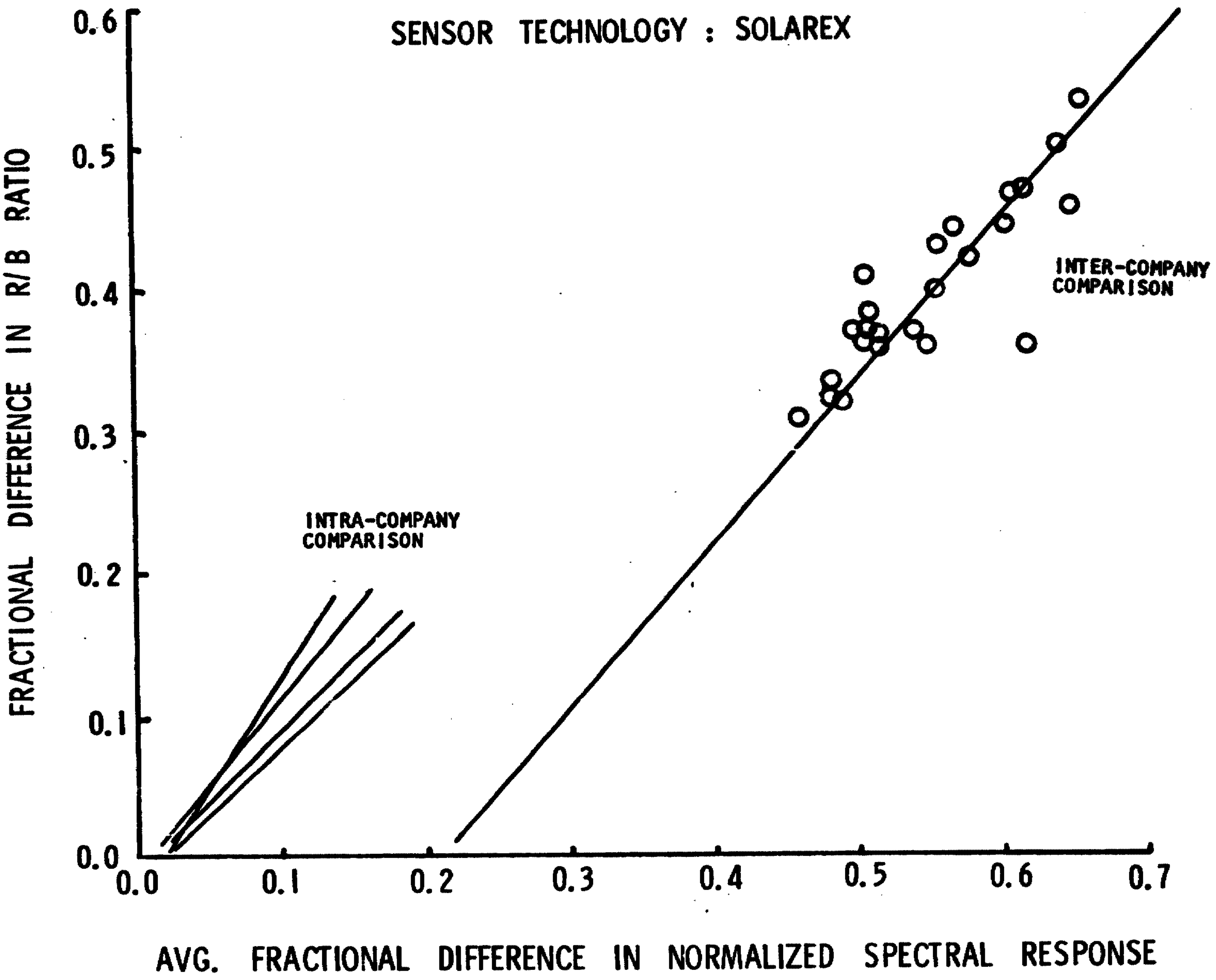


Figure 15. - Red/blue ratio, spectral response correlation for Sensor Technology cells compared with a Solarex reference