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SENSITIVITY OF SOLAR-CELL PERFORMANCE TO ATMOSPHERIC VARIABLES
II - DISSIMILAR CELLS AT SEVERAL LOCATIONS

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SENSITIVITY OF SOLAR-CELL PERFORMANCE TO ATMOSPHERIC VARIABLES II. DISSIMILAR CELLS AT SEVERAL LOCATIONS

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ABSTRACT

Fifteen solar cells, having dissimilar spectral response curves and cell construction, were measured at various locations in the United States to determine sensitivity of cell performance to atmospheric water vapor and turbidity. The locations selected represent a broad range of summer atmospheric conditions, from clear and dry to turbid and humid. Cell short-circuit current under direct normal incidence sunlight, the intensity, water vapor and turbidity were measured. Regression equations were developed from the limited data base in order to provide a single method of prediction of cell current sensitivity to the atmospheric variables.

SUMMARY

Fifteen solar cells, having dissimilar spectral response curves and cell construction, were measured at various locations in the United States to determine the sensitivity of their performance to atmospheric variables. The locations selected represent a broad range of summer atmospheric conditions, from clear and dry to turbid and humid. Schuepp turbidity values from 0.04 to 0.259, water vapor from 0.70 cm to 2.35 cm and air masses from 0.93 to 2.0 were measured during the trip. The calibration values--defined as the ratio of measured cell short-circuit current to incident intensity--were compared with the atmospheric variables and inserted in a regression equation developed to predict cell sensitivity. It was found that there was a correlation between the regression constants obtained and the cell spectral response curves. It appears that cell spectral response determines the regression constants and hence the sensitivity of cell calibration value to atmospheric changes.

INTRODUCTION

Solar cells, which are currently being used for power generation applications on earth by a variety of manufacturers, differ markedly in design and materials used. The cells, eventually combined into large sized arrays and placed in the field, are subjected to environments which may alter their performance. In order to determine their initial performance and subsequent change, if any, the arrays are compared against a reference or standard solar cell. These cells are identical in material and construction to the cells in the array and are periodically calibrated against a total incidence detector. In the case of the cells presently used as standards in the ERDA National Photovoltaic Program, the calibration is performed relative to a normal incidence pyrheliometer under direct normal incidence sunlight (Ref. 1). The standard cells are measured at the short-circuit point of their I-V characteristic and the calibration procedure results in a single calibration value--the ratio of cell short-circuit current generated to the direct solar intensity normally incident on the cell surface.

Both the solar spectral irradiance distribution and the total irradiance vary with changes in the atmospheric constituents. Therefore, the solar cell calibration value can be expected to be sensitive to the atmospheric constituents present during calibration because of the different spectral response characteristics of cell and pyrheliometer. In a previous report (Ref. 2), a simple regression equation was developed for data on a single solar cell. This equation describes the sensitivity of the particular cell's performance to atmospheric turbidity, water vapor, and air mass. This being the case, it is highly desirable to determine the sensitivity of available cells to atmospheric composition and to determine how these changes are related to the basic spectral response of each cell.

Fifteen solar cells, typical of types currently available for terrestrial and space use having dissimilar spectral response curves and/or construction design, were measured within a two-week period at various locations in the United States to determine sensitivity to water vapor, turbidity, and air mass. Silicon, GaAs and Cu_2S/CdS solar cells were included. The locations were selected to represent a broad range of summer atmospheric conditions, ranging from clear and dry to turbid and humid. The sensitivity of the calibration value of each cell to water vapor, turbidity, and air mass was evaluated by regression analysis and the results are presented in this report.

APPARATUS AND MEASUREMENT

The apparatus used to measure the calibration value of each cell consisted of a pyrheliometer and solar cell collimating tube shown in Figure 1. Measurement of the direct solar radiation at normal incidence was obtained using a normal incidence pyrheliometer. The pyrheliometer was mounted on a sun tracker to provide direct intercomparison intensities during the measurement period. The pyrheliometer has a 10:1 collimation ratio and is temperature compensated to within $\pm$ 1% over the temperature range -20^oC to $+40^oC$. The units were calibrated by Eppley Laboratories with respect to IPS 1956 standard. During measurement, each cell was inserted in the holder at the end of the 10:1 collimating tube and connected to the .1 ohm $\pm$ .1% load resistor. A multichannel voltmeter was used to record cell output voltage, temperature, and pyrheliometer output voltage.

The fifteen solar cells used in this study represented a wide variety of cell constructions and spectral responses. There were 13 silicon solar cells, one GaAs cell and one Cu_2S/CdS cell. Some were developed especially for terrestrial application, while others were space cells which have been applied to terrestrial use or have some unique features. This range of cell types was selected in this study to provide a comprehensive survey of available cells. The cells were all mounted in the special holders described in Ref. 2.

Concurrent with measurements of cell short-circuit current, I_{SC}, cell temperature, and the normal incidence irradiance,

I_n, the Schuepp turbidity, B, and water vapor, W, and relative air mass M_r, were measured by the sunphotometers shown in Figure 2. The procedures used to determine B and W using the sunphotometer are described in Ref. 2. The main differences between the work in this report and that of Ref. 2 are: (1) the altitude of each location visited was used to estimate the pressure needed to determine the atmospheric variables in lieu of actual barometeric measurements, and (2) cell short circuit currents were temperature corrected to a common temperature (25° C) in the absence of a temperature controller.

REGRESSION EQUATION

The form of the regression equation used to determine the sensitivity of the calibration value of each cell to water vapor, turbidity, and air mass was as previously described in Reference 2, namely

$$\log \frac{I_{sc}}{I_n} = \log C_0 + \log C_1 \left[10(B-0.045)+1\right] M + \log C_2 (WM_r)^{0.25} \qquad \text{eq. (1)}$$

where C_0, C_1, and C_2 are constants determined by a least square fit of the data. C_0 is the "extraterrestrial calibration value", C_1 is the turbidity regression constant, and C_2 is the water vapor regression constant. B is the Schuepp turbidity coefficient, W is the precipitable water vapor, M_r is the relative air mass, and M is the absolute air mass. ($M = M_r p/p_o$, where p is the atmospheric pressure at the location and p_o is the standard atmospheric pressure.)

RESULTS AND DISCUSSION

Table I indicates the locations visited and the range of atmospheric parameters measured. As can be seen, the measured turbidities and precipitable water vapor represent a broad range of summer atmospheric conditions, from very clear sky (B = 0.04) to hazy (B = 0.259). Precipitable water ranged from a minimum of 0.70 cm to 2.35 cm. The variation in turbidity does not appear to be strongly correlated with variations in water vapor content. In all, a total of 25 measurements were made on each of 12 cells, 24 on 2 cells, and 23 on one cell.

Figure 3 summarizes the results obtained for the regression constants C_1 and C_2, where plotted points are indicated by cell number, for all the cell studied. Values for the turbidity regression constant, C_1, go from 0.98 to 1.018, while the water vapor regression constants, C_2, range from 1.05 to 1.115. As can be seen from Equation 1, regression constants with values less than 1 indicate a decrease in cell calibration value with increase in the associated atmospheric variable while constants greater than 1 indicate an increase in calibration value with increase in the atmospheric variable.

Except for the GaAs cell (#110) there appears to be a correlation between water vapor and turbidity regression constants. The Cu_2S/CdS cell (#67) appears indistinguishable from silicon solar cells. It can be seen that cells with low C_1 constants have high C_2 constants, and vice versa. To qualitatively gain some understanding of this relationship between constants, relative spectral response curves were plotted in Figure 4 for cells 72, 26, and 43 (located at the extreme and middle portions of the calibration plots); cell 110 was also plotted for comparison. It can be seen from Figure 4 that there is a shift in peak response from blue to red in going from cells 72 to 26 and then to 43.

Since losses in spectral irradiance due to increased turbidity occur mainly in the blue region of the solar spectrum, cells with higher blue relative spectral response should experience increased loss in short circuit current with increase in atmospheric turbidity. For all except 4 of the cells studied herein, this loss in cell current outweighed the concurrent loss in normal incident irradiance, resulting in turbidity regression constants less than 1. It also follows that those cells with higher blue response have a lower regression constant.

Similarly, cells with higher red response lose current with increased atmospheric water vapor due to the loss of spectral irradiance in the near infrared, primarily in the 0.940 μm region. However, in this case, the normal incident irradiance loss beyond the spectral region of cell response far outweighs the loss of current, resulting in a water vapor regression constant greater than 1 for all cells measured. It also follows that cells with higher red response have a lower water vapor regression constant. As might be expected the spectral response of the cell determines the sensitivity of the calibration value to the atmospheric variables.

Table 2 shows a comparison of results of regression analyses performed on cell 01 using the separate data bases obtained at Cleveland (ref. 2) and at the other locations visited. As can be seen, the regression constants C_0 and C_1 obtained at Cleveland are 0.3 to 0.4% higher than the constants obtained from data taken at the several locations visited. This difference is insignificant considering the limited amount of data. The standard deviation of the difference between measured and predicted calibration values was 1% for the data taken at Cleveland and was 0.5% for data taken at the different locations. For the other cells studied, the range of standard deviation was 0.3% to 1%, except for GaAs, which had a standard deviation of 2%. Error analysis of the uncertainties in the measured values of I_{sc}, I_n, M, B, and W indicate precision errors of 1 to 1.5% are to be expected.

The anomalous behavior of GaAs in the correlation curve between regression constants, as well as the relatively high standard deviation, possibly may be attributed to its drastically different spectral response, especially the sharp cut off at about 0.88 um.

SUMMARY OF RESULTS

Measurements of 15 solar cells with dissimilar spectral response and construction were made at five geographically separated locations in the contiguous United States to determine the sensitivity of the cell calibration value to atmospheric water vapor and turbidity. A regresssion equation was used to obtain regression constants associated with each atmospheric variable. The following results were obtained:

1. There is a correlation between regression constants and solar cells, cells with low turbidity regression constants had high water vapor regression constants and conversely.

2. The value of the regression constants and the sensitivity of cell calibration value to the atmospheric variables, water vapor content and turbidity appear to be closely related to spectral response of the silicon and Cu_2S/CdS solar cells.

3. The gallium arsenide solar cell data could not be correlated with the other cells.

NOTE: The data set used in this report is available upon request. Mail request to:

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REFERENCES

1. Brandhorst, H.; Hickey, J.; Curtis, H.; Ralph, E.: Interim Solar Cell Testing Procedures for Terrestrial Applications. NASA TM X-71771, 1975.

2. Klucher, T. M.: Sensitivity of Solar Cell Performance to Atmospheric Variables I. Single Cell
To be published.

TABLE I. - LOCATIONS VISITED AND RANGE OF ATMOSPHERIC PARAMETERS

- NEWARK, DELAWARE
- GAINESVILLE, FLORIDA
- PASADENA, CALIFORNIA
- PHOENIX, ARIZONA
- ALBUQUERQUE, NEW MEXICO

<u>RANGE OF ATMOSPHERIC PARAMETERS</u>

TURBIDITY	0.04 - 0.259
WATER VAPOR	0.70 - 2.35 CM
AIR MASS	0.93 - 2.00

TABLE 2 - COMPARISON OF RESULTS OF REGRESSION ANALYSIS

CLEVELAND VS. SEVERAL LOCATIONS

	CELL NO.	C_0 - OUTER SPACE	C_1 - TURBIDITY	C_2 - WATER VAPOR
CLEVELAND	01	1.017 $MA/MW/CM^2$	.991	1.114
LOCATIONS	01	1.013 $MA/MW/CM^2$	.988	1.114

STANDARD DEVIATIONS IN PERCENT OF DIFFERENCES BETWEEN MEASURED AND CALCULATED CALIBRATION VALUES

MEASUREMENT SITE	CELL NUMBER	STANDARD DEVIATION
CLEVELAND	SILICON - 01	1%
SEVERAL LOCATIONS	SILICON - 01	0.5%
SEVERAL LOCATIONS	G_aA_s - 110	2%
SEVERAL LOCATIONS	OTHER CELLS	.3 → 1%

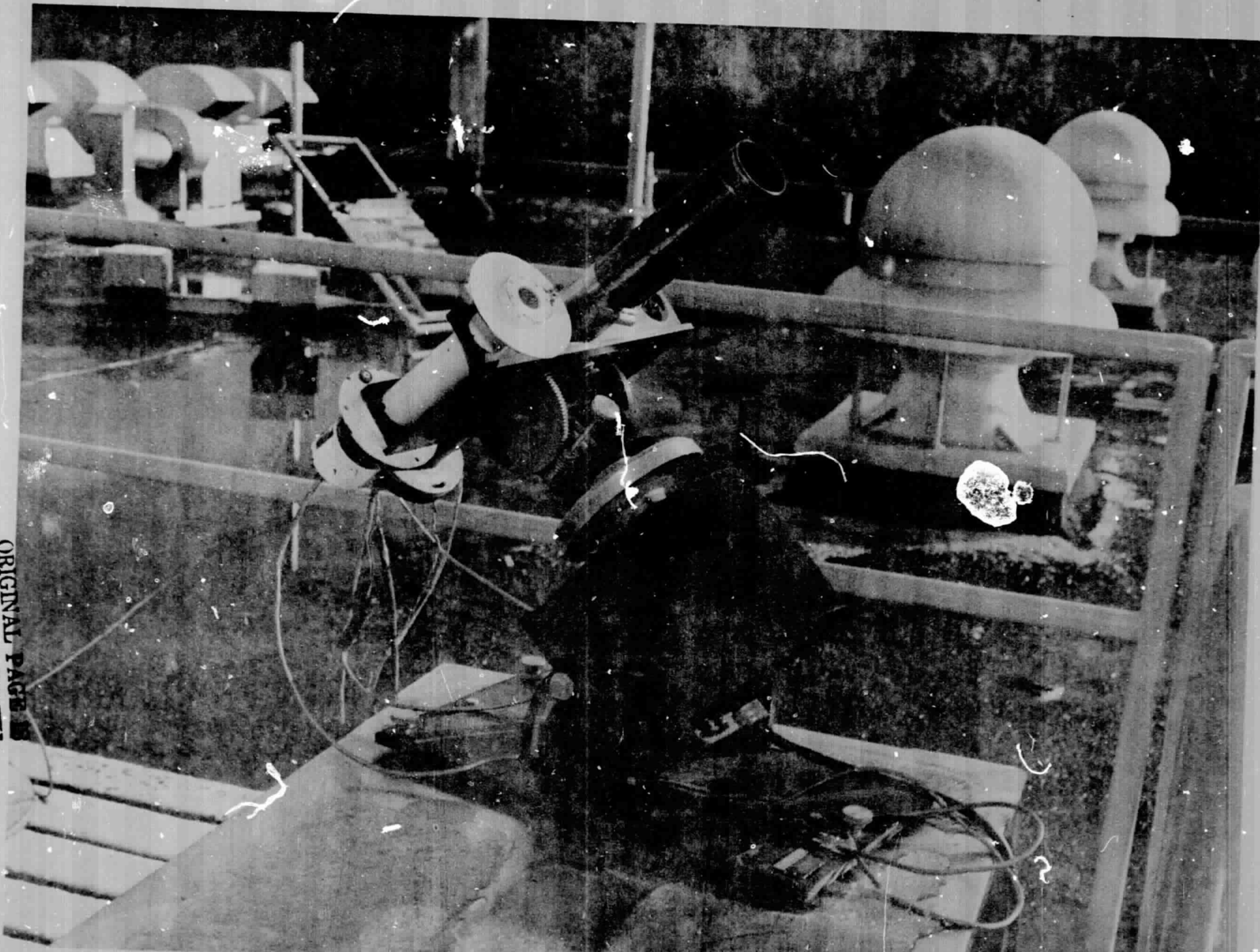

Figure 1. - Solar cell calibration apparatus

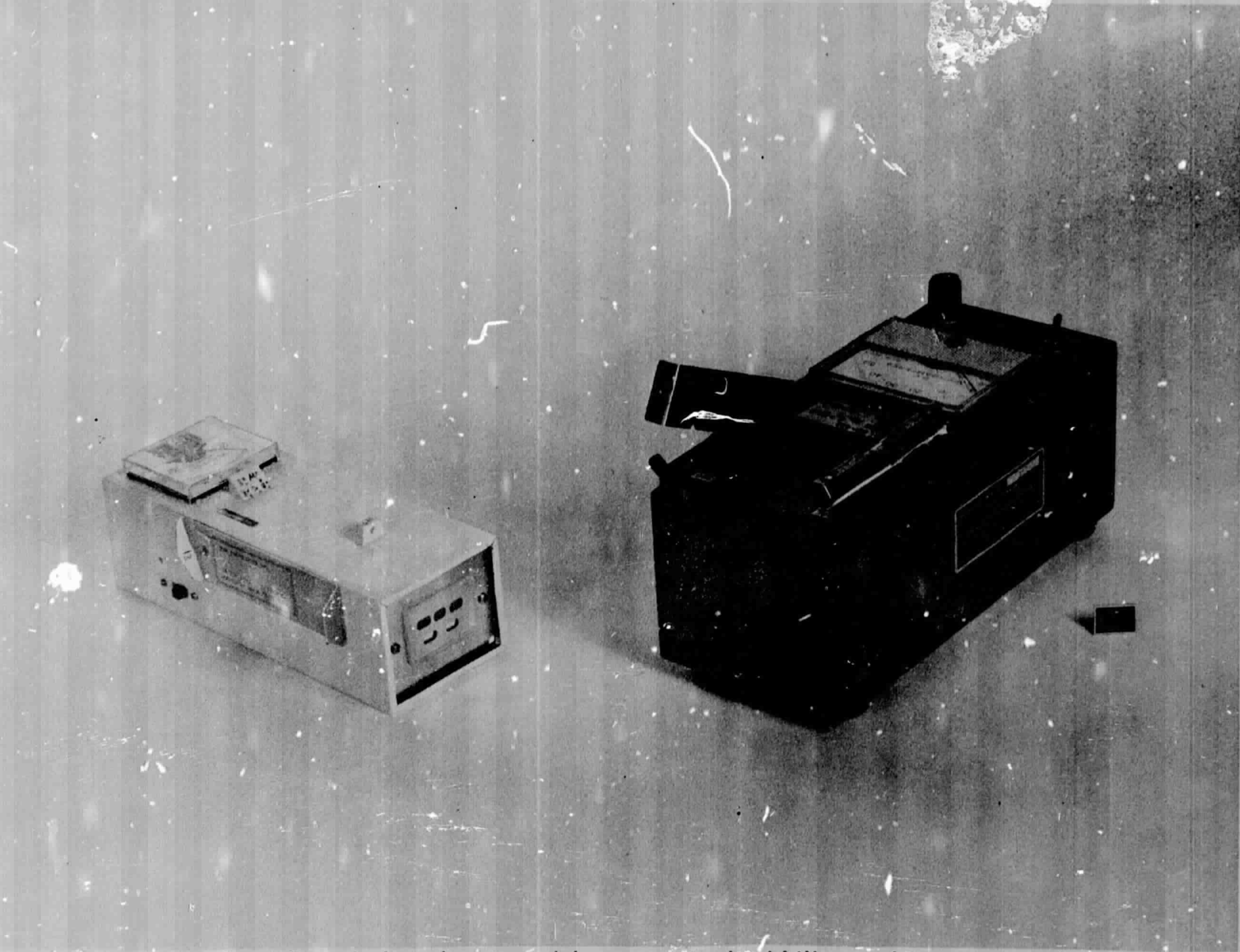

Figure 2. - Sunphotometers used to measure turbidity, water vapor and relative air mass

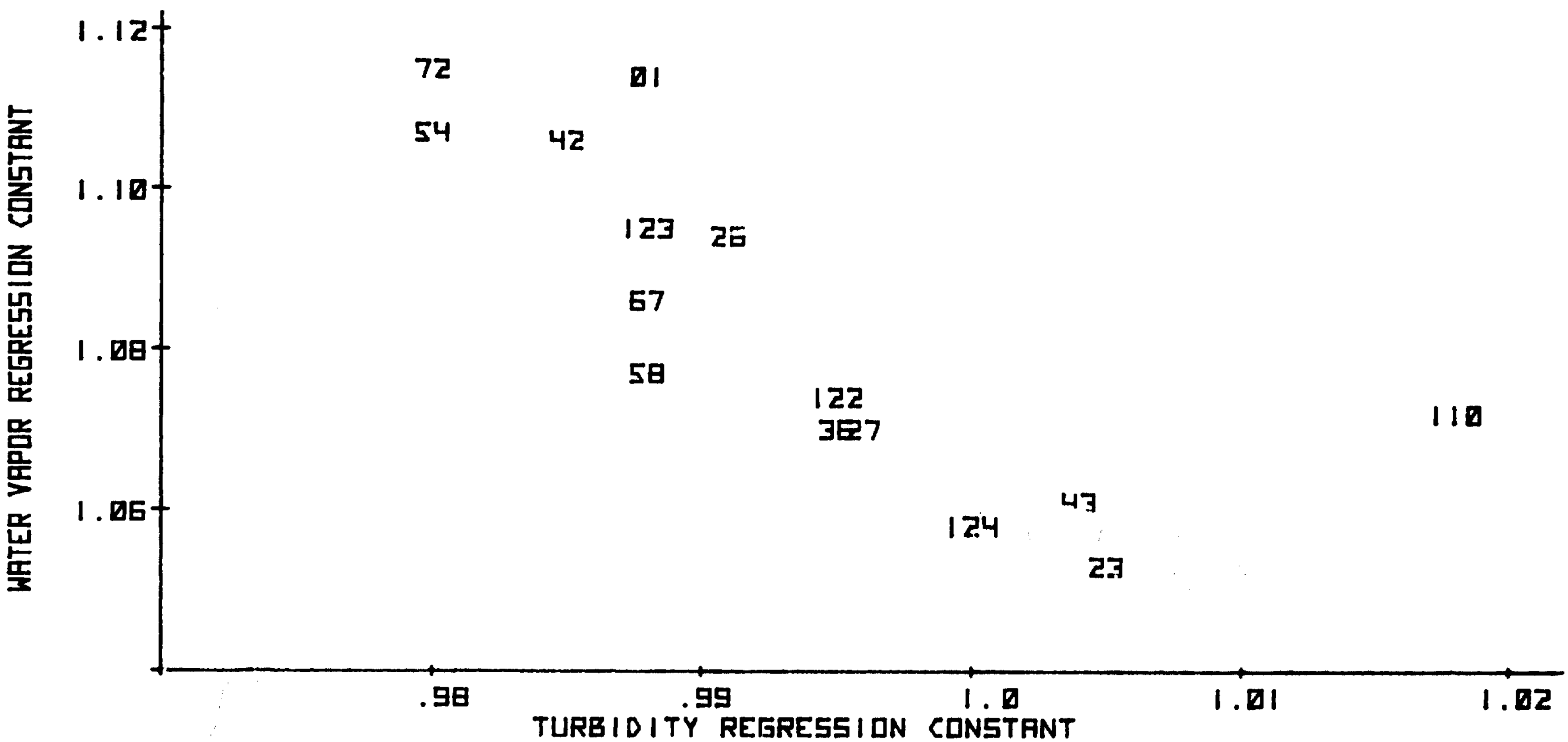

Figure 3. - Correlation between turbidity and water vapor regression constants

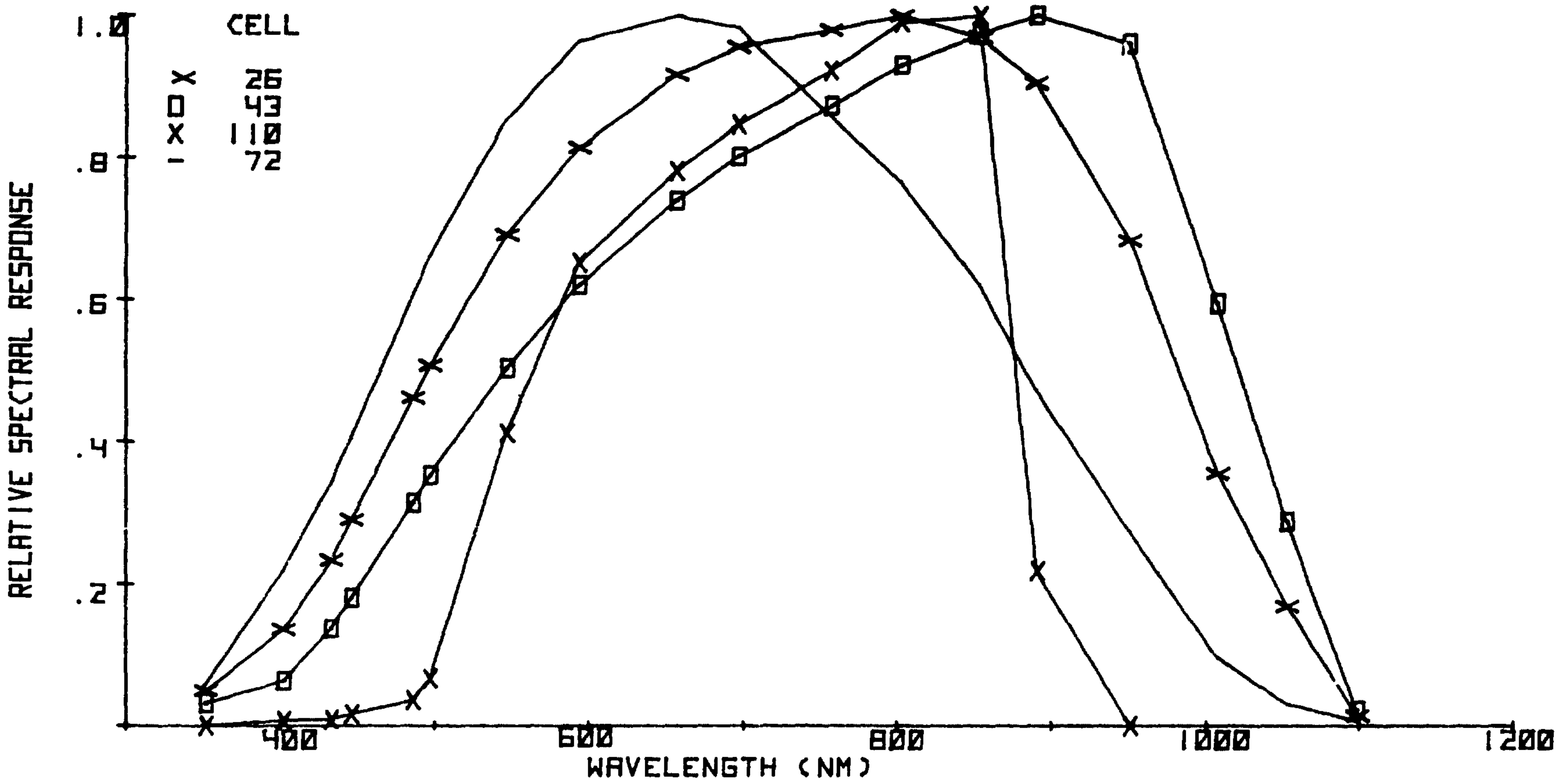

Figure 4. - Comparison of relative spectral response curves of 4 cells