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ERDA/NASA 1022/76/3
NASA CP-2010
Technical Report II-2

(NASA-CR-2010) ERRORS IN SHORT CIRCUIT MEASUREMENTS DUE TO SPECTRAL MISMATCH BETWEEN SUNLIGHT AND SOLAR SIMULATORS (NASA) 26 p HC A03/MF A01 CSCL 10A

N77-26620

Unclas
H1/44 35423

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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

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ABSTRACT

Errors in short-circuit-current measurement were calculated for a variety of spectral mismatch conditions. Parameters included were the differences in spectral irradiance between terrestrial sunlight and three types of solar simulator, as well as the differences in spectral response between three types of reference solar cells and various test cells. The simulators considered are a short-arc xenon-lamp AMO sunlight simulator, an ordinary quartz halogen lamp, and ELH-type quartz-halogen lamp. The three types of solar cell are a silicon cell, a cadmium sulfide cell and a gallium arsenide cell.

INTRODUCTION

The output of solar cells has been measured using solar simulators for many years. No simulator exactly duplicates the spectral distribution of terrestrial solar irradiance (spectral irradiance); hence there are spectral mismatches between sunlight and solar simulators. The short-circuit current of a solar cell is proportional to total irradiance and is a function of spectral irradiance. Therefore, there may be errors in short-circuit-current measurements due to spectral mismatch when using a solar simulator. In an attempt to reduce this spectral error, a calibrated reference cell, with spectral response similar to the cell being measured, is used to adjust the simulator intensity. The feasibility of this practice can be substantiated with the following analysis.

The short-circuit current of a solar cell may be calculated from the spectral response of the cell (R_λ) and the spectral irradiance incident on the cell (E_λ)

$$I = \int E_\lambda \; R_\lambda \; d\lambda \tag{1}$$

For clarity in the subsequent analysis, two subscripts are added to the current symbol indicating cell function (reference or test) and light source (sunlight or simulator). Hence $I_{ref-sun}$ is short circuit current calculated for the reference cell in sunlight. $I_{cell-sim}$ is for the test cell in the simulator.

In measuring a solar cell, either in sunlight or with a simulator, the key performance parameter desired is $I_{cell-sun}$ at a standard irradiance level. However, when using a solar simulator, the value $I_{cell-sim}$ is actually measured. Also, the irradiance of the simulator has been measured using the calibrated reference cell. The measured value $I_{cell-sim}$ is multiplied by the ratio $(I_{ref-sun}/I_{ref-sim})$ to adjust to the proper intensity. (In practice, the simulator irradiance level is adjusted, which is the mathematical equivalent.) Therefore, the quantity $I_{cell-sim} \left[\frac{I_{ref-sun}}{I_{ref-sim}}\right]$ is actually measured when the parameter $I_{cell-sun}$ is desired (Fig. 1). This can be shown mathematically as:

$$I_{cell-sun} = \int E_{sim} R_{cell} \; d\lambda \left[\frac{\int E_{sun} \; R_{ref} d\lambda}{\int E_{sim} \; R_{ref} d\lambda} \right] \tag{2}$$

It can be seen that if the simulator has the same spectral irradiance as the sun ($E_{sun} = E_{sim}$), the quantity in brackets is unity and $I_{cell-sun}$ equals $I_{cell-sim}$. Similarly, if the test and reference cells have identical spectral responses ($R_{ref} = R_{cell}$) the terms containing E_{sim} cancel and an exact value of $I_{cell-sim}$ is measured independent of the spectral distribution of the simulator. In practice, absolute matching of spectral responses is rarely achieved, nor do simulators exactly duplicate terrestrial sunlight hence errors can be expected. The percent error in the measurement is:

$$\left[\frac{I_{cell-sun} - I_{cell-sim} \left[\frac{I_{ref-sun}}{I_{ref-sim}} \right]}{I_{cell-sun}} \right] \times 100\% \qquad (3)$$

The purpose of this paper is to calculate the magnitude of such errors for a variety of simulators and reference-test cell pairs.

SPECTRAL IRRADIANCE DATA

To calculate the various short circuit currents, several spectral irradiances and spectral responses are needed. The solar irradiance used is the air mass 2 curve by Thekaekara given in the "Interim Solar Cell Testing Procedures for Terrestrial Applications" (Ref. 1). This is shown in figure 2. Figures 3, 4 and 5 show measured spectral irradiance curves for three types of solar simulators:

Figure 3 - a short arc xenon lamp simulator

Figure 4 - a quartz-halogen tungsten lamp

Figure 5 - an ELH lamp

All have been normalized to equal area. The short arc xenon lamp simulator, measured using a high resolution spectrophotometer, is a typical AMO simulator, rich in ultraviolet light. The quartz-halogen tungsten lamp shown is a standard of spectral irradiance supplied by NBS. The lamp is a 1000-watt quartz-halogen bulb and is typical of many "tungsten lamp" simulators. The ELH lamp is a 300-watt quartz halogen lamp within a dichroic-coated reflector. The reflector transmits a significant portion of the infra-red radiation while reflecting the visible. Hence the output beam has much less infrared light than the normal quartz-halogen lamp.

Upon inspection of the four spectral irradiance curves, it can be seen that the xenon arc lamp and the ELH lamp give fairly good matches to the AM2 solar spectrum. However, the plain quartz-halogen lamp gives a poor match.

SPECTRAL RESPONSE DATA

To complete the data needed for the analysis, the spectral response of several reference cell-test cell combinations are needed. This was done mathematically by using one reference cell spectral response and generating many test cell spectral responses by perturbations on the reference cell response. Figure 6 shows a spectral response of a typical silicon cell. This is used as the reference cell response. One of the test cell spectral responses is indicated by the X's. The system for generating different test cell responses was as follows. The reference cell response was transformed in the y-direction (response) by an amount equal to 25% of the maximum standard cell response. This transformation was done on only part of the wavelength region as the example in figure 6 shows. There is no transformation beyond 0.9 μm in this example. The transformation could be either positive or negative. Literally hundreds of cell responses were generated by varying the wavelengths at which the perturbation started and stopped. The 25% value was chosen to be representative of a fairly poor match between reference cell and test cell in practice.

With a solar spectral irradiance and three simulator spectral irradiances along with a reference cell response and many test cell responses, all combinations of short-circuit current measurement error may be calculated. This analysis was also done for a cadmium sulfide solar cell and a gallium arsenide solar cell. Again, a set of test cells was generated from the reference cell response. The reference cell responses for cadmium sulfide and gallium arsenide are shown in figures 7 and 8.

RESULTS AND DISCUSSION

Table I summarizes the results for the silicon cell reference. For each of the three simulators, the average of the absolute value of about 100 different reference cell-test cell combinations is given. Also shown is the largest error found. The xenon lamp produces the smallest errors. The ELH lamp is just slightly higher than the xenon. This is in accord with the closeness of their spectral irradiances to AM2 sunlight. The tungsten-halogen lamp produces much larger errors than either the xenon or ELH lamps. This was expected because the tungsten-halogen lamp gives the worst spectral fit to the sunlight curve. Average errors of 8.4% with a maximum of 11%, when using a reference cell of the same general spectral response are much too large to tolerate. This makes the tungsten-halogen lamp simulator a very poor choice for measuring solar cells unless much closer spectral matching of test and reference cells is ensured. The xenon simulator produces the lowest errors, is the most expensive and probably best represents the current state of the art in solar simulators. Hence it appears to be the best choice for measuring silicon solar cells. However, the ELH lamps have only slightly greater errors than the xenon lamp simulator. Their advantages of simplicity and low cost seem to make them a good second choice for a solar simulator source.

The error calculations were repeated for the cadmium sulfide and gallium arsenide reference cell responses. Tables II and III give the results for these two types of cells. In both cases, the trends are essentially the same as discussed for the silicon cell case. The error magnitudes shift somewhat but the tungsten-halogen lamp is still an acceptable solar simulator. In the gallium arsenide case, the average error was less for the ELH lamp than for the xenon lamp, and the errors are somewhat larger than for the other two types of cells. This appears due to the very narrow spectral response range of the gallium arsenide cell.

It is interesting to note that, in general, the short arc xenon lamp simulator is the best choice for measuring terrestrial photovoltaic devices, even though it is essentially an airmass zero simulator. This can be explained by considering the black body temperature of the various radiation sources. The sun can be considered approximately a 6000°K black body. The effect of the atmosphere on solar irradiance is, of course, quite significant. However, the terrestrial spectral irradiance still has roughly the same overall shape as the AMO curve, and hence about the same black body radiation temperature. A tungsten filament can be considered to be a 3000°K black body, while a xenon arc is much closer to the 6000°K temperature of the sun. Thus, the xenon lamp will have a much better fit to either AMO or terrestrial sunlight than a plain tungsten lamp. The ELH lamp is a special case due to the effect of the dichroic-coated reflector. It is deficient in the ultraviolet region but this has little or no effect on the results presented here.

EXPERIMENTAL RESULTS

The above data were all computer generated. Therefore, to assess the accuracy of these results, measurements of several silicon cells were made under the different light sources. A terrestrial silicon cell (Z-01) was chosen as the reference cell and six other silicon cells were used as test cells. Figures 9 through 14 show spectral response of Z-01 compared to each of the six other cells. Z-01 and Z-00 (Fig. 9) are both terrestrial cells from one manufacturer. Their responses are almost identical. The other five cells are from other terrestrial solar cell suppliers A variety of spectral response shapes is represented by this group of cells. The spectral mismatchs between Z-01 and each of the last five cells are about the same magnitude as used in the calculations. Each cell was measured outdoors in a collimating tube. Sunlight intensity was measured with a normal incidence pyrheliometer (NIP).

The collimating tube had the same field of view as the NIP (5.7°). The short circuit currents for each cell, normalized to 100 mW/cm^2 are shown in Table IV under the "SOLAR" heading. Each cell was then measured in a xenon arc simulator, an ELH lamp simulator and a tungsten lamp simulator. Cell Z-01 was used as the reference cell. These results are also shown in Table IV. The current Z-01 was identical in all three cases because it was the reference. Cell Z-00, (the same manufacturer of Z-01) had nearly the same current in all three simulators as it has in terrestrial sunlight. This agreement is due to the excellent spectral match between Z-00 and Z-01. For the other five silicon cells, errors of different magnitude arise. Again, the tungsten lamp gives larger errors in current than either the xenon or ELH lamp simulators. The average errors of 0.92% for xenon, 1.87% for ELH, and 10.9% for tungsten were calculated excluding cell Z-00. These data are in excellent agreement with the calculated results shown in Table I.

These data are indicative of the amount of spectral matching required for accurate measurements. If the spectral responses for the reference cell and test cell are essentially identical (as Z-00 and Z-01 in Fig. 9), almost any light source is adequate. However, in practice, such spectral response matching is probably rare and the cases represented by the calculations (Fig. 6) or the experimental data (Figs. 10-14) are more representative. In this case xenon and ELH-type lamp simulators give acceptably low errors (<2%), while the tungsten lamp simulators give rise to excessively high errors.

SUMMARY OF RESULTS

It has been shown that solar simulators utilizing either short-arc xenon lamps or ELH-type quartz-halogen lamps as a radiation source give low errors (<2%) when making performance measurements of terrestrial photovoltaic cells. This analysis assumes that a reference cell, matched in spectral response to the test cell, is used to set the simulator irradiance. A simulator using a plain tungsten lamp as a radiation source gives larger errors unless the reference-cell - test-cell spectral match is extremely good.

REFERENCE

1. H. W. Brandhorst, et al: Interim Solar Cell Testing Procedures for Terrestrial Applications. NASA TMX-71771 (1975).

TABLE I. - CALCULATED ERRORS IN I_{sc} DUE TO SPECTRAL MISMATCH FOR THREE SIMULATORS

SILICON CELL

SIMULATOR	AVE. ERROR	MAX. ERROR
XENON	1.2%	2.2%
TUNGSTEN	8.4	11.0
ELH	1.4	3.5

TABLE II. - CALCULATED ERRORS IN I_{sc} DUE TO SPECTRAL MISMATCH FOR THREE SIMULATORS

CADMIUM SULFIDE CELL

SIMULATOR	AVE. ERROR	MAX. ERROR
XENON	1.4%	2.9%
TUNGSTEN	6.7	12.8
ELH	2.8	6.5

TABLE III. - CALCULATED ERRORS IN I_{SC} DUE TO SPECTRAL MISMATCH FOR THREE SIMULATORS

GALLIUM ARSENIDE CELL

SIMULATOR	AVE. ERROR	MAX. ERROR
XENON	4.8%	5.3%
TUNGSTEN	13.5	15.7
ELH	3.4	5.8

TABLE IV. - MEASURED I_{sc} FOR VARIOUS TERRESTRIAL CELLS USING Z-01 AS A STANDARD UNDER DIFFERENT SOLAR SIMULATORS

CELL	SUNLIGHT	XENON		TUNGSTEN		ELH	
		I_{sc}	% Δ	I_{sc}	% Δ	I_{sc}	% Δ
Z-01	112.2	112.2		112.2		112.2	
Z-00	113.6	113.1		113.6		112.9	
Z-36	116.8	117.6	0.7	126.0	7.9	116.5	-0.3
Z-23	97.9	98.2	0.3	116.0	18.5	99.7	1.8
Z-70	102.3	100.7	-1.6	97.2	- 5.0	98.1	-4.1
Z-27	104.7	106.7	1.9	114.4	9.3	106.9	2.1
Z-43	95.3	95.5	0.2	108.5	13.9	96.3	1.0
AVE. ERROR			0.9%		10.9%		1.9%

Figure 1. - Spectral distribution of terrestrial sunlight

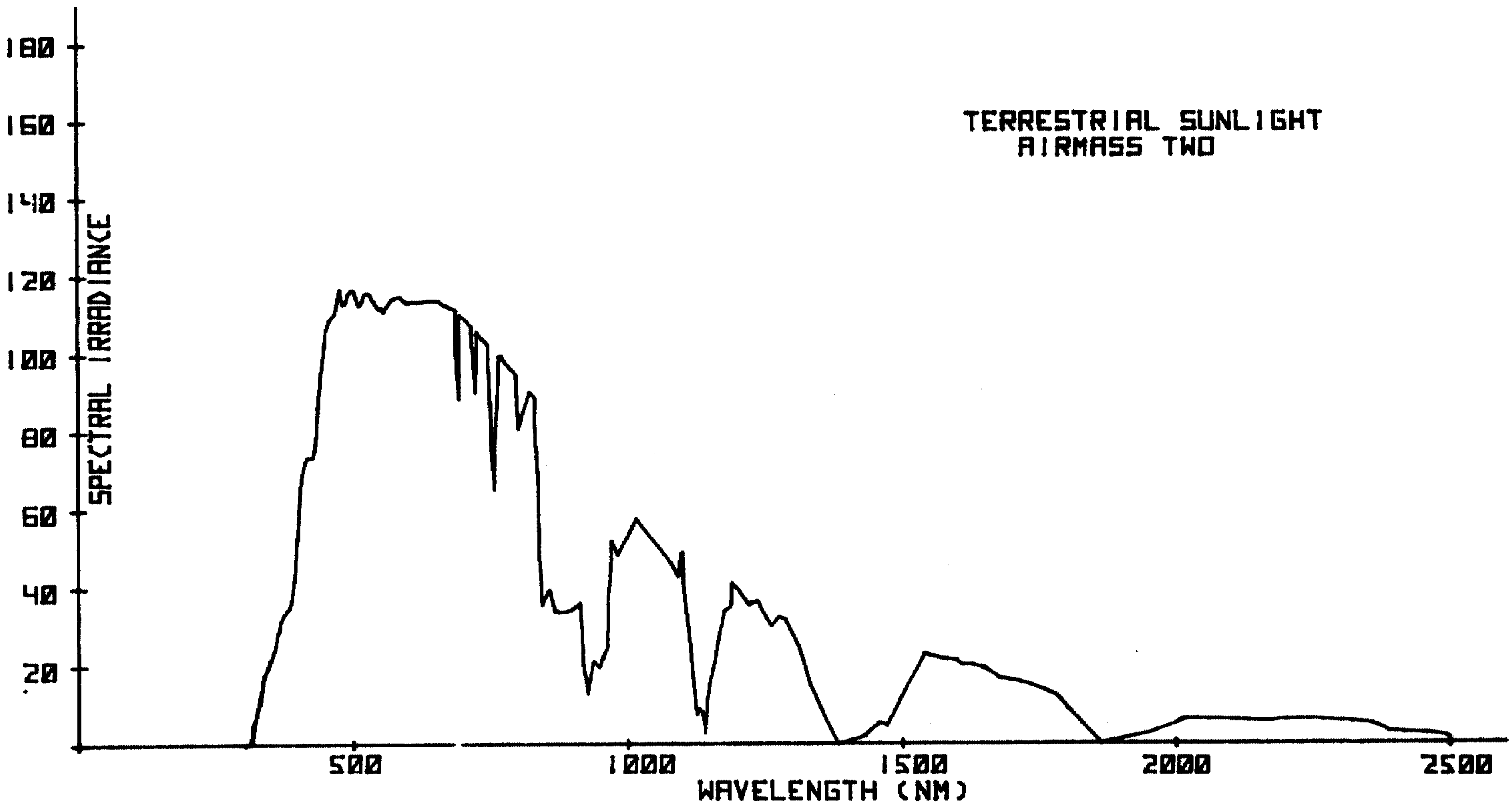

Figure 2. - Spectral distribution of xenon lamp simulator

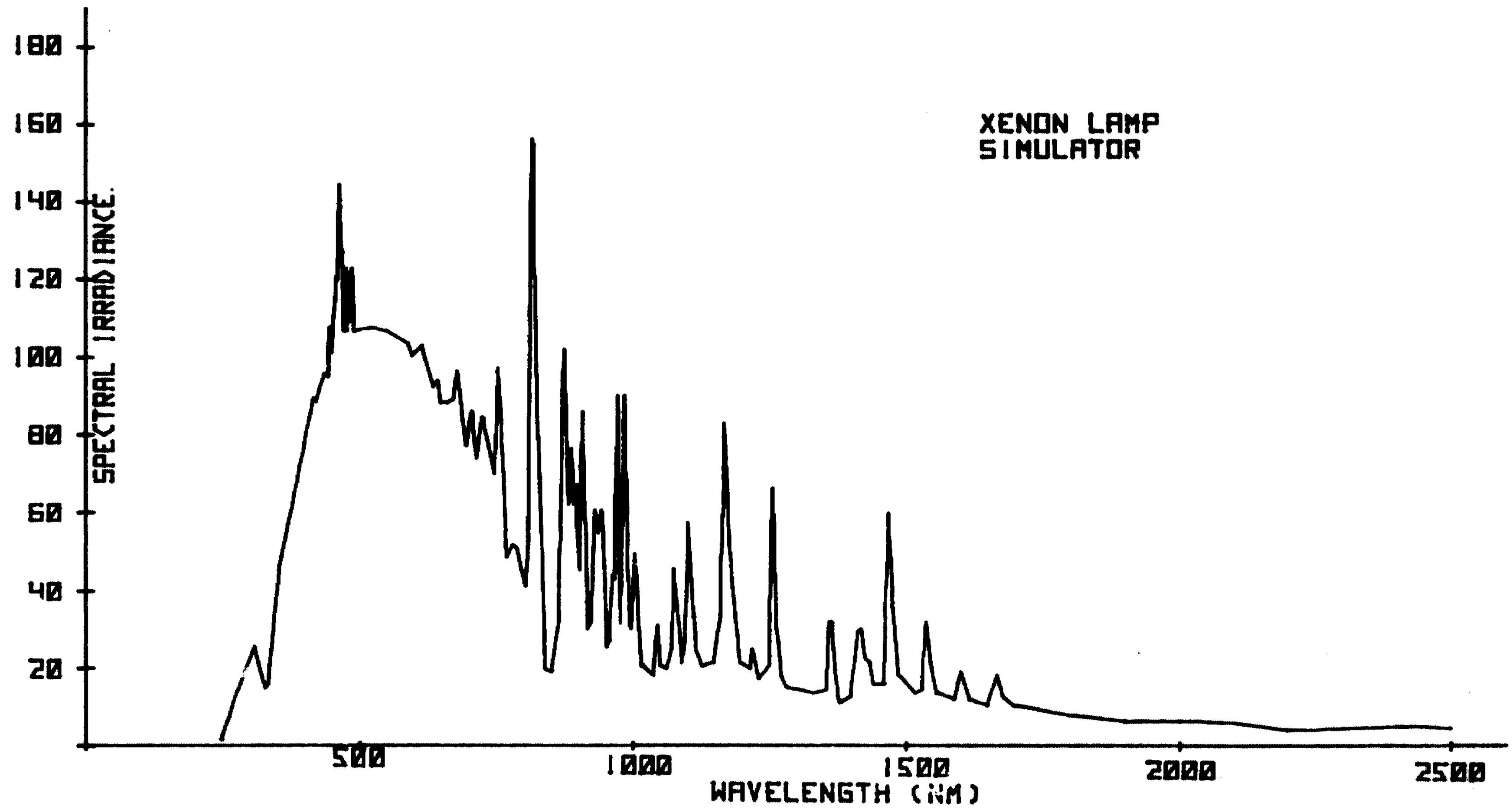

Figure 3. - Spectral distribution of tungsten lamp simulator

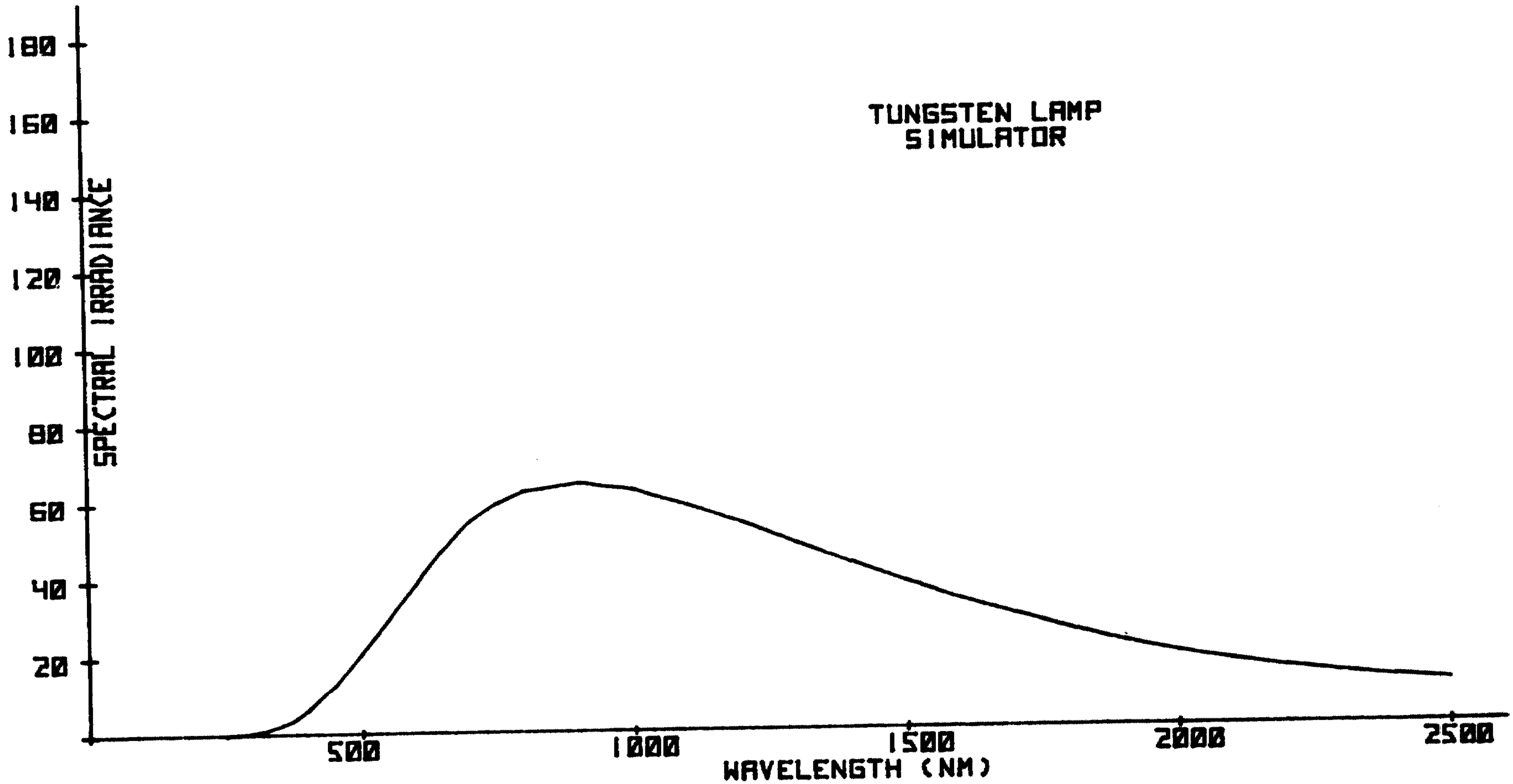

Figure 4. - Spectral distribution of ELH lamp simulator

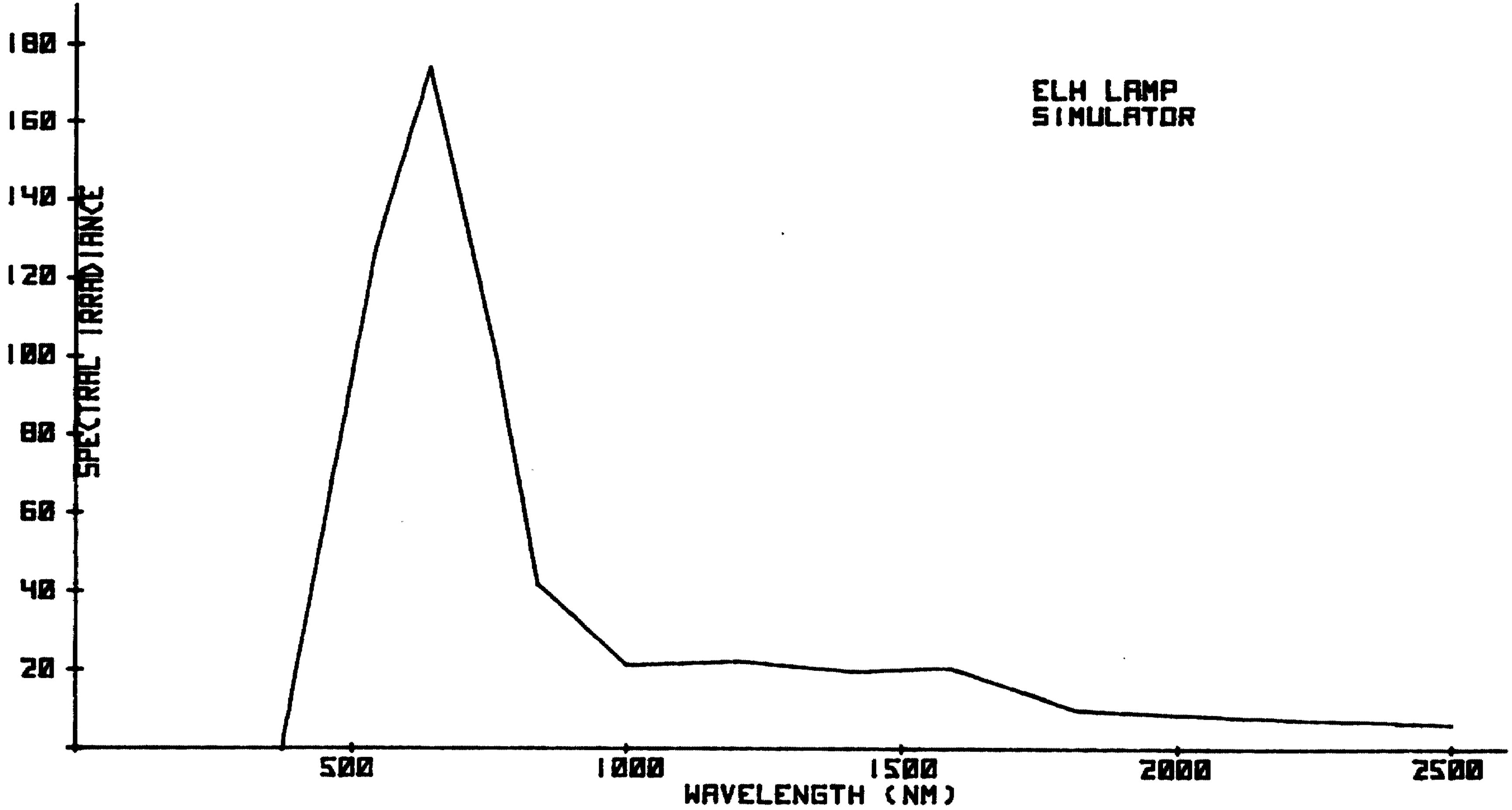

Figure 5. - Example of calculated and standard solar cell relative spectral responses

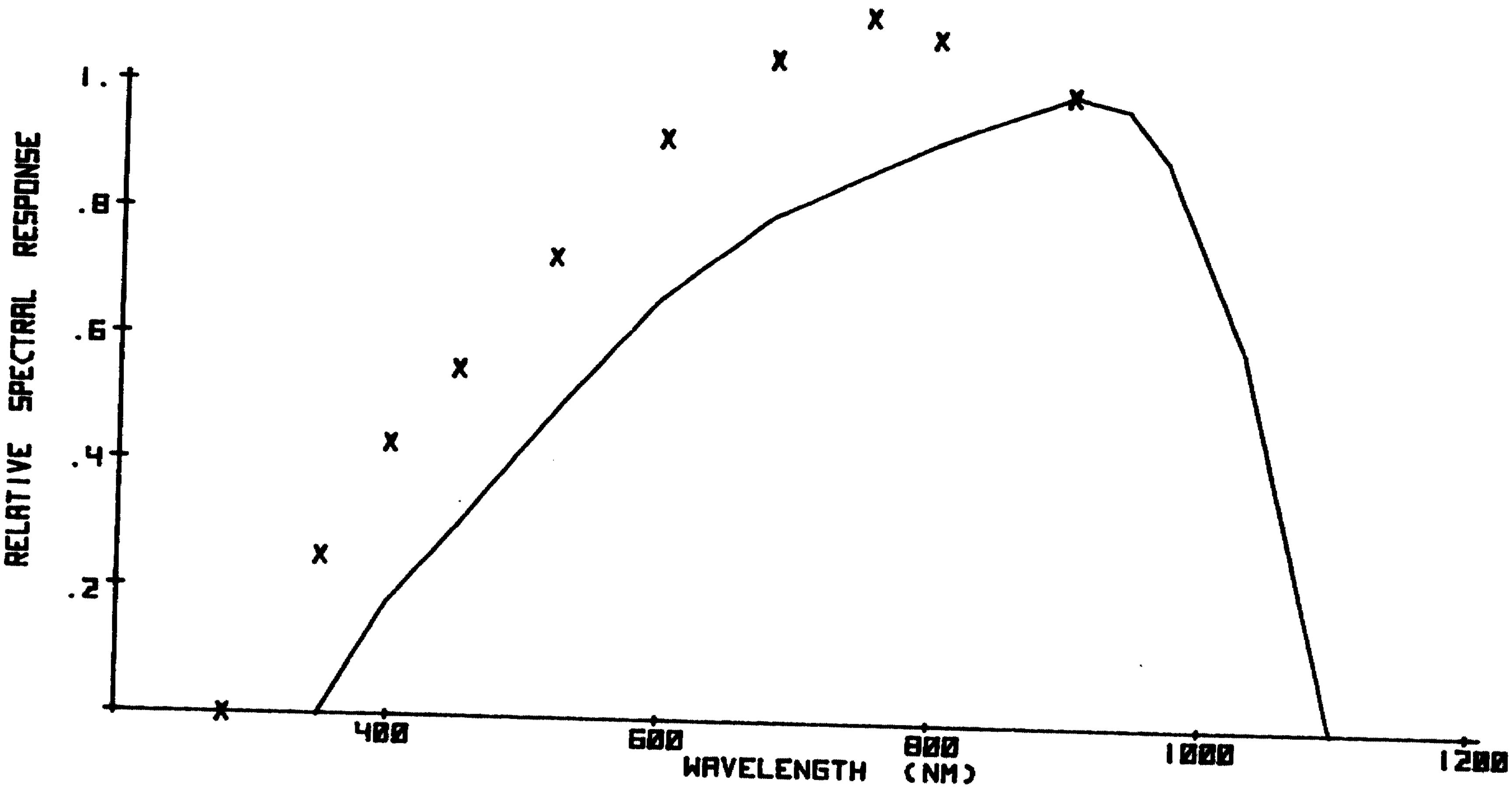

Figure 6. - CdS solar cell spectral response

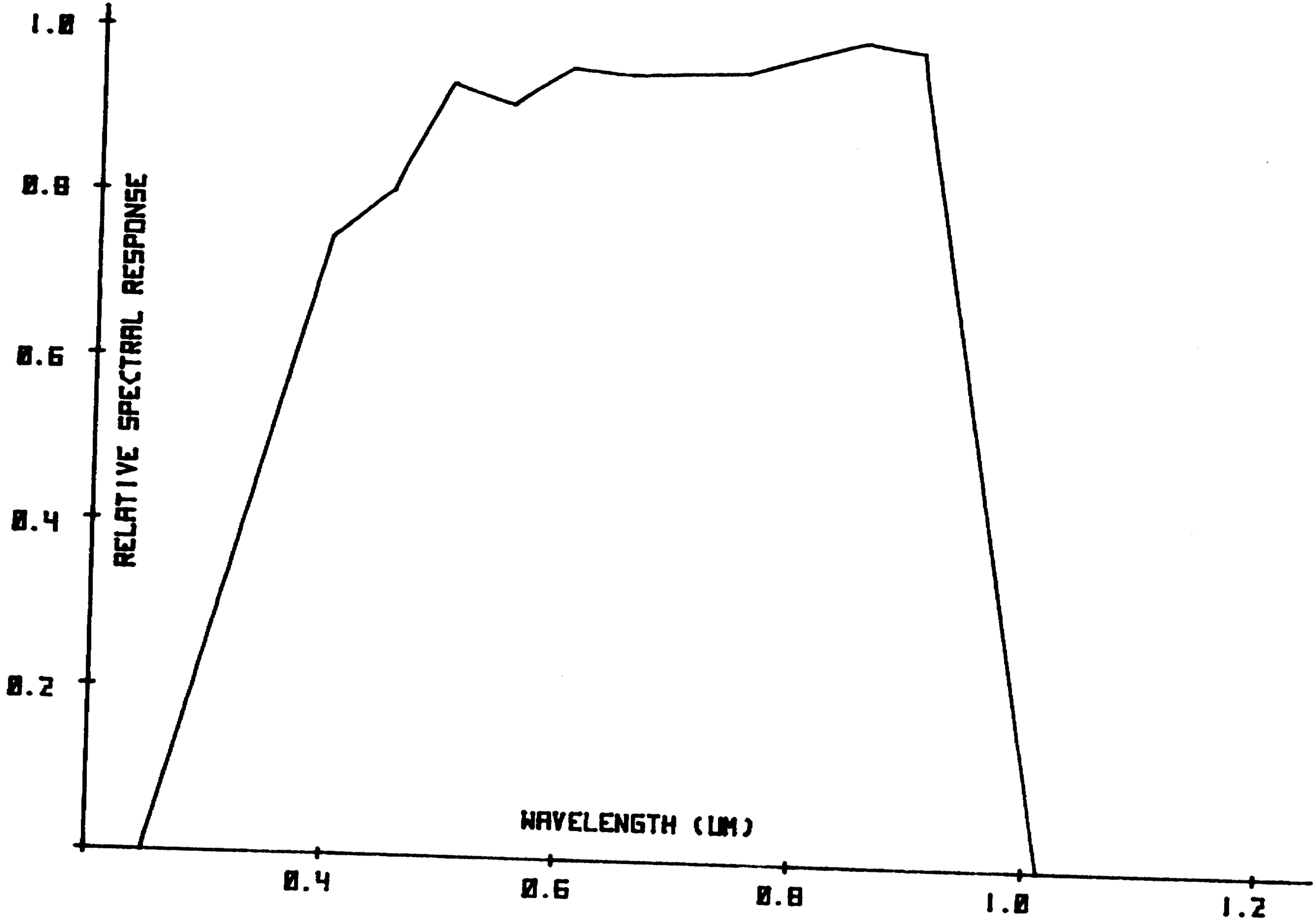

Figure 7. - GaAs solar cell spectral response

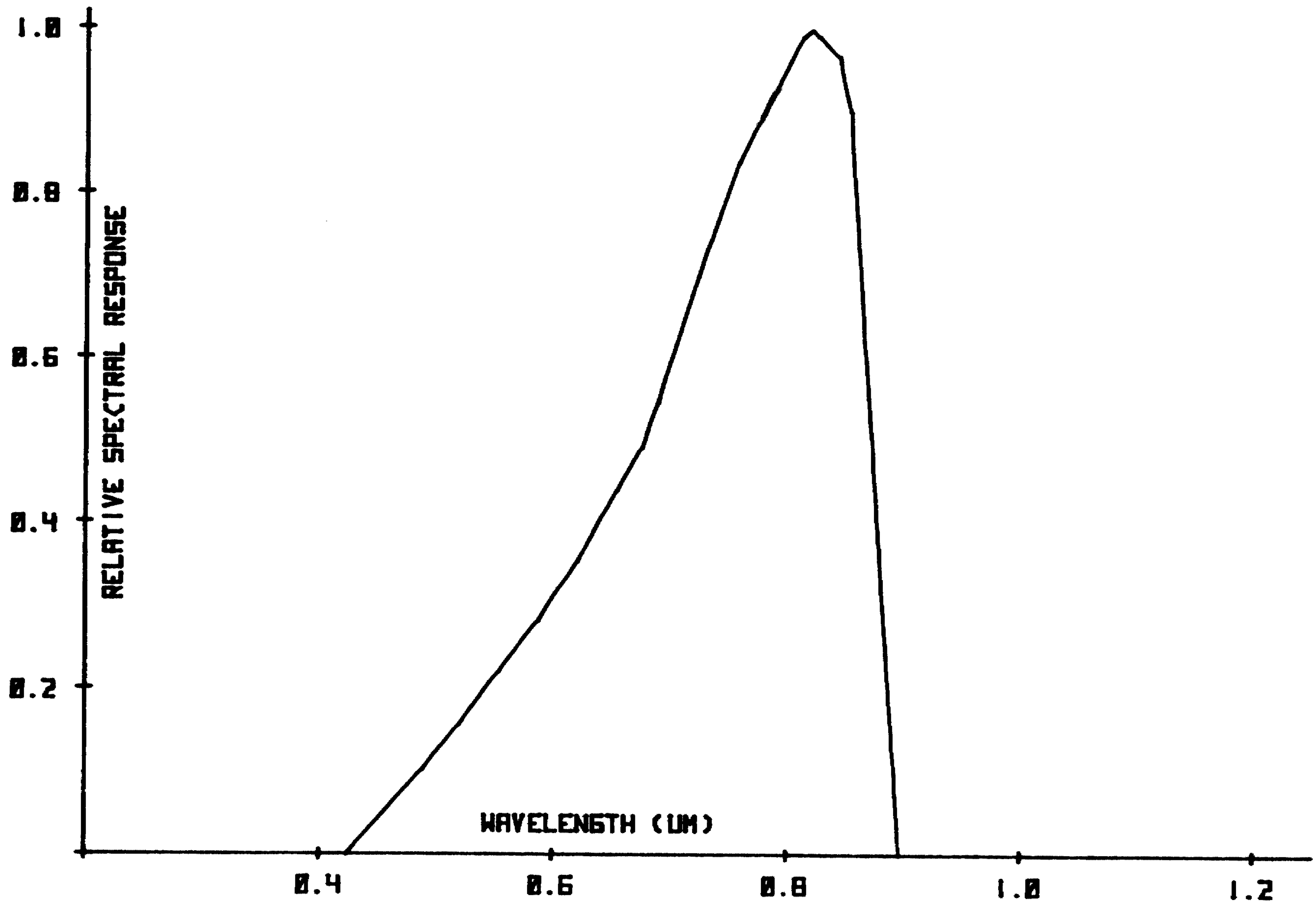

Figure 8. - Comparison of spectral responses of cells Z-00 and Z-01

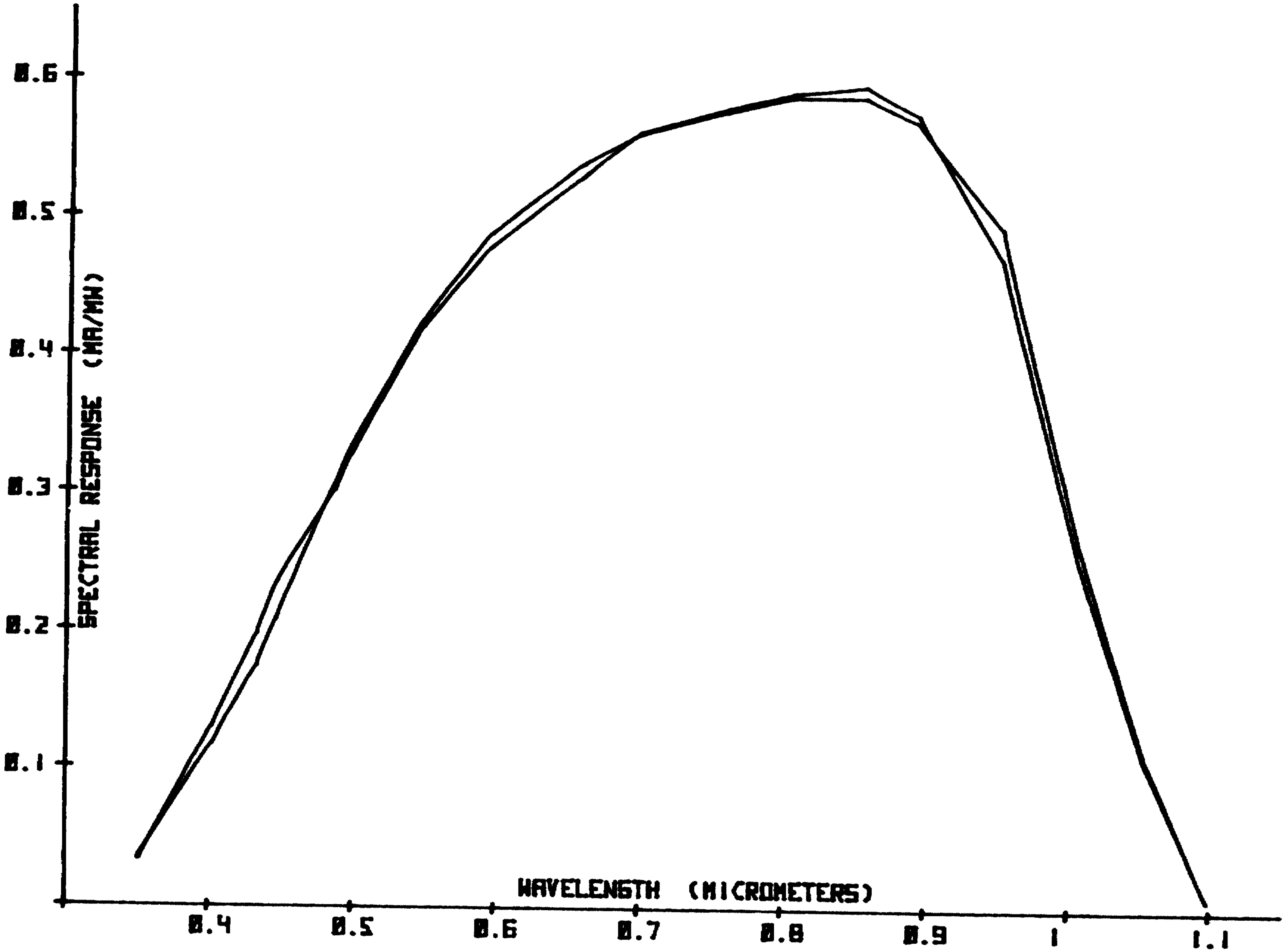

Figure 9. - Comparison of spectral responses of cells Z-23 and Z-01

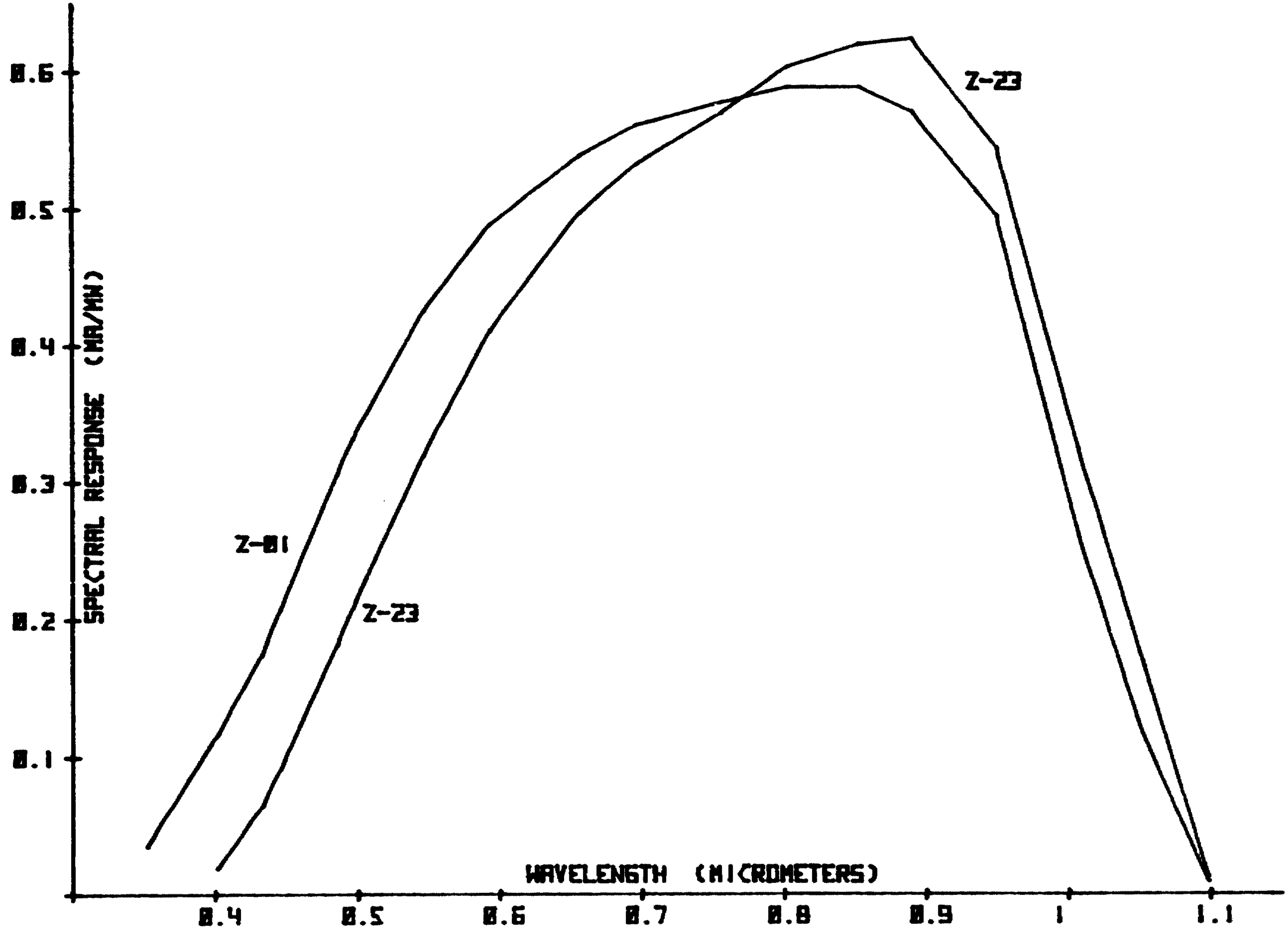

Figure 10. - Comparison of spectral responses of cells Z-27 and Z-01

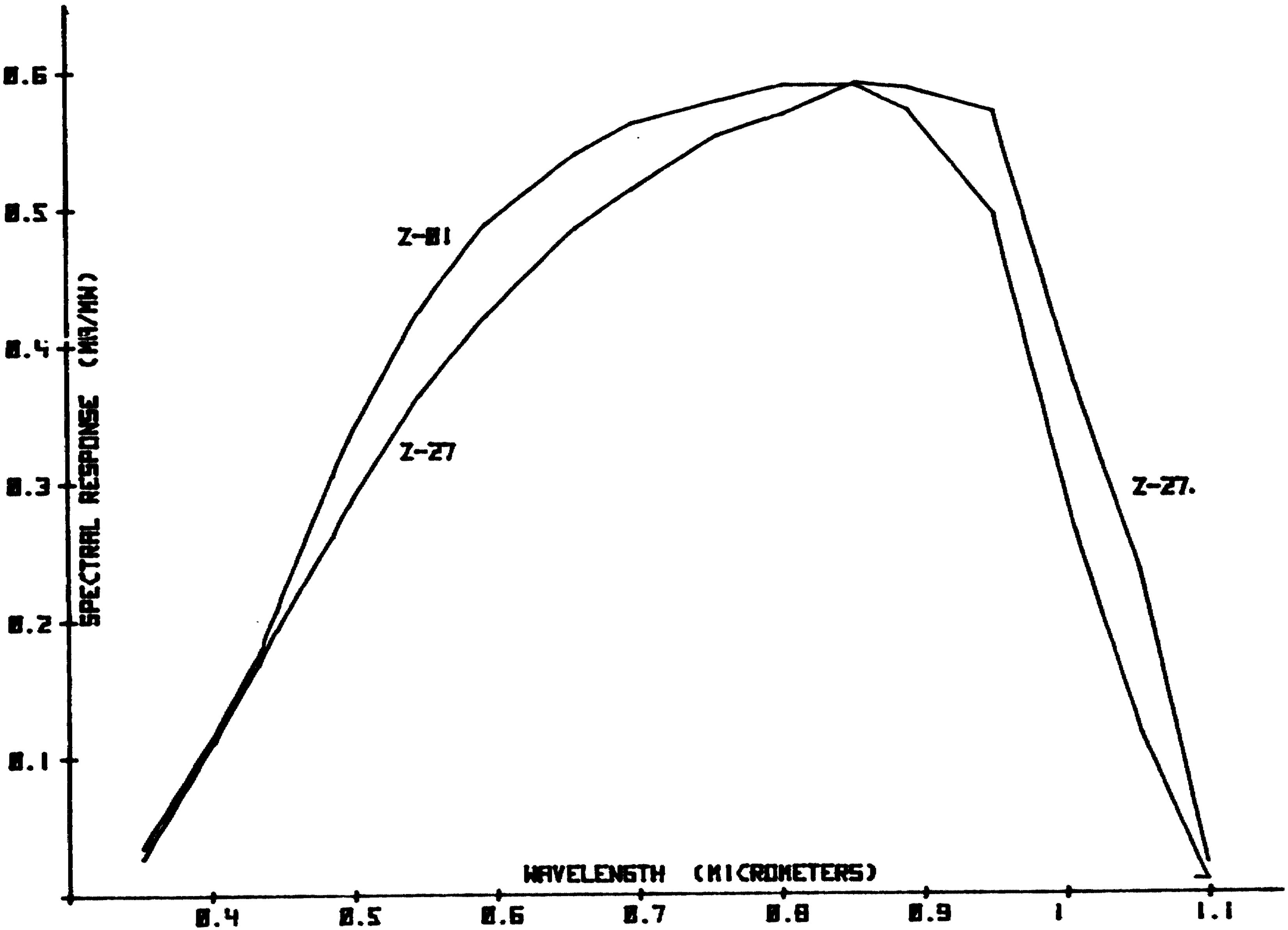

Figure 11. - Comparison of spectral responses of cells Z-36 and Z-01

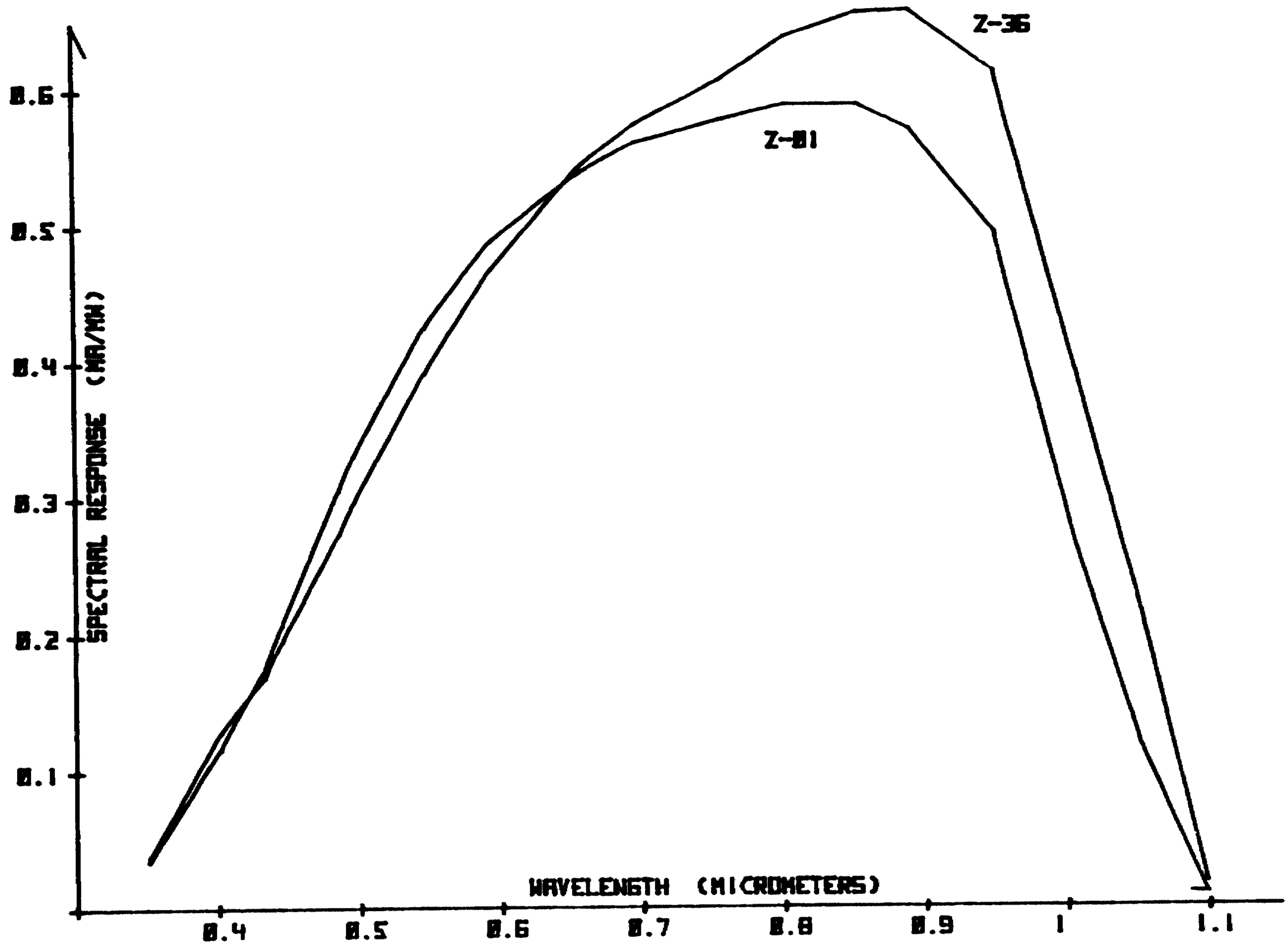

Figure 12. - Comparison of spectral responses of cells Z-43 and Z- 01

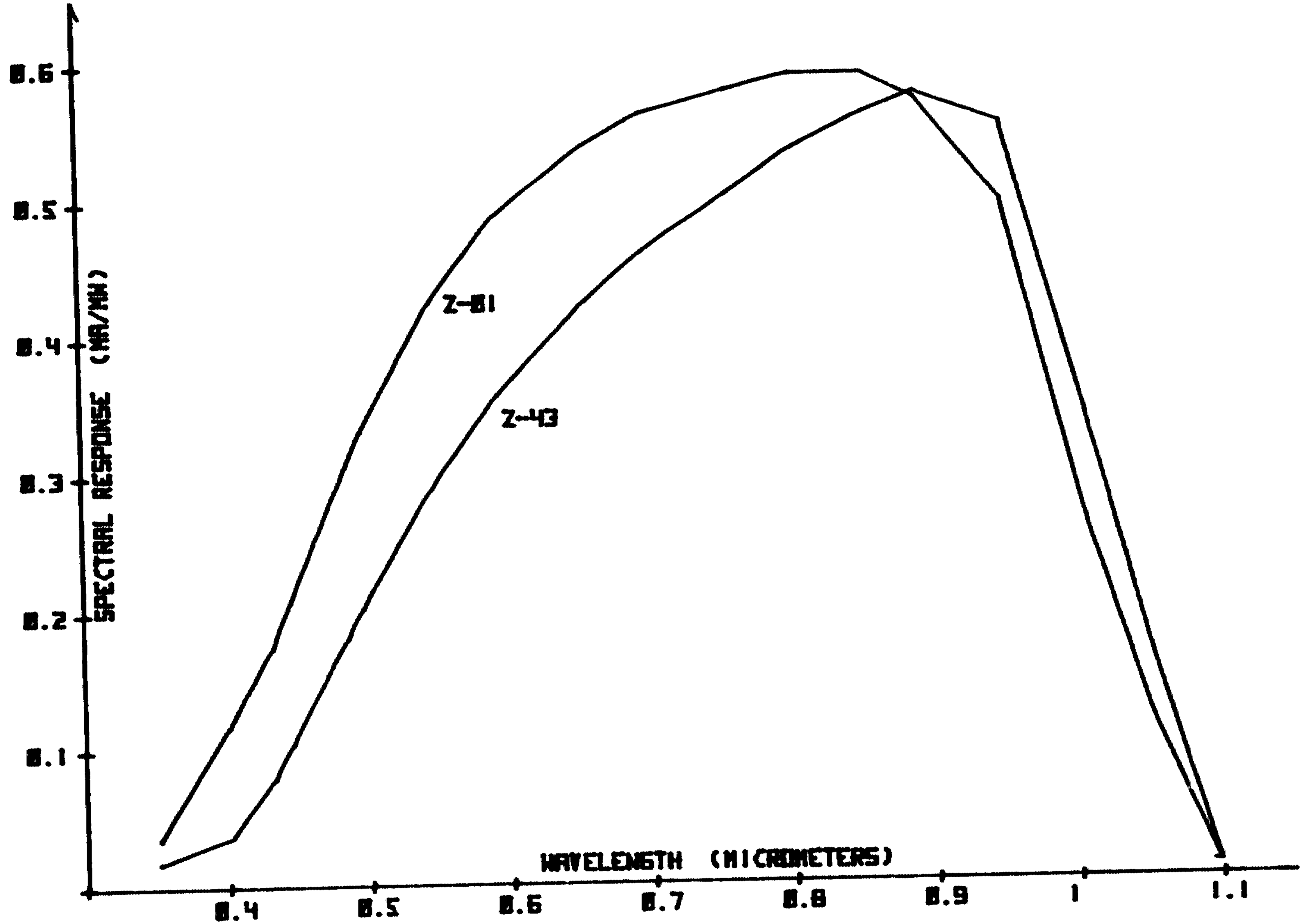

Figure 13. - Comparison of spectral responses of cells Z-70 and Z-01