AM0 Efficiency Measurements

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Summary

Procedures for measuring the AM0 current versus voltage characteristics and calculating the efficiency are discussed. The various factors influencing the determination of the efficiency includes the I–V measurement system, reference cell calibration, standard reporting conditions, area measurement, light source characteristics, temperature measurement and control, and the measurement procedures. Each of these sources contribute to the precision index and bias limit which is combined to obtain the total uncertainty in the efficiency. This paper discusses these factors and how to minimize differences in the reported AM0 efficiency of a given PV cell between various laboratories.

Introduction

In measuring the current versus voltage (I–V) characteristics with respect to standard reporting conditions, the reference total and spectral irradiance must be established along with a reference temperature and device area definition. For AM0 efficiency measurements, the total and spectral irradiance are defined as the extraterrestrial solar output at 1 astronomical unit (AU) distance from the sun. The reference temperature is 25° or 28°C (depending on the laboratory) while a total cell area definition which, including the area covered by grids and contacts, is generally accepted. The AM0 standard reporting conditions have not been formalized by consensus standards but have been informally adopted by NASA, JPL, and the European Space Agency (ESA) and published in various reports. The AM0 efficiency in percent is normally expressed as:

$$\eta = \frac{100 \cdot P_{max}}{A \cdot E_{ref}} = \frac{100 \cdot V_{max} \cdot I_{max}}{A \cdot E_{ref}} \tag{1}$$

where V_{max} and I_{max} are the voltage and current at the maximum power P_{max}, A is the device total area, and E_{ref} is the reference total irradiance. A value of $1353 Wm^{-2}$ is often used for E_{ref} [ref. 1,2]. However, measurements of the solar constant since 1980 suggest that $1367 Wm^{-2}$ is a much better value [ref. 3]. In computing η using (1), the assumption is made that the device is illuminated by a "perfect" solar simulator. Since the only location where this is true is in space at 1 AU from the sun, the simulator is set using a primary AM0 reference cell whose short-circuit current ($I_{sc}^{R,R}$) at 1 AU has been determined by high altitude aircraft, balloon, or spacecraft flight. The irradiance of the solar simulator is adjusted until the fractional error F, in the measured current of the test cell is unity using [ref. 4]

$$F = \frac{I_{sc}^{T,S}}{I_{sc}^{T,R}} = \frac{I_{sc}^{R,S}}{I_{sc}^{R,R}} \cdot M \tag{2}$$

where the first superscript refers to the test device (T) or to the reference cell (R), and the second superscript refers to the source spectrum (S) or to the reference spectrum (R). M is called the spectral mismatch parameter and can be expressed [ref. 4-6] as

$$M = \frac{\int_{\lambda 1}^{\lambda 2} E_{sor}(\lambda) R_T(\lambda) d\lambda}{\int_{\lambda 1}^{\lambda 2} E_{ref}(\lambda) R_T(\lambda) d\lambda} \cdot \frac{\int_{\lambda 3}^{\lambda 4} E_{ref}(\lambda) R_R(\lambda) d\lambda}{\int_{\lambda 3}^{\lambda 4} E_{sor}(\lambda) R_R(\lambda) d\lambda} \tag{3}$$

The spectral irradiance of the light source is $E_{sor}(\lambda)$, the spectral irradiance of the reference spectrum is $E_{ref}(\lambda)$, the spectral response of the test device is $R_T(\lambda)$, and the spectral response of the reference cell is $R_R(\lambda)$. The limits of integration $\lambda 1$ and $\lambda 2$ should at least equal the spectral response limits of the test device, and $\lambda 3$ and $\lambda 4$ should at least be equal to the spectral response limits of the reference cell. Notice that if the test device and reference cell have identical spectral responses, the M is unity. Most AM0 measurement groups assume M is unity since the reference cell is normally of the same type as the test device.

Reference 7 reports that when M is with 0.005 of unity (spectral mismatch error < 0.5%), the uncertainty in computing M can exceed the error in assuming M is unity. Dividing (1) by (2) gives η for a non-ideal simulator using the reference cell method

$$\eta = \frac{100 \cdot V_{max} \cdot I_{max} \cdot I_{sc}^{R,R}}{A \cdot E_{ref} \cdot M \cdot I_{sc}^{R,S}} \tag{4}$$

These seven quantities account for all sources of difference in the efficiency. We neglect any errors in V_{max} due to the spectral and total irradiance (F different from unity) because they are normally small.

Uncertainty Analysis

A standard method has been developed to estimate the uncertainty interval for a given quantity such as the efficiency [ref. 8-10]. Using this method, the uncertainty limit (sometimes used synonymously with the terms total error or accuracy) which is expected to include 99% of all results can be written as

$$U_{99} = B + t_{95} \cdot S \tag{5}$$

with

$$B = \left[\sum_{i=1}^{J}(\theta_i \cdot b_i)^2\right]^{(1/2)} \tag{6}$$

and

$$S = \left[\sum_{i=1}^{J}(\theta_i \cdot s_i)^2\right]^{(1/2)} \tag{7}$$

where t_{95} is the student's t value for 95% confidence ($t_{95} \sim 2$ for more than 30 degrees of freedom or replications), and J is the total number of elemental error sources. Each error source has an individual bias limit (b_i) precision index (s_i) that is associated with random sources. The precision index is usually associated with the standard deviation of an individual error source. The precision index (S) is often incorrectly taken to be the accuracy or total error but neglects the bias errors (B) which often dominate the contribution to the uncertainty limit. The sensitivity coefficient (θ_i) is obtained by partial differentiation of the result with respect to one of the parameters in the result. For example, in (4) the result is η and the parameters are P_{max}, A, and E_{ref}, each with their elemental error sources. If the elemental errors in (4) are expressed as percentages the θ_i is unity. Assuming that M is unity will introduce a bias error as will assuming that a 2 by 2cm cell is actually 4cm². An uncertainty analysis of PV efficiency measurements is summarized in reference 7.

I–V Measurement System

The I–V measurement system needed for the determination of V_{max}, I_{max}, and $(I_{sc}^{R,S})$ will introduce errors because of the instrumentation used for data acquisition. A summary of typical precision indexes and bias limits for common instrumentation in measuring voltage and current is given in reference 7. In general, most groups use instrumentation that have a negligible contribution to the uncertainty limit ($<0.1\%$). Also, the contacting method can cause substantial errors (100%) in the I–V characteristic [ref. 11]. The voltage and current contacts should be in close proximity to prevent unrealistically large fill factors [ref. 11]. The resistance between the voltage and current contact should be monitored to ensure a good Kelvin connection (resistance×device area $< 1W\bullet cm^2$). For devices with multiple current contact pads on the grid, a separate Kelvin contact to each pad should be used with the current contacts connected together and the voltage contacts connected together. Some devices can change their I–V characteristics depending upon the voltage bias rate, bias direction, illumination time, and time at a fixed voltage prior to the I–V measurement [ref. 11]. For these devices the important factor to remember is that P_{max} in (1) is only defined for steady-state conditions.

Temperature Measurement and Control

Because V_{max}, I_{max}, and $(I_{sc}^{R,S})$ all vary as function of temperature, any deviation of the device temperature from the reference temperature will introduce an error in the efficiency. The error in the temperature can be minimized by controlling the temperature but cannot be eliminated because of imperfect temperature control, temperature sensor calibration errors, and temperature gradients between where the temperature is measured and the junction temperature. Typically, the best that can be obtained is a 1°C bias limit and a 0.1°C precision index in the device junction temperature.

Area Measurement

The device area can be a source of large errors if it is not carefully considered [ref. 7]. If the standard area definition is not used errors over 100% are possible (active area). More subtle errors can and do occur from sources which include light trapping, poor mesa etches, irregular edges, and other fabrication related artifacts (a small perimeter to area ratio minimizes edge related errors). Errors in the actual measurement of the total device area also occur. For example, a 2 by 2cm device measured on a X-Y translation stage with a $1\mu m$ resolution and a $10\mu m$ bias error would contribute $\sim 0.1\%$ to the total uncertainty. The same device measured with vernier caliper with a 0.01mm resolution and a bias error of 0.1mm would add $\sim 1\%$ to the total uncertainty. Worse yet is to simply assume that a 2 by 2 cm device is actually $4cm^2$.

Light Source

Spatial uniformity and temporal stability of the source illumination will affect the measurement of I_{max} and $(I_{sc}^{R,S})$. The error due to temporal instability (lamp flicker) can be minimized if I_{max} and $(I_{sc}^{R,S})$ in (4) are measured during the same time period. The error η because of spatial nonuniformity of the light source can be minimized if the primary AM0 reference cell has the same geometry as the test device and the calibration of primary reference cell is transferred to a monitor cell in the test

plane, thereby allowing the test device to be measured in the same location as the primary reference cell. This procedure will not correct for the spatial uniformity changing with time but does allow the current of the test device to be measured with a precision error of less than 0.05% [ref. 11,12].

The spectral mismatch parameter (3) can be a major source of uncertainty in η measurements. The AM0 community has minimized this bias error resulting from the assumption that M is unity by obtaining a primary reference cell of the same type as the test device. This may not always be possible in a research environment where the quantum efficiency is being altered by changing fabrication processes, antireflection coatings, radiation damage, and energy gap, making the cost and time of obtaining a new primary AM0 reference cell for each change prohibitive. Table 1 demonstrates that the same short-circuit current ($I_{sc}^{T,R}$) can be obtained using equation 2, independent of the primary AM0 (Fig. 1) or terrestrial (Fig. 2) reference cell used. Figure 3 compares the AM0 spectral irradiance in reference 13 with the measured Spectrolab X-25 solar simulator spectral irradiance used in Table 1. The primary terrestrial reference cells were calibrated in Golden, CO using the tabular method [ref. 12]. The primary AM0 reference cells were calibrated by R. Hart of NASA Lewis Research Center. This procedure (equation 4) has been used successfully (<1.5% error) for terrestrial and AM0 reference cells for a wide variety of test cell-reference cell combinations [ref. 7, 12, 14, 15]. An uncertainty analysis of this procedure found that a 5% random error in the measurement of the relative spectral response of the test and reference cell and spectral irradiance of the light source gave a 0.4% error in M for a wide variety of test cell-reference cell combinations and light sources [ref. 7]. The limiting factor in using M in (4) is not the error in M but the calibration error in the reference cell itself and the ability to correct for spatial nonuniformity and temporal instability.

Tandems

Perhaps the most difficult challenge facing the PV efficiency measurement community today is how to measure the efficiency of multi-junction devices with respect to standard reporting conditions [ref. 16]. For tandems where the cells are independent of each other (mechanically stacked or monolithic multi-terminal) the efficiency of each device can be separately measured using (4) and then added to obtain the tandem efficiency. The only problem with this procedure is the cost and difficulty in obtaining primary AM0 reference cells for each cell in the stack as the structure is being optimized. The requirement of "matched" AM0 reference cells for each cell in the stack can be relaxed if spectral mismatch corrections are applied to each cell in the tandem structure.

Two-terminal multi-junction cells pose a unique problem because even if a "matched" primary reference cell can be obtained allowing the short-circuit current of the test device ($I_{sc}^{R,R}$) to be determined the fill factor P_{max}, and η may be in error [ref. 16,17]. The fill factor is determined by the spectral irradiance of the light source even when the short-circuit current is correct. This is because the fill factor is affected by the current mismatch between the individual component cells in the multi-junction device and this current mismatch is determined by the spectral irradiance of the light source. A multi-source simulator has been proposed as a method of ensuring that the multi-junction device is being measured with respect to standard reporting conditions [ref. 17]. This method requires the computation of F in (2) for each of the light-source-reference cell combinations that selectively illuminate each of the junctions in the multi-junction device. Each of the light sources should be filtered so that only one of the junctions responds to the light (e.g., a 640nm cut off filtered light source for an AlGaAs top cell and a separate light source with a 660nm cut on filter for the bottom cell). The uncertainty of this technique has been estimated to be ±3% based upon comparing measurements under a single-source simulator with measurements made under a

multi-source simulator that used this single-source simulator's spectral irradiance as the reference spectral irradiance [ref. 17].

Summary

A large number of procedural and measurement related artifacts can and do occur when determining the efficiency of a PV device with respect to standard reporting conditions. A variety of procedures have been discussed for reducing the uncertainty in efficiency measurements. When careful attention is paid to what is actually being measured and care is taken to minimize artifacts, then a total uncertainty of less than ±2% in efficiency is possible. The uncertainty in the reference cell calibration which has been established at ±1% is only a part of the uncertainty in the efficiency. The measurement of tandem efficiencies will pose a challenge to many groups that do not have the resources to apply spectral mismatch corrections and build a multi-source solar simulator.

References

[1] H. Tada, J. Carter, B. Anspaugh, and R. Downing, "Solar Cell Radiation Handbook", JPL Tech. Rep. 82-69, 1982.

[2] "Standard for Solar Constant and Air Mass Zero Spectral Irradiance Tables", ASTM Standard E490.

[3] R. Wilson, H. Hudston, C. Frolich, and R. Brusa, "A Long-term Downward Trend in Total Solar Irradiance", Science, **234**, pp 1114-1117, 1986.

[4] C.R. Osterwald, "Translation of Device Performance Measurements to Reference Conditions", Solar Cells, **18**, pp 269-279, 1986.

[5] C.H. Seaman, "Calibration of Solar Cells by the Reference Cell Method– the Spectral Mismatch Problem," Solar Energy, **29**, pp 291-298, 1982.

[6] "Standard Practice for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and Photovoltaic Reference Cell", ASTM Standard E973.

[7] K.A. Emery, C.R. Osterwald, and C.V. Wells, "Uncertainty Analysis of Photovoltaic Efficiency Measurements", *Proc. 19th IEEE PV Spec. Conf.*, pp 153-159, 1987.

[8] R.B. Abernathy and R.P. Benedict, "Measurement Uncertainty: A Standard Methodology", Instrument Soc. of America, **24**, pp 75-79, 1985.

[9] "Instruments and Apparatus Part 1: Measurement Uncertainty", ANSI/ASME standard PTC 19.1, 1985.

[10] "Fluid Flow Measurement Uncertainty", ISO draft standard ISO DIS 5168 for the International Organization for Standardization Committee ISO TC30 SC9, 1987.

[11] K. Emery and C. Osterwald, "Measurement of PV Device Current as a Function of Voltage, Temperature, Intensity, and Spectrum", Solar Cells, **21**, pp 313-327, 1987.

[12] K.A. Emery and C.R. Osterwald, "Solar Cell Efficiency Measurements", Solar Cells, **17**, pp 253-274, 1986.

[13] C. Wehrli, "Extraterrestrial Solar Spectrum", Physical-Metrological Observatory and World Radiation Center, publication No. 615, Davos-Dorf, Switzerland, July 1985.

[14] K.A. Emery, C.R. Osterwald, T.W. Cannon, D.R. Myers, J. Burdick, T. Glatfelter, W. Czu-batyj, and J. Yang, "Methods for Measuring Solar Cell Efficiency Independent of reference Cell or light Source", *Proc. 18th IEEE PV Spec. Conf.*, pp 623-628, 1985.

[15] K.A. Emery, C.R. Osterwald, L.L. Kazmerski, and R. Hart, "Calibration of Primary Ter-restrial Reference Cells – Comparison with Primary AM0 Reference Cells", *Proc. 8th European Community PV Solar Energy Conf.*, Naples, Italy, 1988.

[16] K.A. Emery, C.R. Osterwald, T. Glatfelter, J. Burdick, and G. Virshup, "A Comparison of the Errors in Determining the Conversion Efficiency of Multijunction Solar Cells by Various Methods", Solar Cells, **24**, 1988, Special issue of papers presented at the SERI 8th PV AR&D project review meeting, Denver, CO, 1987.

[17] T. Glatfelter and J.Budick, "A Method for Determining the Conversion Efficiency of Multiple Cell Photovoltaic Devices", *Proc. 19th IEEE PV Spec. Conf.*, pp 1187-1193, 1987.

Table 1. A GaAs cell with a primary AM0 calibration at 25°C of 113.0 mA had an uncorrected short-circuit current under the Spectrolab X-25 solar simulator (Figure 3) of 120.2 mA. The corrected short-circuit current $I_{sc}^{T,R}$ is independent of the quantum efficiency of the primary AM0 (Figure 1) or primary terrestrial (Figure 2) reference cell within ±2%, even though the spectral mismatch error varied from -1% to +6%, and the uncertainty of the reference cell calibration was ±1%.

Primary AM0 Reference Cell

sample number	type	current under X25 $I_{sc}^{R,S}$ (mA)	AM0 Current $I_{sc}^{R,R}$ (mA)	M	GaAs test cell $I_{sc}^{T,R}$ (mA)
4606	Silicon	176.1	175.0	1.0400	114.9
3	Silicon	112.7	110.2	1.0426	112.7
D13dd	poly-Si	162.3	157.8	1.0339	113.0
248	InP	8.40	8.035	1.0351	111.1
B25	CuInSe$_2$	47.20	45.18	1.0378	110.9
				mean =	112.5 mA
				std. deviation =	1.3%

Secondary AM0, Primary Terrestrial Reference Cell

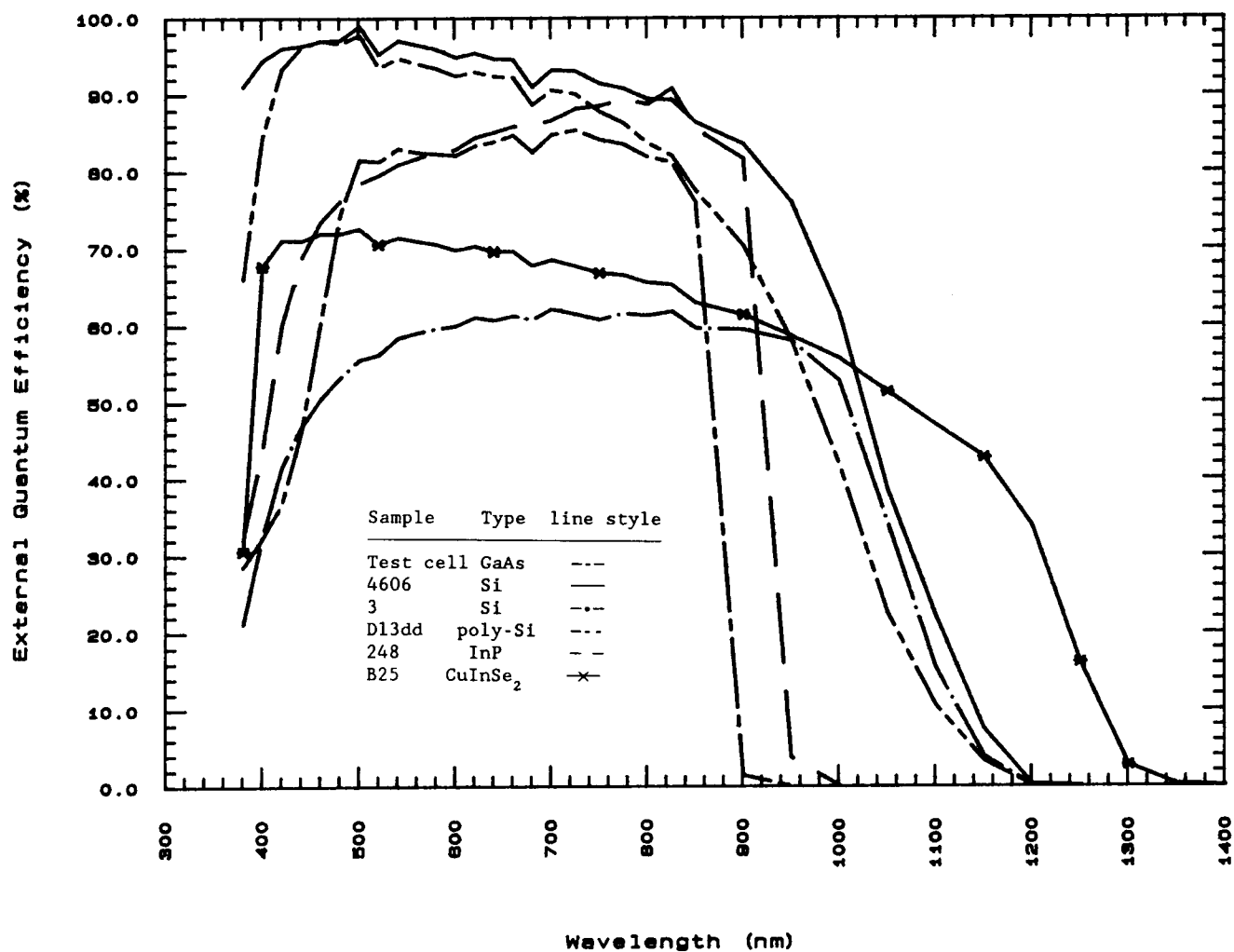|					
S01	Silicon	155.0	154.75	1.0476	114.6
S02	Silicon	169.4	168.95	1.0609	113.0
S03	Silicon	156.4	155.91	1.0536	113.7
DSET31	poly-Si	113.2	108.92	1.0221	113.2
S09 KG5	filtered Si	64.20	58.67	0.9903	110.9
S10 KG5	filtered Si	60.74	55.50	0.9856	111.4
S05	CuInSe$_2$	41.45	40.22	1.0427	111.9
S25	GaAs	111.5	106.95	1.0103	114.1
S26	GaAs	112.2	107.43	1.0207	112.8
				mean =	112.8 mA
				std. deviation =	1.0%

Figure 1. Measured external quantum efficiencies (electron per photon) for the primary AMO GaAs reference cell used as a test cell in table 1 and the other high altitude aircraft flown primary AMO reference cells.
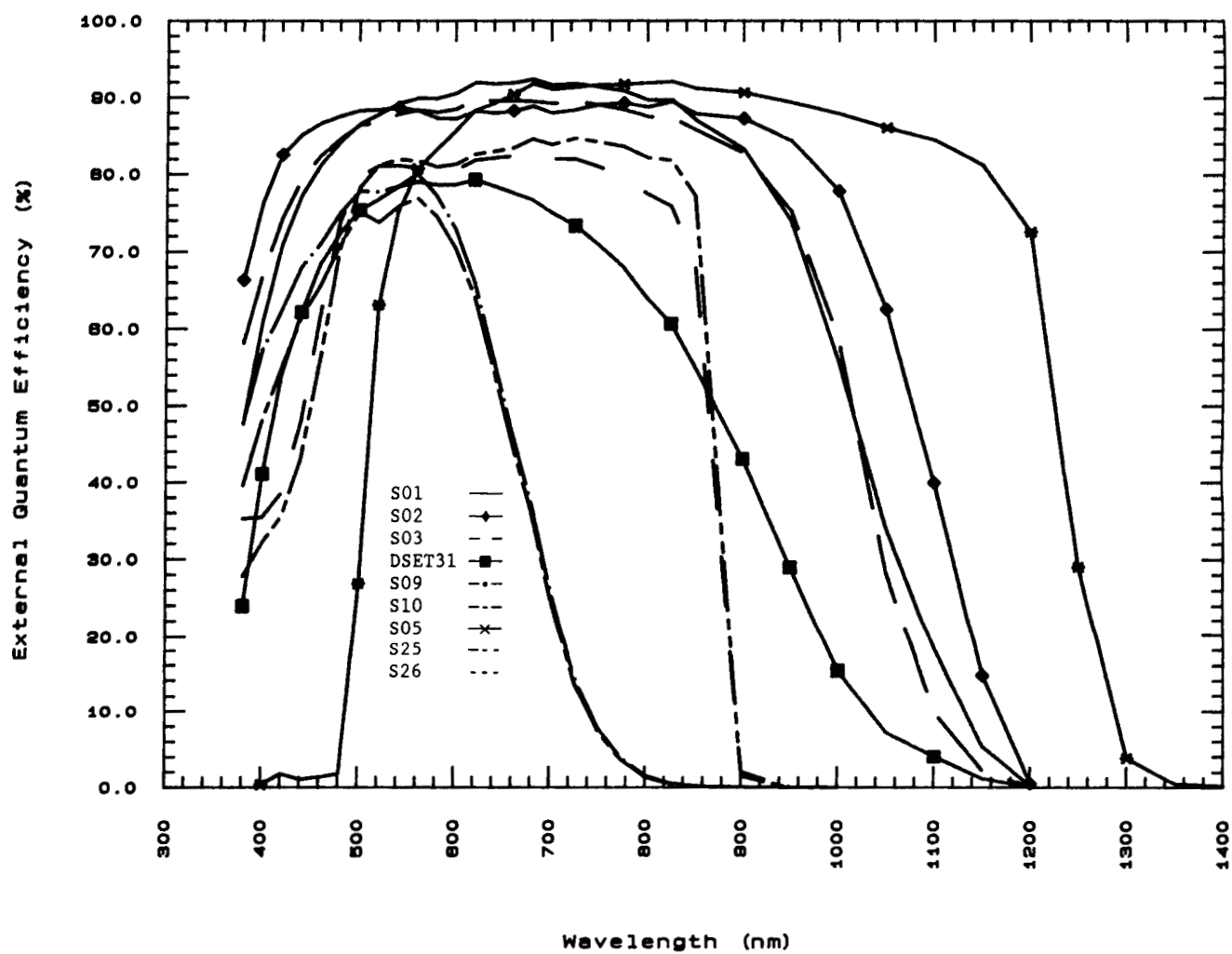
Figure 2. Measured external quantum efficiencies for the primary terrestrial reference cells given in table 1.
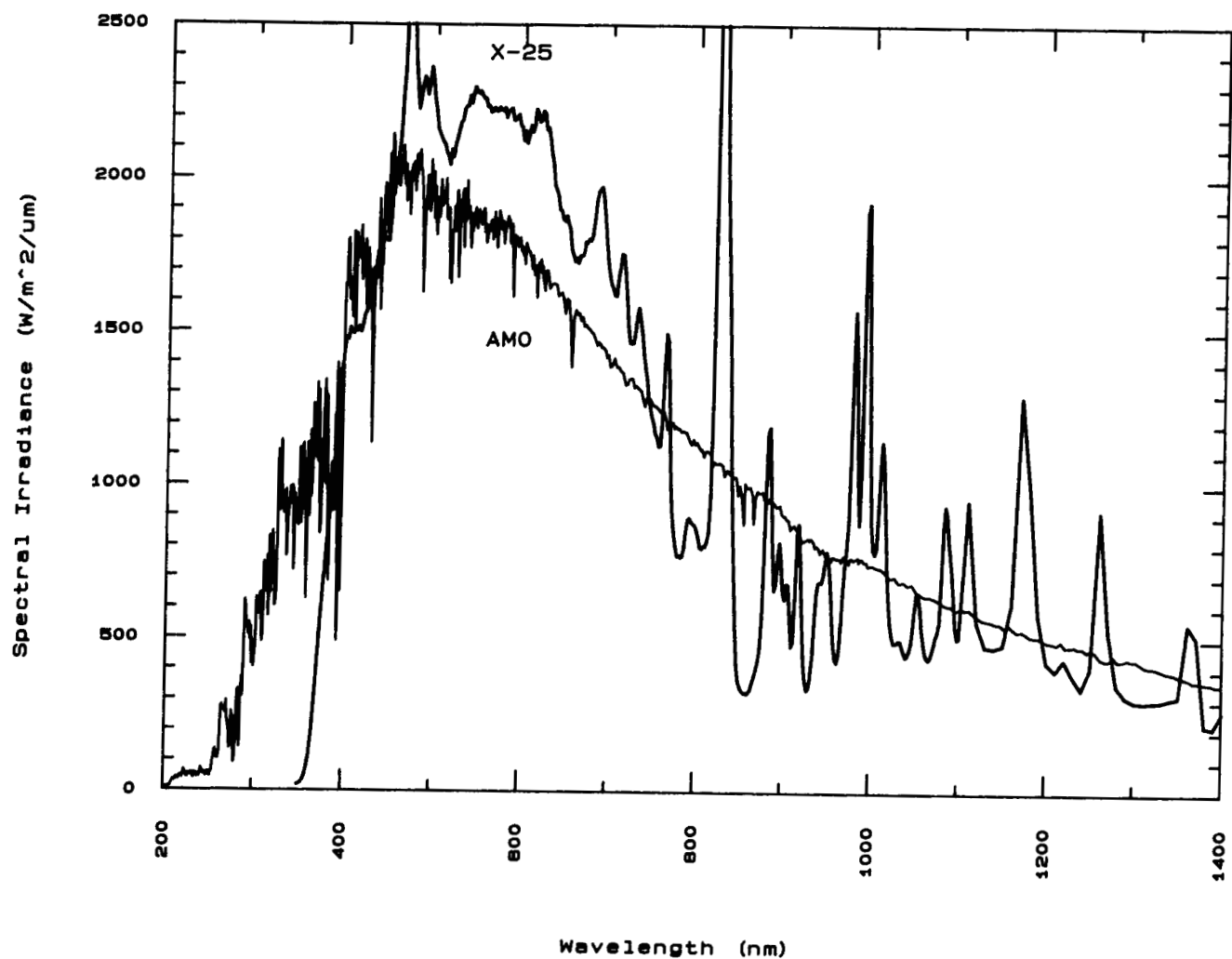
Figure 3. The AMO reference spectral irradiance recommended by the
World Radiation Center [13] ($1367Wm^{-2}$) compared with
the SERI Spectolab X-25 spectral irradiance used calculating
the spectral mismatch error in table 1.