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EFFECT OF ATMOSPHERIC PARAMETERS ON SILICON CELL PERFORMANCE

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ABSTRACT

The effects of changing atmospheric parameters on the performance of a typical silicon solar cell have been calculated. The precipitable water vapor content, airmass and turbidity were varied over wide ranges and the normal terrestrial distribution of spectral irradiance was calculated. The cell short-circuit current was then computed for each spectral irradiance distribution using the cell spectral response. Data are presented in the form of calibration number (cell current/incident irradiance) vs. water vapor content or turbidity.

INTRODUCTION

The spectral distribution of terrestrial solar irradiance varies widely with changing atmospheric parameters. Variables such as amount of precipitable water vapor, airmass, turbidity and ozone content all affect the spectral distribution. For example, increasing water vapor content increases absorption in the infra-red, but has little effect on visible irradiance. Similarly, turbidity generally affects only the visible portion of the spectrum. Solar cells, in general, respond to a limited portion of the terrestrial solar irradiance, below about 1.2 μm.

Hence, any change in the solar irradiance caused by changes in atmospheric composition will have a variable effect on the solar cell output. For example, changes in water vapor content will affect total irradiance but have a lesser effect on solar cell current because most of the water vapor absorption occurs beyond 1.2 μm. The net result is a significant change in the ratio of cell current to irradiance which is defined as the calibration number.

The purpose of this paper is to calculate the effects of changing atmospheric composition on the output of a typical silicon solar cell. The approach is to calculate the direct spectral solar irradiance as a function of the atmospheric parameters and then calculate cell performance using the spectral response curve of the cell.

SPECTRAL IRRADIANCE MODEL

The mathematical model and data used for the calculation of direct solar irradiance is from M. Thekaekara of NASA/Goddard (Ref. 1). The terrestrial spectral irradiance is derived from the following equation using the outer space spectral irradiance distribution (AMO) as the source spectrum.

$$E_\lambda = E_\lambda^o \left[e^{-\left(c_1 + c_2 + \frac{\beta}{\lambda\alpha}\right)m} \right] T_{\lambda i}$$

Where $T_{\lambda i}$ is a transmission factor for various molecular absorptions and has one of the following three different forms at any given wavelength.

$$T_{\lambda 1} = e^{-c_4\sqrt{wm}} \quad ; \quad T_{\lambda 2} = e^{-c_5 wm} \qquad T_{\lambda 3} = 1 - c_6\sqrt{m}$$

Where:

E_λ^o	AMO Spectral Irradiance (Ref. 2)
c_1	optical depth due to ozone
c_2	optical depth due to Rayleigh scattering
λ	wavelength
β, α	turbidity factors
w	precipitable water vapor content
m	air mass
c_4, c_5, c_6	I.R. absorption constants

The ozone and Rayleigh constants are from Elterman (Ref. 3) and the IR constants from Gates (Refs. 4, 5).

This model was used by Thekaekara to derive the AM2 distribution presented in the document Interim Solar Cell Testing Procedures for Terrestrial Applications (Ref. 6). This model computes the direct component only and does not include any forward scattering from the turbidity. For the purposes of these calculations, the lack of forward scattering should have no great effect.

One change was made in the values of the infrared (IR) region constants used by Thekaekara. Figure 1 shows the calculated transmission of the atmosphere containing 20 mm of water vapor at an air mass of 2 in the near IR. The solid curve is calculated with Thekaekara's constants. A broad absorption band from about 0.83 μm to about 1.0 μm is shown. This absorption band does not appear in any available water vapor absorption data on atmospheric transmission

data, hence it appears erroneous. Therefore the IR constants in the wavelength range of 0.835 μm to 0.925 μm were changed to obtain the transmission curve shown by the dotted line. No further changes were made in Thekaekara's model.

The spectral irradiance was calculated for the following range of atmospheric parameters:

water vapor content - 0 to 30 mm

airmass - 1 to 4

turbidity factor, β - 0 to 0.2

turbidity factor, α 1.3

The range of values for airmass, β , and water vapor content should cover almost all possible terrestrial situations. There were 4 airmass values, 6 β values, and 17 water vapor values. Hence 408 (4x6x17) different spectral irradiance distributions were calculated. For each spectral distribution, a calibration number for a single silicon solar cell was calculated as described in the following section.

Cell Performance Calculations

The effect of change in atmospheric parameters on silicon solar cell performance was determined by calculation of the cell calibration number. Cell calibration number is defined as follows:

$$\text{Cal \#} = \frac{\int R_\lambda \, E_\lambda \, d\lambda}{\int E_\lambda \, d_\lambda} \times \text{cell active area}$$

where R_λ = spectral response (mA/mW) of the silicon solar cell.

E_λ solar spectral irradiance ($mW/cm^2 \cdot \mu m$)

The calibration number of the cell is simply the cell short circuit current divided by the irradiance incident upon the cell. A calibration number was calculated for each of the spectral distribution described previously.

The spectral response of the silicon solar cell (#Z-01) used in these calculations is shown in figure 2. The cell is a 2x2 cm cell with SiO antireflection coating. The response of this cell is generally typical of terrestrial silicon solar cells. The response is based on cell active area (3.53 cm^2) and was obtained using a series of narrow band pass monochromatic interference filters. Absolute accuracy of the data are probably no better than $\pm$5%.

THEORETICAL RESULTS AND DISCUSSION

The calculated data are summarized in figures 3-6. Figure 3 shows calibration number plotted against water vapor content at airmass 1 for three different β values. Figure 4 is the same except the airmass is 2. In both of these curves, the calibration number increases sharply with water vapor for awhile then the rate of increase tends to level off. In the airmass 1 curve, the break is at a water vapor content of about 5 mm, while in the airmass 2 curve, it occurs at about 3 mm. In both cases, the water vapor-airmass product is 5 to 6 mm. This suggests that the total water vapor content through which the sunlight passes is the important factor. The increase in calibration number with water vapor content results from the increased absorption primarily in the IR region beyond the response of the cell. This leads to a lowering of the incident irradiance. Because the reduction occurs primarily in the infrared, the cell current is not lowered as much. Since calibration number is current/irradiance, the calibration number increases. This increase can be substantial. For airmass 1 and a beta value of 0.12, the calibration number increases 3.6%, for a change of 5 mm to 20 mm of water vapor. The increase jumps to 5.3% for

the airmass 2 case. For water vapor values below 5 mm, the effect is even more dramatic, however, such low water vapor contents are not normally seen in the terrestrial environment.

Figure 5 shows calibration number as function of beta for three water vapor values and an airmass of 1. Figure 6 is the same plot at airmass 2. In opposition to the water vapor case, the calibration number decreases with increasing beta. Note also that the magnitude of the decrease is much larger for the airmass 2 case than in the airmass 1 case. For example, the calibration number drops 2.8% as beta increases from 0.04 to 0.12 at 20 mm of water and airmass 2. The decrease is only 1.0% at airmass 1. This decrease in calibration number with increasing beta occurs because increases in beta affects the irradiance more heavily in the wavelength region where the cell responds. Cell current is lowered by a larger percentage than the irradiance, hence the calibration number decreases.

Similar curves for higher airmass values can be generated, however, at a combination of airmass 3 or 4 and a high value of either beta or water vapor content, the calculated irradiance becomes quite low. At airmass 3, most of the irradiance levels for beta and water vapor values in figures 3-6 are below 55 mW/cm^2.

EXPERIMENTAL VERIFICATION

The changes in calibration number discussed above are the results of calculations. To verify these results, cell Z-01 was measured outdoors under a range of atmospheric conditions. The cell was placed in a collimating tube and aligned perpendicular to the

sun. The cell short circuit current and the output of a normal incidence pyrheliometer (NIP) were measured simultaneously. Both the NIP and the collimating tube had the same field of view (5.3°). At the same time, airmass, water vapor content, and the Schuepp's turbidity coefficient (β at α = 1.3) were measured. Data were only taken when there was a cloud-free direct solar beam. Thirty-seven different data points were obtained over the following range of parameters:

airmass	1.6 - 4.2
beta	.029 - .119
water vapor	4.6 - 14.1 mm
cal. number	1.058 - 1.149 mA/mW/cm^2

Beta and water vapor content were measured using a Volz sun photometer. Airmass was calculated from the sun angle and atmospheric pressure. The calibration number was calculated directly from the short circuit current of cell Z-01 and the NIP reading. In order to readily compare the measured calibration numbers to the model, spectral irradiances were calculated for each of the 37 data points. Comparison between calculated and measured irradiance is shown in figure 7. A similar comparison for short circuit currents is shown in figure 8. In both figures, the straight line is the locus of points where calculated and measured values are equal.

In the irradiance figure (fig. 7), the measured values are larger than the calculated values with two exceptions. One is at a very low irradiance level ($\sim$ 34 mW/cm^2) and the second near 62 mW/cm^2. No explanation for these anomalies is offered. The difference between the curves is about 6%. In the current figure (fig. 8), the data look similar to the irradiance case except the measured value is now about 9% higher than the calculated value. In both cases, the

consistent differences indicate some non-random error. Possible explanations are the incompleteness of the irradiance model, or an error in the measurement of the atmospheric parameters.

Figure 9 shows the comparison between the measured and calculated calibration numbers. In all cases, the measured value is greater than the calculated value. The average difference is 3.1% with a range of 1.4 to 4.9%. Again, the difference is fairly consistent, considering the data scatter between measured and calculated values for irradiance and cell current.

As noted earlier, one change was made in the infrared absorption constants in Thekaekara's irradiance model. Before the change, the difference between measured and calculated values of calibration number was about 7% with a range of 4% to 10%. However, the basic trends of calibration number with increasing water vapor, turbidity or airmass were the same. This suggests that some small additional modification in the irradiance model could bring agreement between the measured and calculated calibration numbers while having no effect on the variation of calibration numbers with increasing atmospheric parameters.

SUMMARY OF RESULTS

It has been shown that the calibration number (cell current/incident irradiance) of a typical silicon solar cell varies significantly with changing atmospheric parameters. Increases of 5% or more in the calibration number for reasonable changes in atmospheric water vapor content are seen. The effect of changes in turbidity are significant but not quite as large as in the water vapor case. Increasing turbidity reduces the calibration number. Airmass is also an important parameter, especially in the turbidity case, where

changes in calibration number for a given turbidity change are twice as large at airmass 2 than airmass 1. Direct comparison of calculated and experimental data for a silicon solar cell were made under differing atmospheric compositions. Measured values of irradiance, short circuit current, and calibration number were greater than the calculated values by 6%, 9% and 3% respectively. Small changes in the theoretical model may reduce this spread.

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Figure 1. - Transmission of the atmosphere due to water vapor content in the near IR

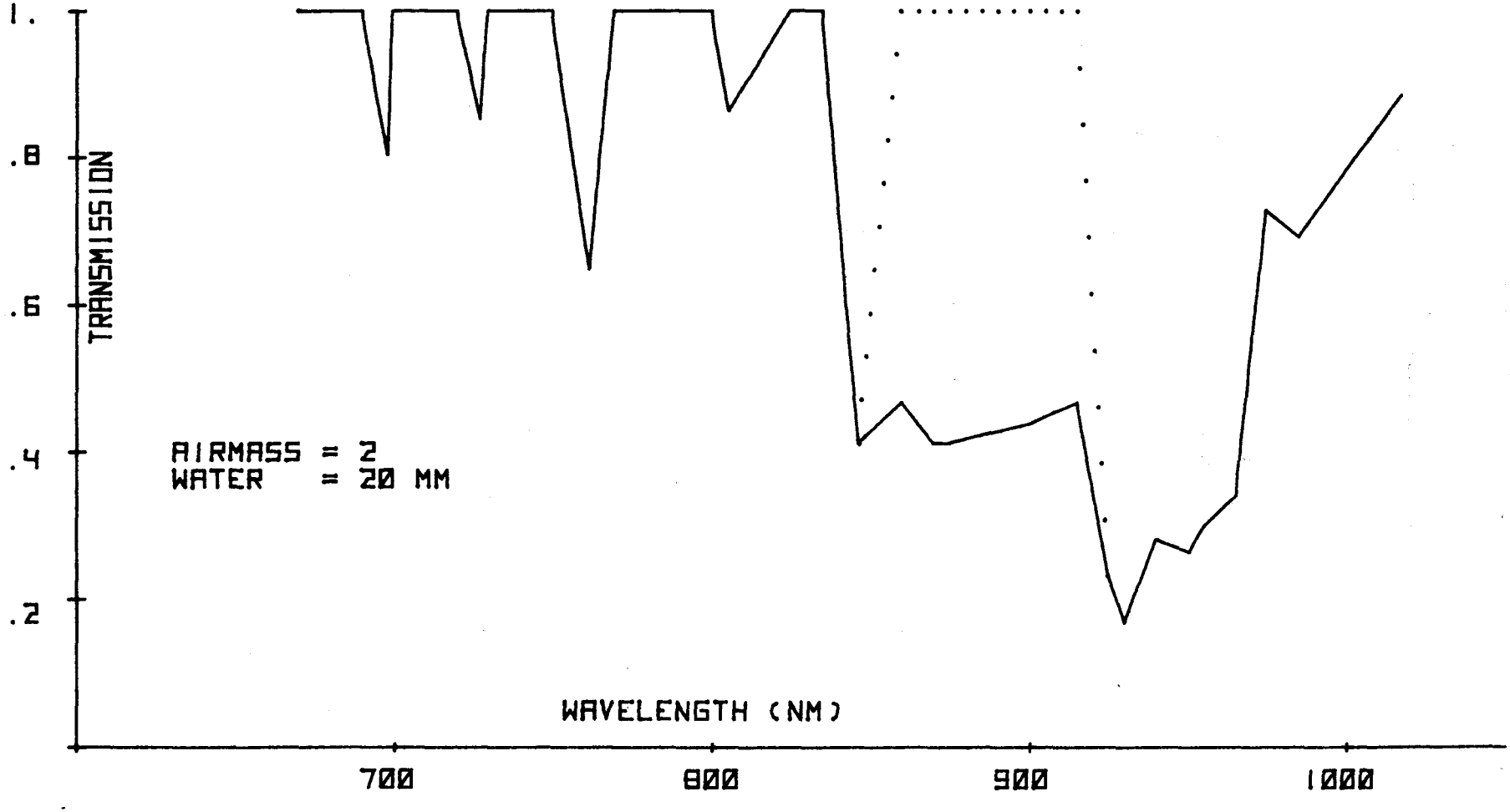


Figure 2. - Spectral response of cell Z-01

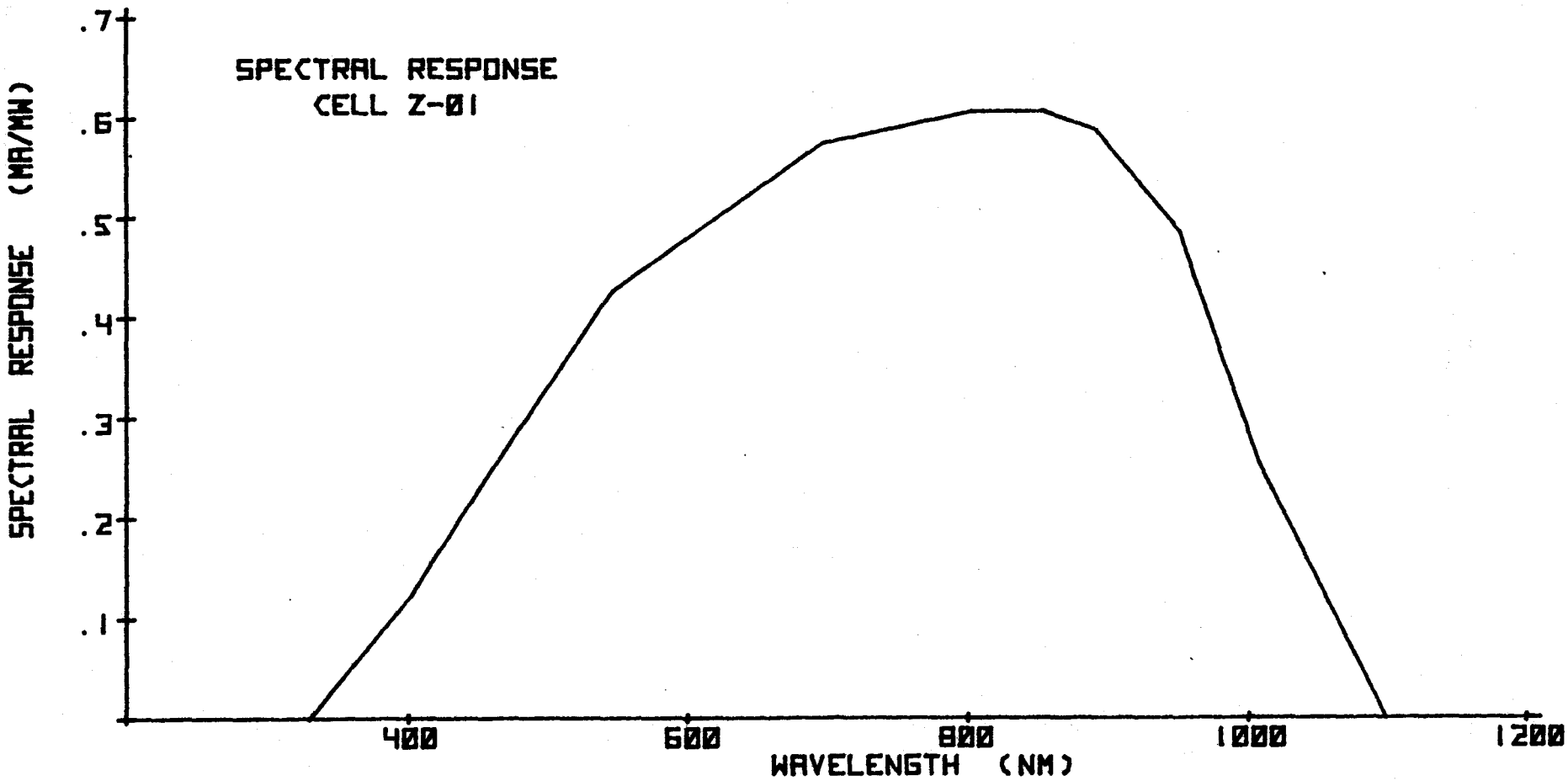


Figure 3. - Effect of water vapor on cell calibration number for Air Mass 1 sunlight

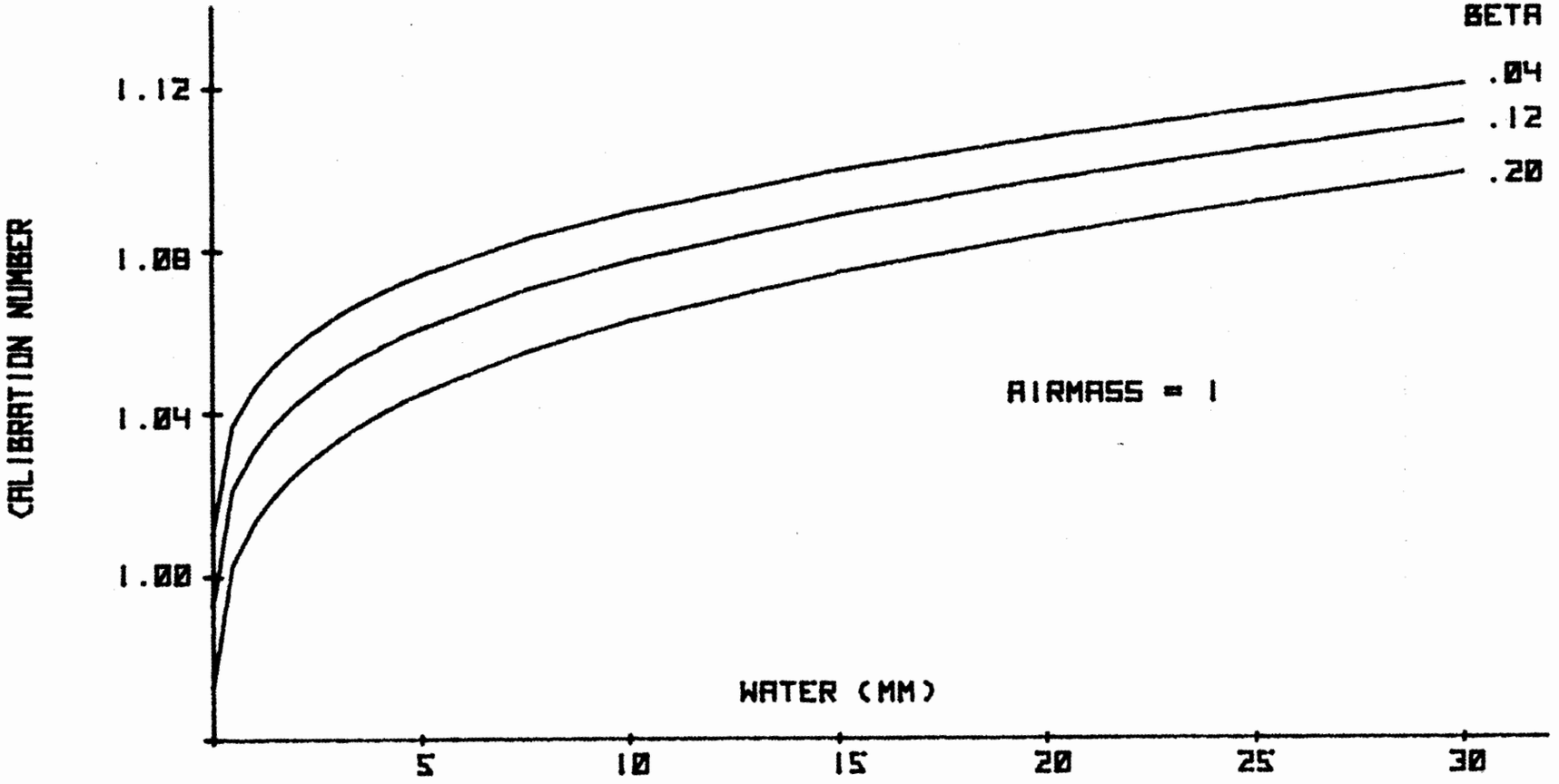


Figure 4. - Effect of water vapor on cell calibration number for Air Mass 2 sunlight

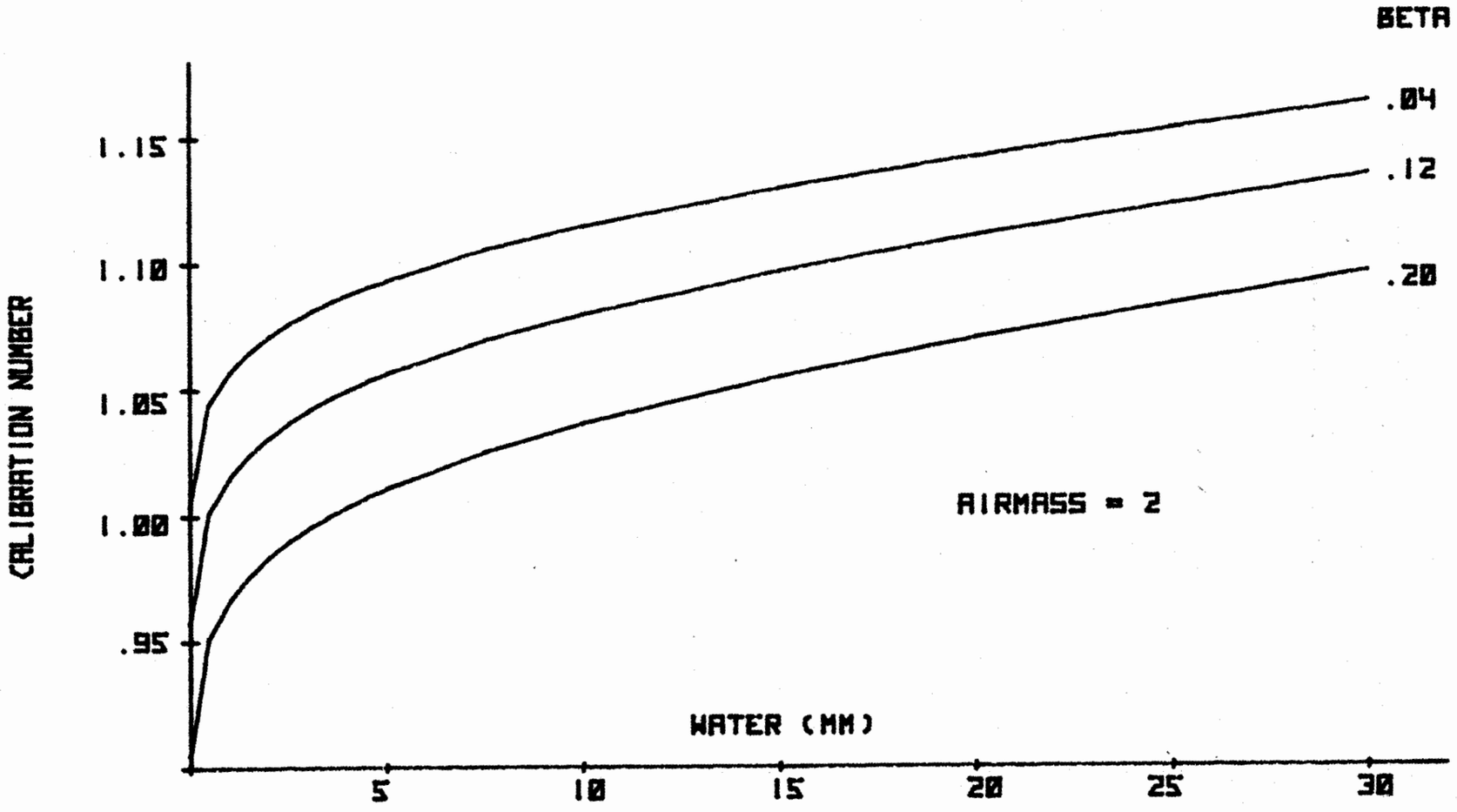


Figure 5. - Effect of turbidity coefficient, beta, on cell calibration number for Air Mass 1 sunlight

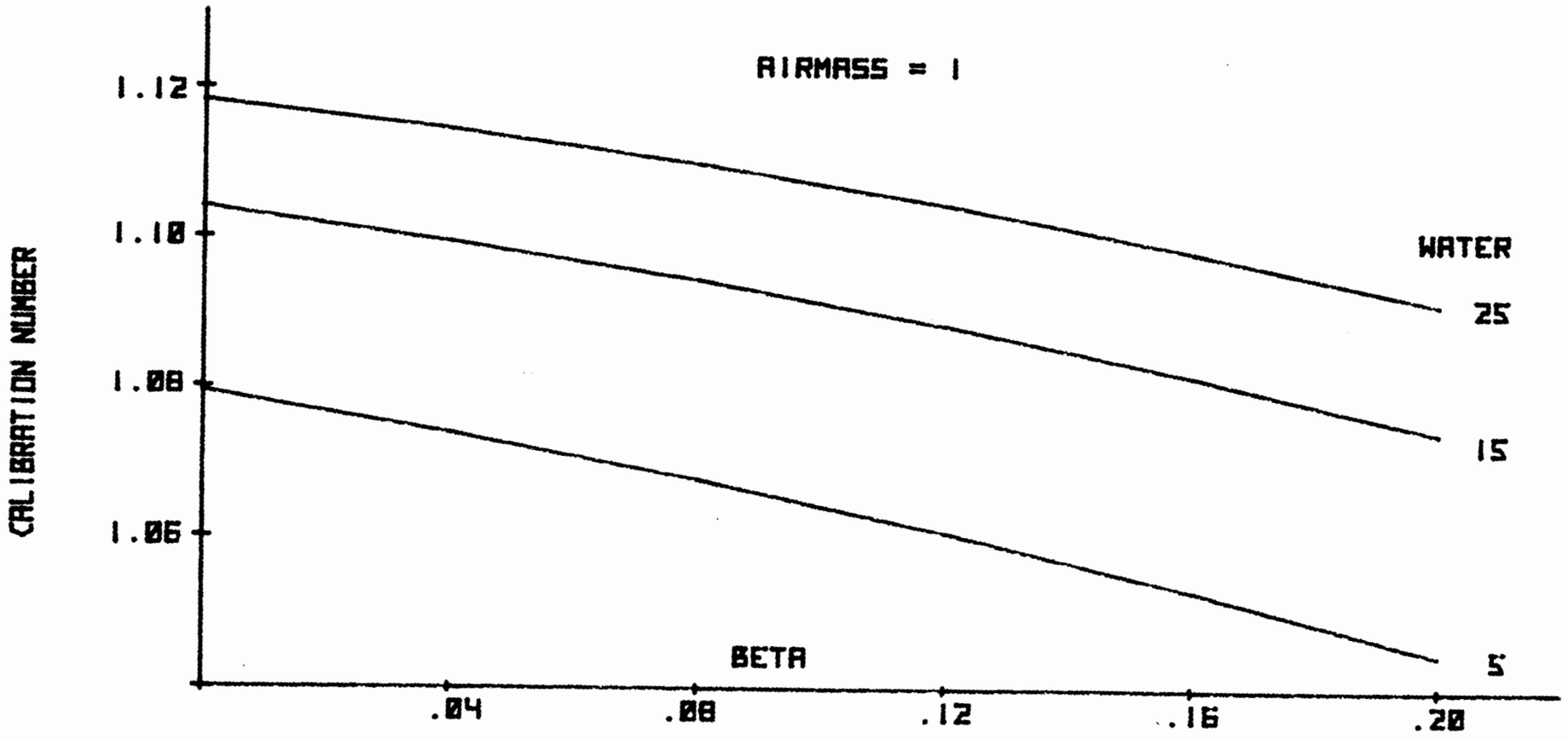
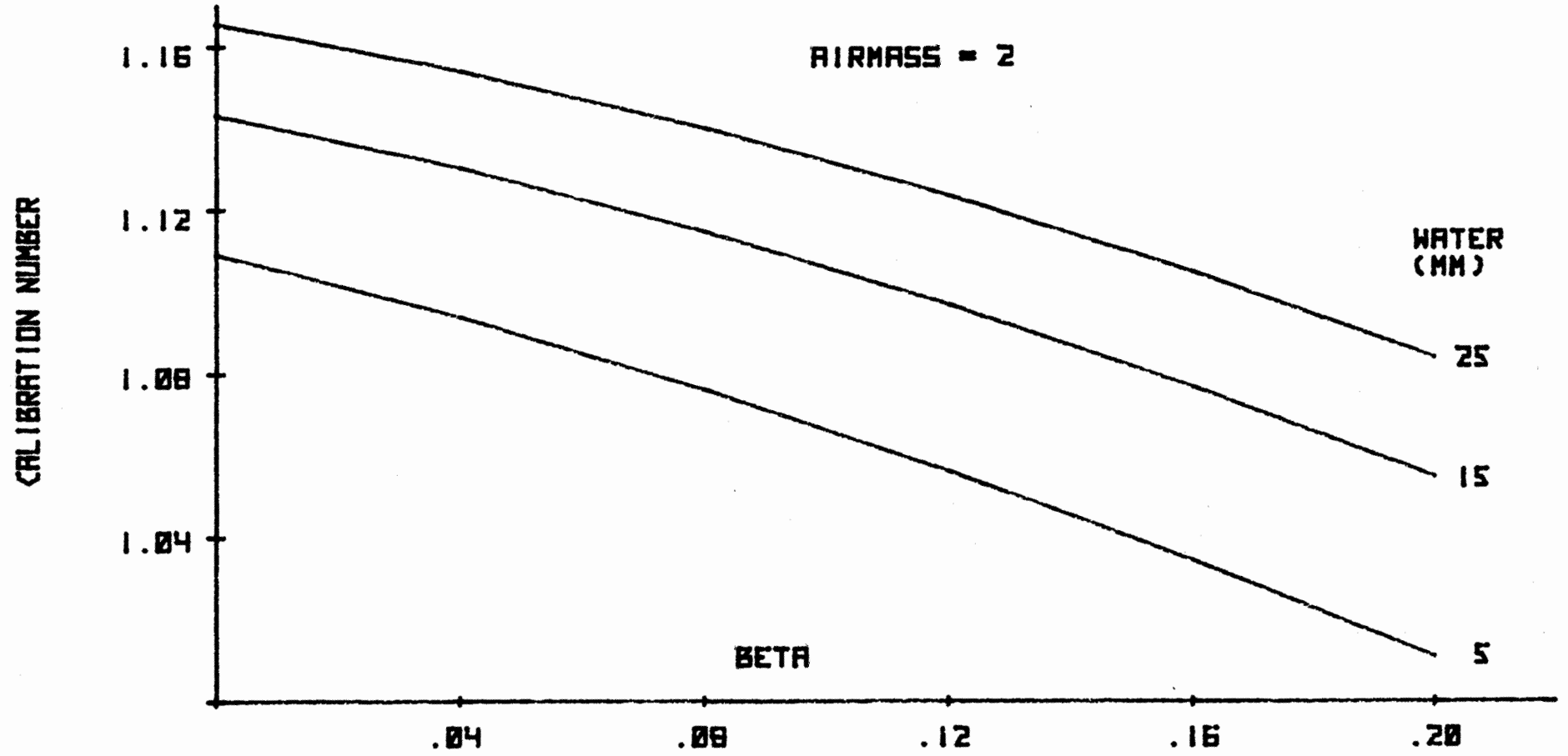


Figure 6. - Effect of turbidity coefficient, beta, on cell calibration number for Air Mass 2 sunlight



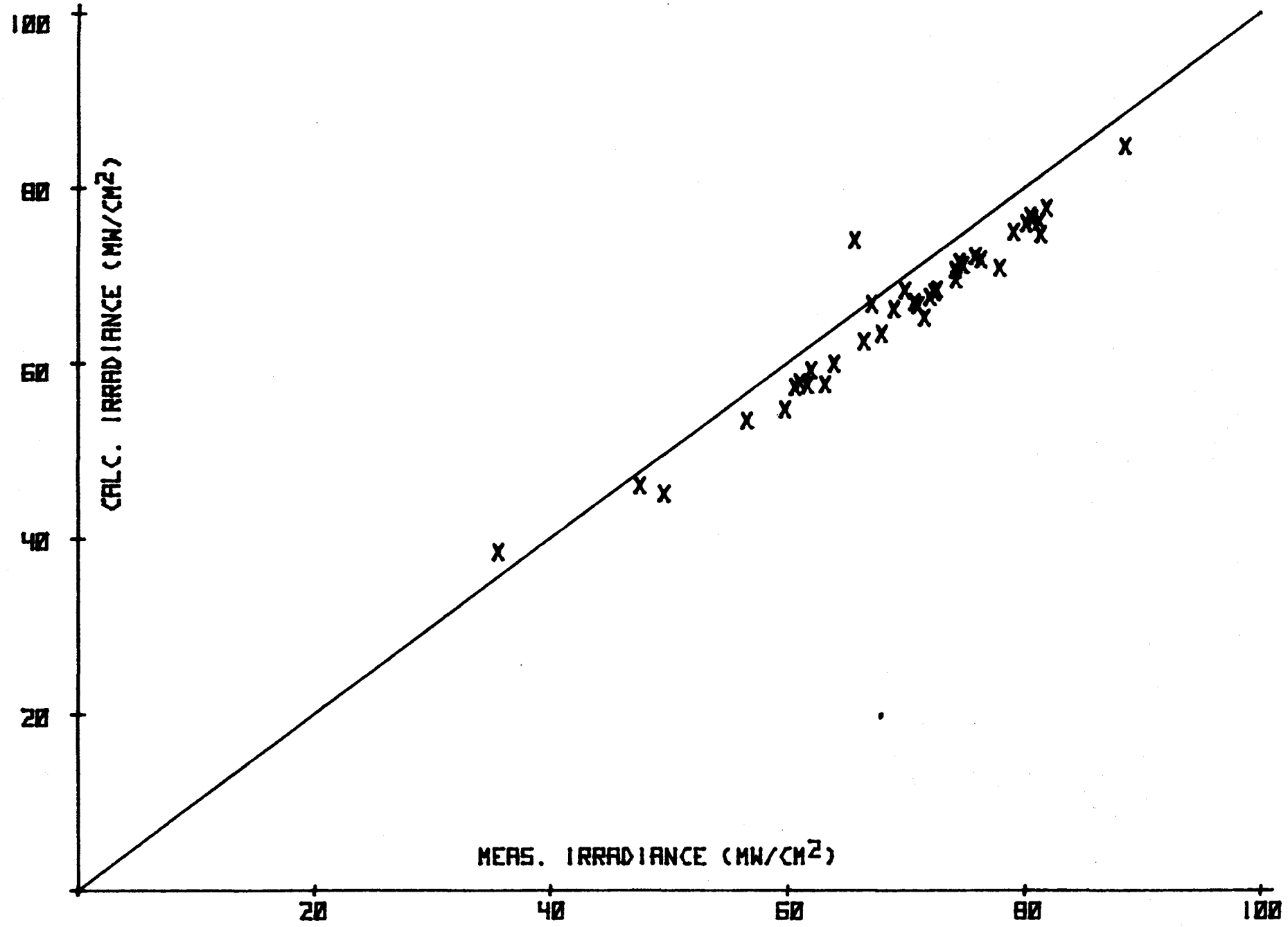


Figure 7. Comparison of calculated and measured irradiance

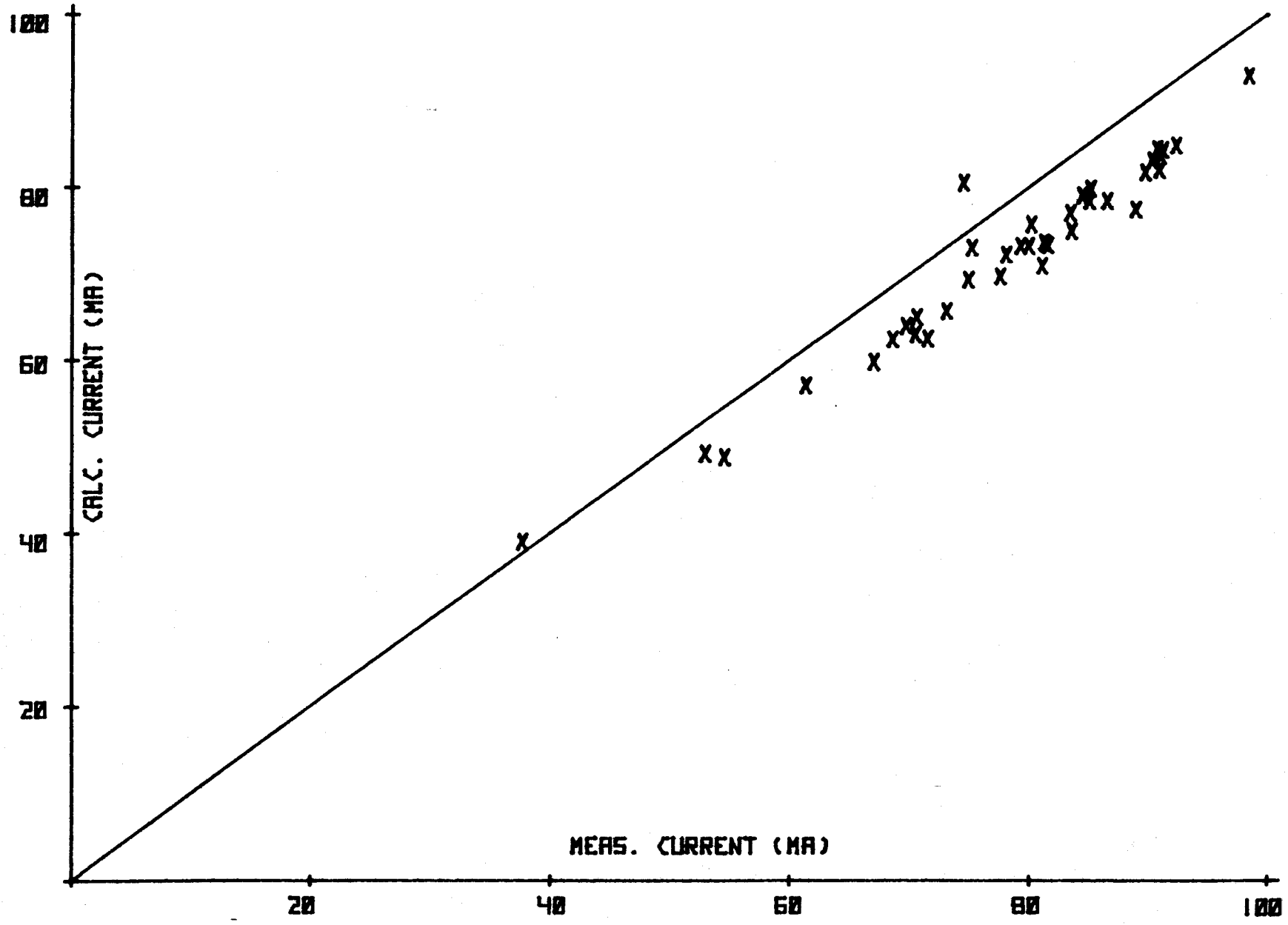


Figure 8. - Comparison of calculated and measured short circuit currents

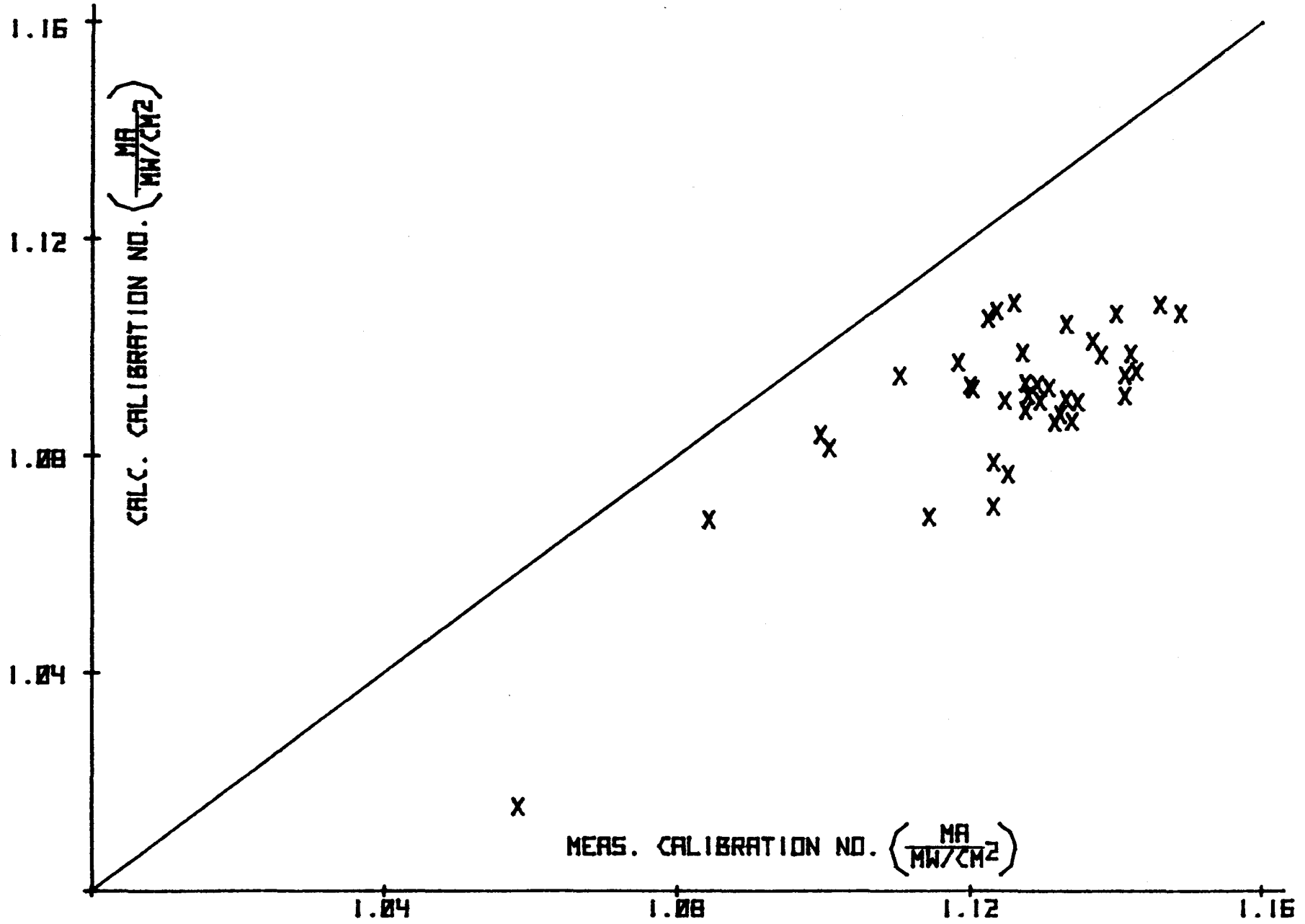


Figure 9. - Comparison of calculated and measured calibration numbers