Technical Report

March 2000 • NREL/TP-520-27942

The Results of the First World Photovoltaic Scale Recalibration

Keith Emery

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

March 2000 • NREL/TP-520-27942

The Results of the First World Photovoltaic Scale Recalibration

Keith Emery

Prepared under Task No. PV00.3401

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.doe.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

The Results of the First World Photovoltaic Scale Recalibration

Keith Emery
National Renewable Energy Laboratory
National Center for Photovoltaics
Measurements and Characterization Division
PV Performance Characterization Team

Abstract

This report presents the results of primary reference cell calibrations conducted at NREL in October and November of 1998. Twenty World Photovoltaic Scale (WPVS) reference cells were calibrated along with six candidate WPVS reference cells. One of NREL's primary Si reference cells with a long calibration history was also calibrated at the same time. This report also documents the small difference when WPVS spectral responsivity and temperature coefficient data are used in the calibrations. The spectral model that was used at NREL to extend the measured spectral irradiance to cover the wavelength range of 300-4000 nm was substantially updated during this event and its effect on the calibration value is also presented.

Acknowledgment

This work was supported by the U.S. Department of Energy under contract number DE-AC36-99GO10337. The assistance of W. Zaaiman at the European Solar Test Installation (ESTI) and L. Ottoson at NREL is acknowledged. The author also wishes to thank the owners of the WPVS primary reference cells at Sandia National Labs, Physikalisch Technische Bundesanstalt (PTB) in Germany, Japan Quality Assurance Organization (JQA) in Japan, Tianjin Institute of Power Sources (TIPS) in China, Fraunhofer Institute of Solar Energy in Germany, Indian Association for the Cultivation of Science in India, Laboratorie Central des Industries Electriques (LCIE) in France, and the National Institute of Metrology (NIM) in China.

Table of Contents

1. Introduction

The World Photovoltaic Scale (WPVS) was established after a formal international intercomparison was conducted during the 1993 to 1996 time period. The results of this intercomparison and the protocol for conducting recalibration were established [1-3]. Of the four WPVS qualified calibration facilities, Physikalisch Technische Bundesanstalt (PTB) in Germany; Japan Quality Assurance Organization (JQA) in Japan, Tianjin Institute of Power Sources (TIPS) in China, and NREL, NREL agreed to perform the first recalibration.

2. World Photovoltaic Scale Sample Set

The following WPVS sample set submitted by the participating organizations for calibration is listed in Table 1.

Table 1. The WPVS Sample Set Submitted for Recalibration.
(The asterisk on the cell identification denotes new cells submitted to be part of the sample set.)

Identification	Organization	Country
93308	JQA/ETL	Japan
93309	JQA/ETL	Japan
930216-1	NREL	U.S.A.
930216-2	NREL	U.S.A.
930417-1	LCIE	France
930417-2	LCIE	France
TDB9303	TIPS	China
TDC9305	TIPS	China
NIM9351	NIM	China
NIM9352	NIM	China
PX102C	ESTI	European Union
PX201C	ESTI	European Union
RS-69	PTB	Germany
RS-78	PTB	Germany
Y45	Sandia	U.S.A.
Y124	IACS	India
930318-5*	JQA/ETL	Japan
980512-1*	Sandia	U.S.A.
980512-2*	Sandia	U.S.A.
RS-06*	PTB	Germany
RS-07*	PTB	Germany
RS-12*	JQA/ETL	Japan

Intermittent temperature and electrical connection problems were observed in the NIM (National Institute of Metrology in China) and TIPS samples similar to what was observed at NREL during the previous WPVS calibration. Several sample boxes were inadvertently shipped to the wrong organization. This was because of a lack of sample identification on the box. As in the previous WPVS calibration, the TIPS cells were mislabeled as IDB9303 and IDB9305. It was difficult to manage the reference cell cables during the recalibration because the corresponding reference cells for most removable cables were not identified on the cable. Some of the labeled cables had stickers identifying the wires that tended to slide off. Problems with cabling were further complicated because several of the cables were interchangeable and not compatible.

3. Reference Cell Calibration Procedures

Similar procedures and equipment used in the previous WPVS calibration at NREL were employed in this calibration [1-3]. The temperature control of the LICOR LI-1800 spectroradiometer was substantially improved with the replacement of a resistive heater for the detector and preamplifier operating at 40±0.5°C, with a thermoelectric-controlled heater operating at 20 ± 0.02°C.

The calibration procedure involves measuring each cell's short-circuit current under natural sunlight simultaneously with the light's intensity and absolute spectral irradiance. The procedure's details are very similar to those presented in reference 4. Four reference cells' short-circuit currents (I_{sc}) are measured simultaneously with active biasing to zero volts as shown in Figure 1.

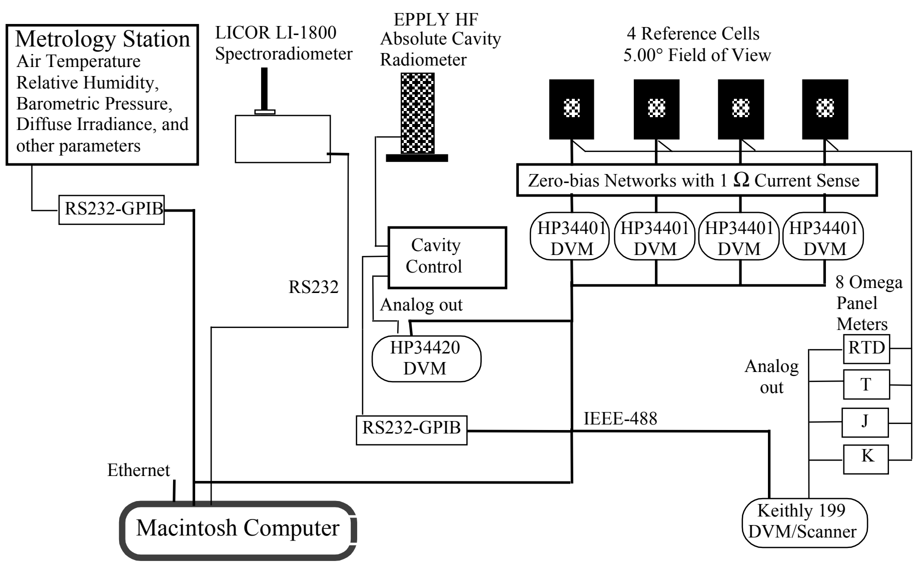

Figure 1. Block diagram of the NREL primary reference cell calibration facility [4].

Collimating tubes limit the field of view for the cells to 5.00°. The total irradiance (E_{tot}) is measured by an absolute cavity radiometer with a 5.00° field of view that is directly traceable to the World Radiometric Reference [5]. A LICOR model LI-1800 spectroradiometer with a

5.00° field of view collimating tube measures the spectral irradiance ($E_s(\lambda)$) between 350 and 1100 nm. An atmospheric transmittance model uses this spectral information to compute the spectral irradiance from 305 to 4045 nm [4,8]. The transmittance model was recently updated to include more accurate AM0 spectral irradiance and absorption coefficients [8]. Each instrument and the set of cells being measured is mounted to a separate tracker with a line-frequency time base. The accuracy of the tracking is periodically verified by inspection.

Each $E_s(\lambda)$ measurement takes approximately 30 seconds. During that time, approximately 30 I_{sc} and E_{tot} readings are collected with temperature data to complete a data set. Sets with an I_{sc}/E_{tot} range exceeding 0.5%, or standard deviation exceeding 0.1%, are rejected. Sets with an E_{tot} range greater than 0.5% are rejected as well.

The I_{sc} for each set of data is corrected to 25°C using the WPVS assigned temperature coefficient [3]. The WPVS quantum efficiency was used in the computations. Spectral correction is applied using the cell's relative spectral response, the spectral irradiance derived from the atmospheric transmittance model ($E_{sm}(\lambda)$), and the global normal reference spectrum listed in IEC standard IEC 60904-3 ($E_{ref}(\lambda)$) as factors. Using this information, the calibration value, CV, for each data set can be computed using:

$$CV = \frac{I_{sc}}{E_{tot}} \bullet \frac{\int_a^b E_{ref}(\lambda)\cdot S_r(\lambda)d\lambda}{\int_a^b E_{ref}(\lambda)d\lambda} \bullet \frac{\int_a^b E_{sm}(\lambda)d\lambda}{\int_a^b E_{sm}(\lambda)\cdot S_r(\lambda)d\lambda}$$

Finally, at least three days worth of valid data with at least 10 sets per day are averaged to give the reported CV and standard deviation. The 95% confidence uncertainty limit for these measurements is estimated at ±1% with the elemental uncertainties given in Table 2 [4].

Table 2. Estimated Uncertainty in the Calibration Value Using NREL's Primary Reference Cell Calibration Procedure [4].

Source	Bias (%)	Random (%)
Isc measurement	0.02	0.02
Isc time constants	0	0.2
Absolute cavity radiometer	0.37	0.13
Spectral correction factor	0	0.05
Temperature correction factor	0	0.05
Thermal offset voltages	0.05	0.05
Total	0.37	0.32

The absolute-cavity-radiometer model HF 23734 was recalibrated in October 1998 prior to the WPVS calibration and is documented in reference 5. The estimated U_{95} uncertainty for the 1998 absolute-cavity-radiometer calibration, with respect to the World Radiometric Reference, is 0.24% [5]. This calibration uncertainty was based upon a standard deviation of 0.06% for 66 measurements over a period of three days and compared against six cavity radiometers that have been to the Davos IPC-IVIII calibration [5]. The spectral correction factors varied from -4% to + 0.4%. The estimated uncertainty in the spectral correction factor may be unrealistically low, but is certainly below 0.2 % for the accurate quantum efficiencies used in this study [6]. The temperature corrections varied from ±0.35 %, depending on the air temperature and the thermal conductivity of the reference cell package with the temperature-controlled plate.

4. WPVS Analysis and Calibration Values

Calibration data was collected on the October 10, October 19, November 12, November 13, and November 15, 1998. The direct-beam total irradiance varied from 728 to 971 W/m^2. The ratio of plane-of-array diffuse to direct was typically 15%. The cell temperatures were near the 25°C plate temperature for samples where the temperature could be well controlled. The temperatures of the other samples ranged from a low of 18°C to a high of 32°C. The temperature-dependent quantum efficiency was not used in determining the temperature coefficient as recommended in the 1993 Photovoltaic Energy Project (PEP) final report [3]. Instead, the quantum efficiency at 25°C was used for measurements at NREL on the Spectrolab X25 solar simulator, along with the internal temperature sensor. The reference cell Y124 was sent to NREL in December 1999 after the U.S. sanctions on India were lifted. The WPVS cell's 930216-1 and Y124 were calibrated on December 23, 24, 27, and 30. The December 1999 calibration data for 930216-1 was 0.8% greater than the 1998 calibration data. The December 1999 data for 930216-1 was not used in computing the WPVS calibration value.

4.1 Effect of WPVS temperature coefficient and quantum efficiency

The four WPVS calibration laboratories used their own temperature coefficient and quantum efficiency data, not the WPVS data supplied in the final report [3]. If the 1993 WPVS calibration values supplied by NREL were based upon the WPVS temperature coefficients and quantum efficiencies, the calibration values would have decreased an average of 0.06% ± 0.08%. The maximum change in the WPVS calibration value would have been 0.21% and the minimum change - 0.08%. These results are shown graphically in Figure 2. The differences between NREL and the supplied temperature coefficients are negligible, and can be attributed to the light source that they were measured under. The temperature correction varied from a high of +0.4% to a low of -0.7%. If sample TDB 9303 is not included, the temperature corrections varied by ±0.4%. This is because samples TDB 9303 and TDB 9305 have connectors that extend below the back surface, making temperature control problematic without an adapter plate.

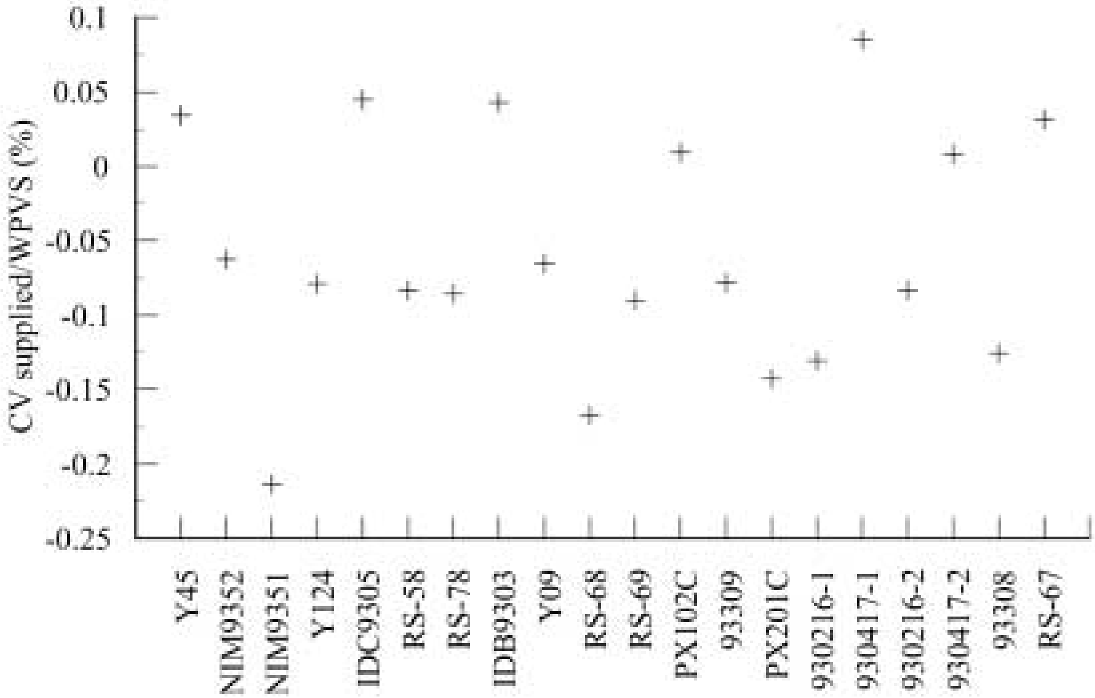

Figure 2. Comparison of the calibration value using the supplied v*ersus* the WPVS determined I_{sc} temperature coefficient and spectral responsivity.

4.2 Effect of updated versus previous spectral model

The primary difference between the spectral model used in previous calibrations and the current calibration is the extraterrestrial source spectrum. The extraterrestrial spectrum recommended by the World Radiation Research Laboratory [7] had unrealistically low values in the 900 to 1000 nm region that were being used for the IR aerosol and water-vapor fit [8]. The effects of the new versus old model on the calibration value for the 1998 NREL recalibration are shown in Figure 3.

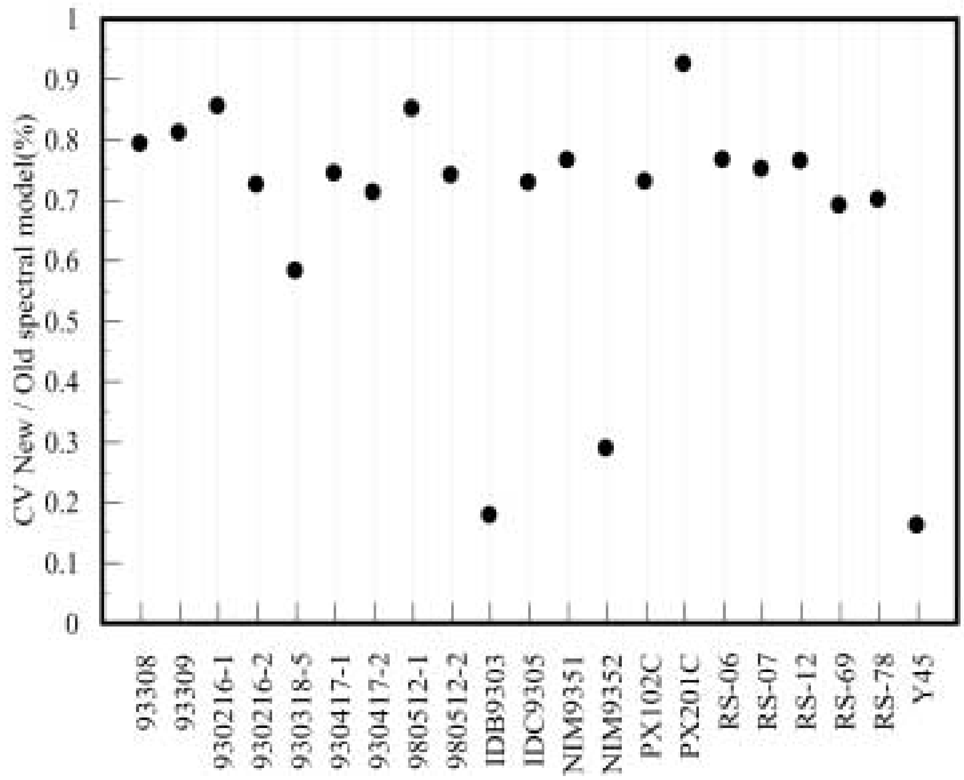

Figure 3. Percent change in the calibration value using the spectral model used for PEP 1993 *versus* spectral model used for PEP 1998. The WPVS determined I_{sc} temperature coefficient and quantum efficiency were used along with the NREL 198 WPVS calibration data.

4.3 Calibration values for WPVS cells

The new WPVS calibration values were obtained by averaging all previous valid calibration values as discussed in the 1993 Final PEP meeting held in Golden, Colorado on March 4-8, 1996 [3]. Table 3 summarizes the results of the 1998 WPVS NREL calibration. These results are shown graphically in Figure 4.

Table 3. WPVS Calibration Values at 25°C, IEC 904 Global Reference Spectrum.
(The previous calibration values were taken from [3].)

ID	NREL (mA)	JQA/ ETL (mA)	PTB (mA)	TIPS (mA)	NREL '98 (mA)	old WPVS (mA)	σ (%)	new WPVS (mA)	σ (%)	old/new I_{sc} (%)
930216-1	122.9	124.1	121.98	124.17	122.02	123.29	0.85	123.03	0.87	-0.21
930216-2	123.2	124.4	121.99	124.27	122.23	123.47	0.91	123.22	0.91	-0.20
930417-1	124.1	125.8	123.61	126.45	124.39	124.99	1.08	124.87	0.96	-0.10
930417-2	122.2	123.9	121.45	124.87	122.41	123.11	1.27	122.97	1.13	-0.11
93308	126.5	126.1	125.32	127.52	124.67	126.36	0.72	126.02	0.87	-0.27
93309	126.7	125.9	125.15	127.78	125.08	126.38	0.89	126.12	0.90	-0.21

NIM 9351	122.1	120.9	119.59	121.59	117.89	121.05	0.90	120.41	1.41	-0.52
NIM 9352	120.8	120.3	118.46	121.10	119.01	120.17	0.98	119.93	0.96	-0.19
PX102C	116.2	117.5	116.09	118.40	115.63	117.05	0.94	116.76	0.98	-0.24
PX201C	122.5	123.9	122.04	124.71	[122.23]	123.29	1.00	123.29	-	0.00
PTB RS-58	126.1	126.7	124.80	128.82		126.61	1.32	126.61	1.32	-0.00
PTB RS-67	125.4	126.2	123.91	127.10		125.65	1.08	125.65	1.08	0.00
PTB RS-68	125.1	126	123.57	127.69		125.59	1.37	125.59	1.37	0.00
PTB RS-69	125.6	126.1	123.44	127.60	123.30	125.69	1.37	125.21	1.46	-0.38
PTB RS-78	117.3	117.7	115.80	119.19	116.49	117.50	1.19	117.30	1.10	-0.17
TDB 9303	133.8	136.5	133.24	135.05	134.17	134.65	1.08	134.55	0.95	-0.07
TDC9305	124.3	126.4	123.48	124.19	125.21	124.59	1.01	124.71	0.90	0.10
Y09	93.4	94.08	93.26	94.35		93.77	0.56	93.77	0.56	0.00
Y45	126.5	126.8	126.93	129.86	125.45	127.52	1.23	127.11	1.29	-0.33
Y124	107.9	111.3	109.12	105.32	106.35	108.41	2.30	108.00	2.17	-0.38

The data for Y124 was collected in December 1999. The change in the WPVS value for the recalibrated cells varied from a 0.5% drop for NIM9351 to a 0.1% increase for TDC9305. The average decrease in WPVS calibration values was 0.16%.

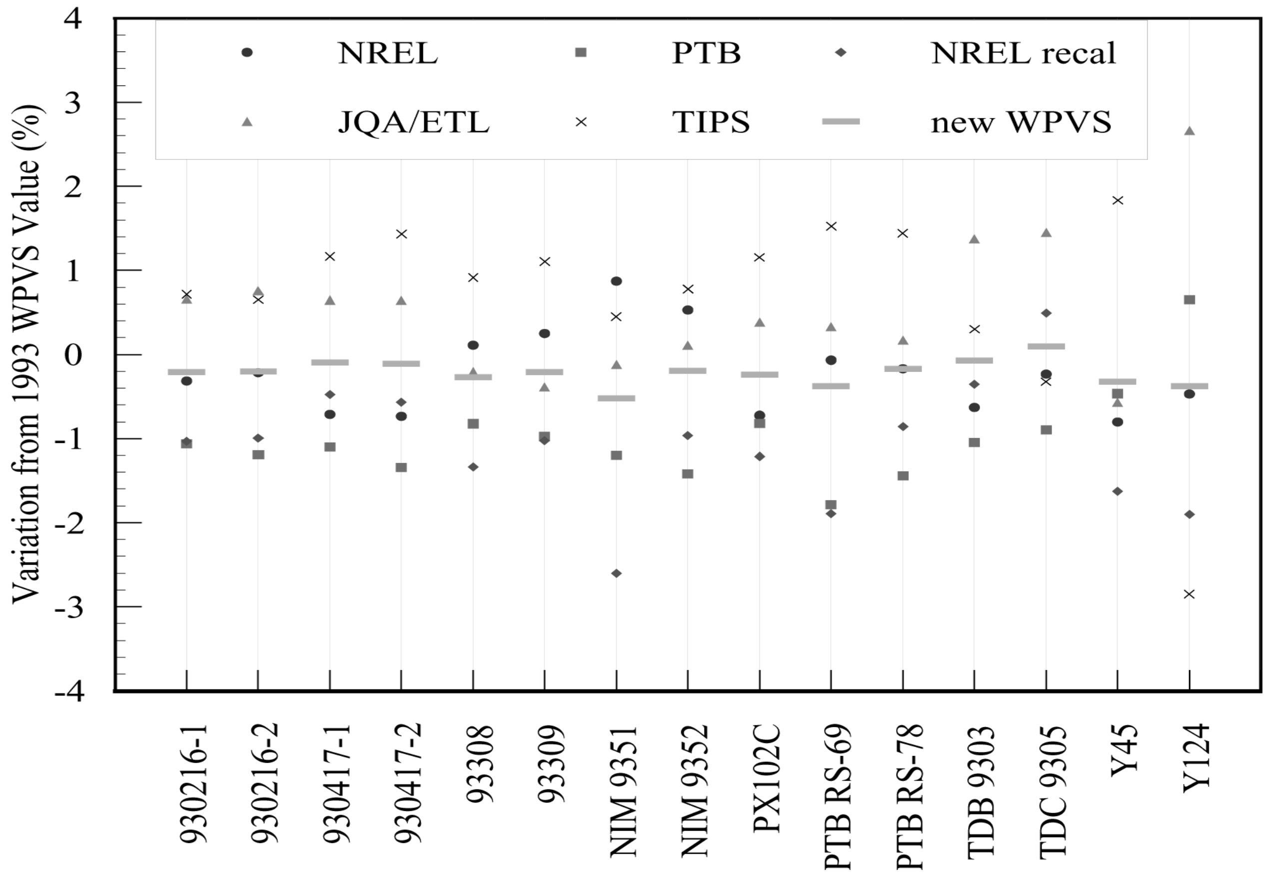

Figure 4. Comparison of previous and new WPVS calibration values for the cells that participated in the 1998 WPVS recalibration.

4.4 Calibration values for candidate WPVS cells

The temperature coefficient for the five candidate WPVS cells is listed in Table 4. The quantum efficiencies for these cells are shown in Figures 5-10. The package design is similar to the PRC Kochmann design described in reference 3. The cells exhibited no electrical or temperature sensor problems. Table 5 lists the calibration values assigned to these candidate cells using the supplied temperature coefficient and quantum efficiency. Table 6 gives the calibration values using the temperature coefficient measured at NREL (except RS-12) and the quantum efficiency measured at NREL. The differences are compared graphically in Figure 11. The supplied quantum efficiencies for the JQA cells 930318-5 and RS-12 appear too low (380 to 480 nm range). The supplied quantum efficiencies for 980512-1 and 980512-2 appear to have large errors at 300 and 310 nm. There was no significant difference between NREL and PTB, and the differences between NREL and Sandia were not significant for wavelengths greater than 320 nm.

Table 4. Comparison of NREL's and the Supplied I_{sc} Temperature Coefficients (ppm/°C) Normalized at 25°C.

Sample ID	NREL	PTB	JQA	Sandia
930318-5	796		890	
980512-1	642			589.5
980512-2	631			559.8
RS-06	627	590		
RS-07	506	540		
RS-12	-		500	

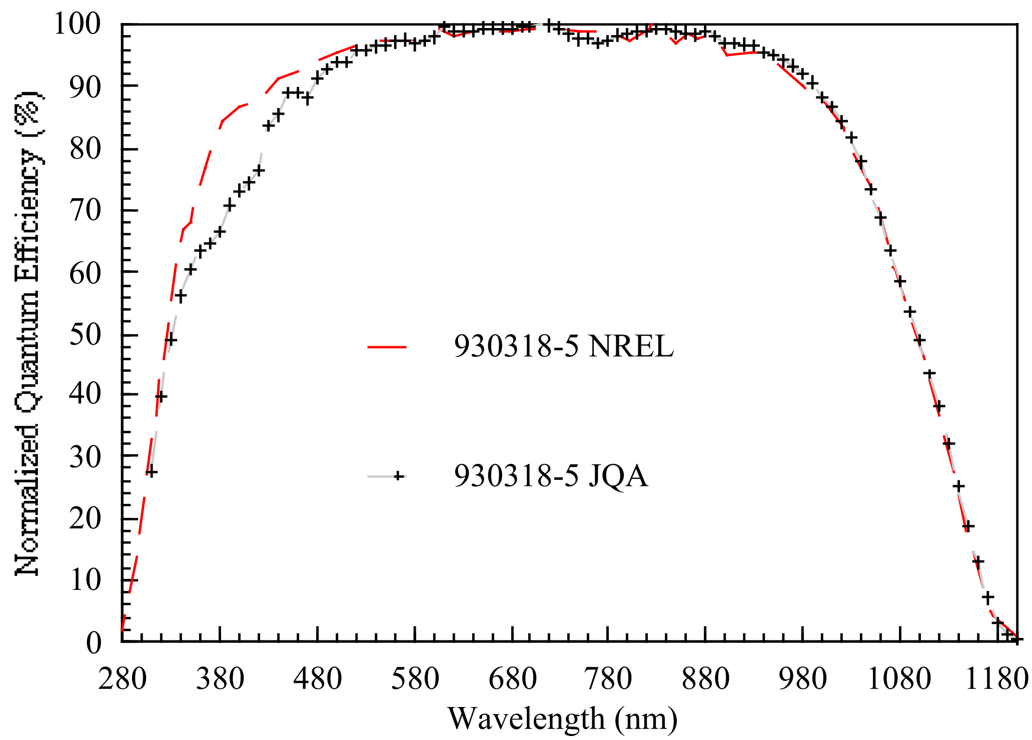

Figure 5. NREL and JQA QE on sample 930318-5.

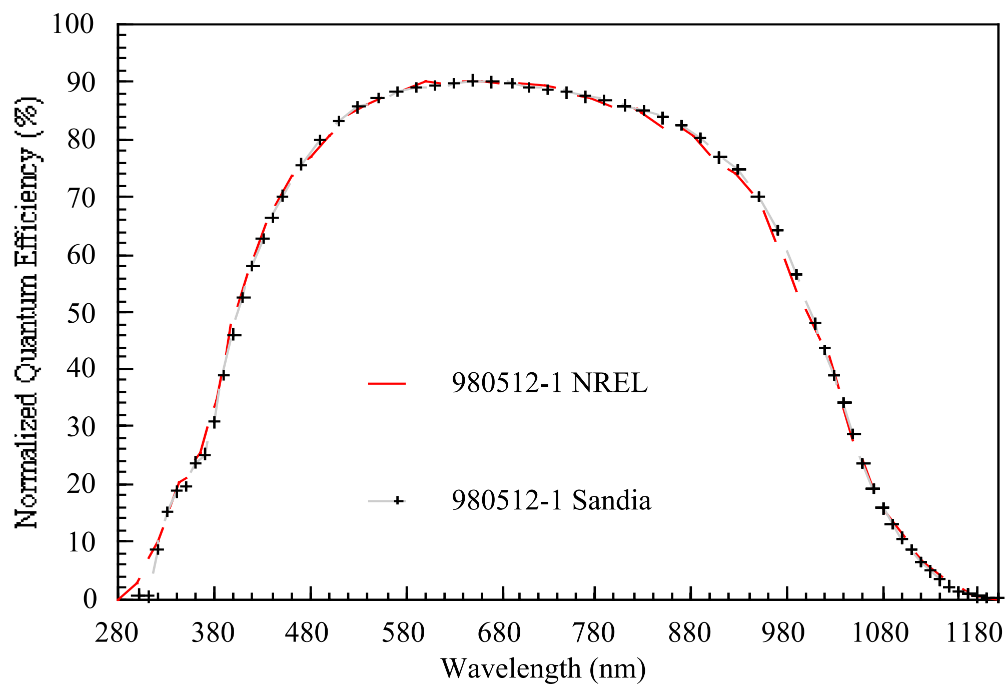

Figure 6. NREL and Sandia QE on sample 980512-1.

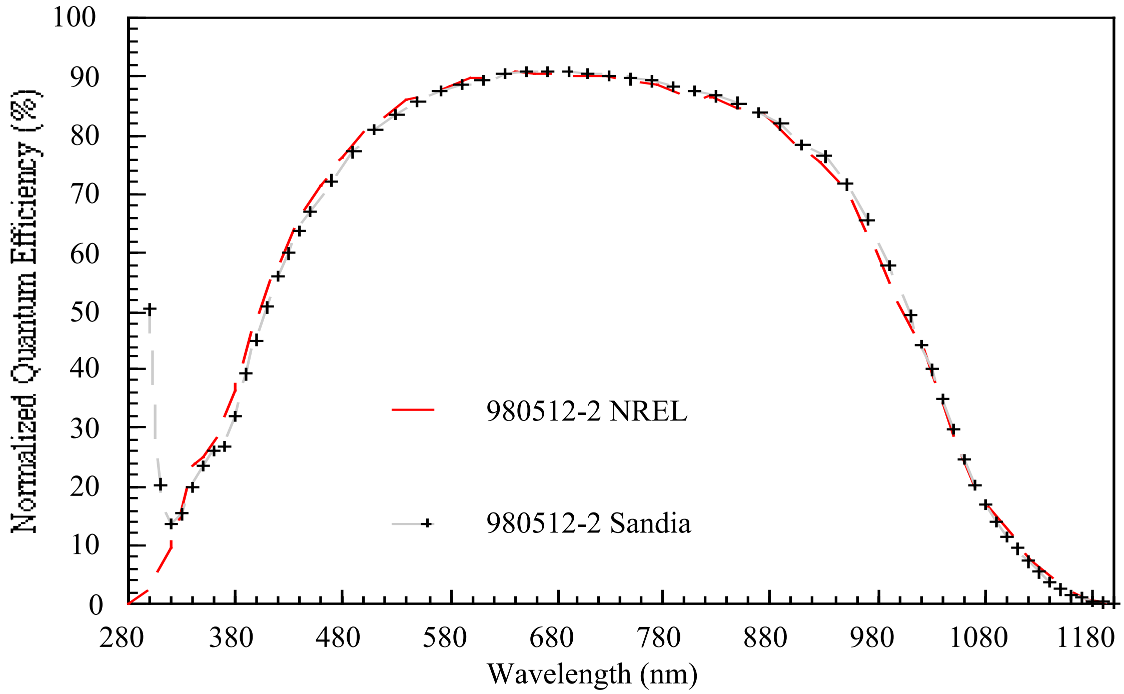

Figure 7. NREL and Sandia QE on sample 980512-2.

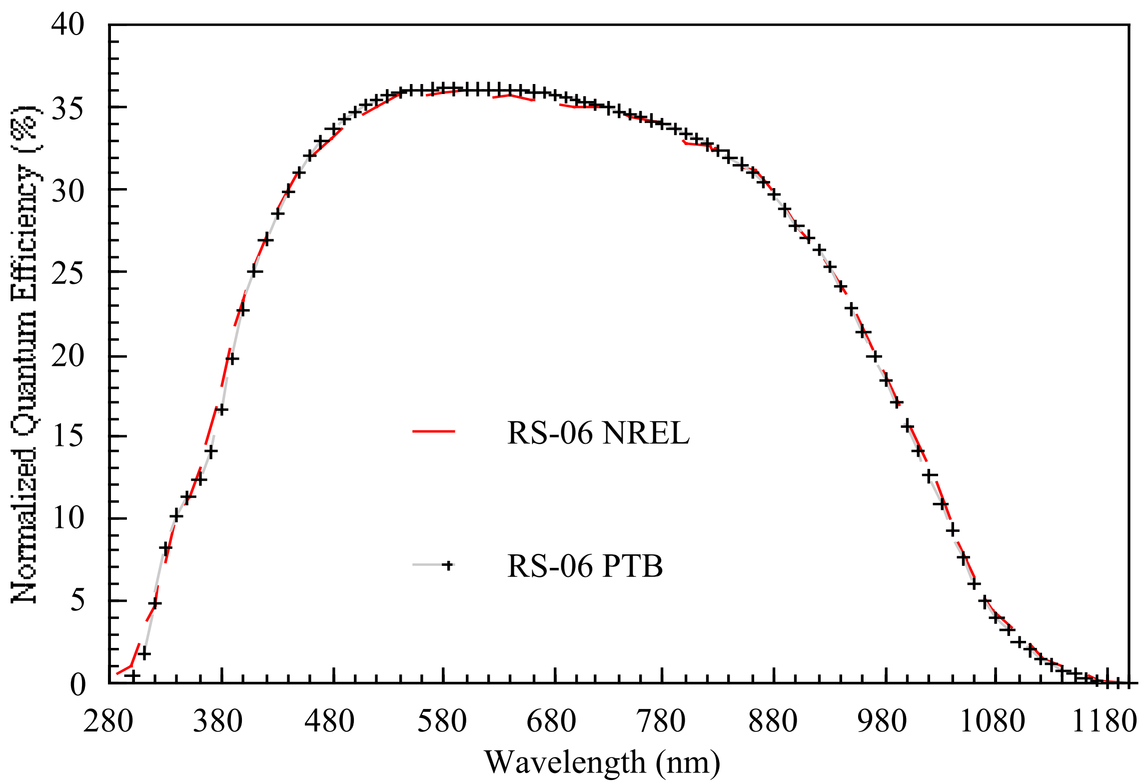

Figure 8. NREL and PTB QE on sample RS-06.

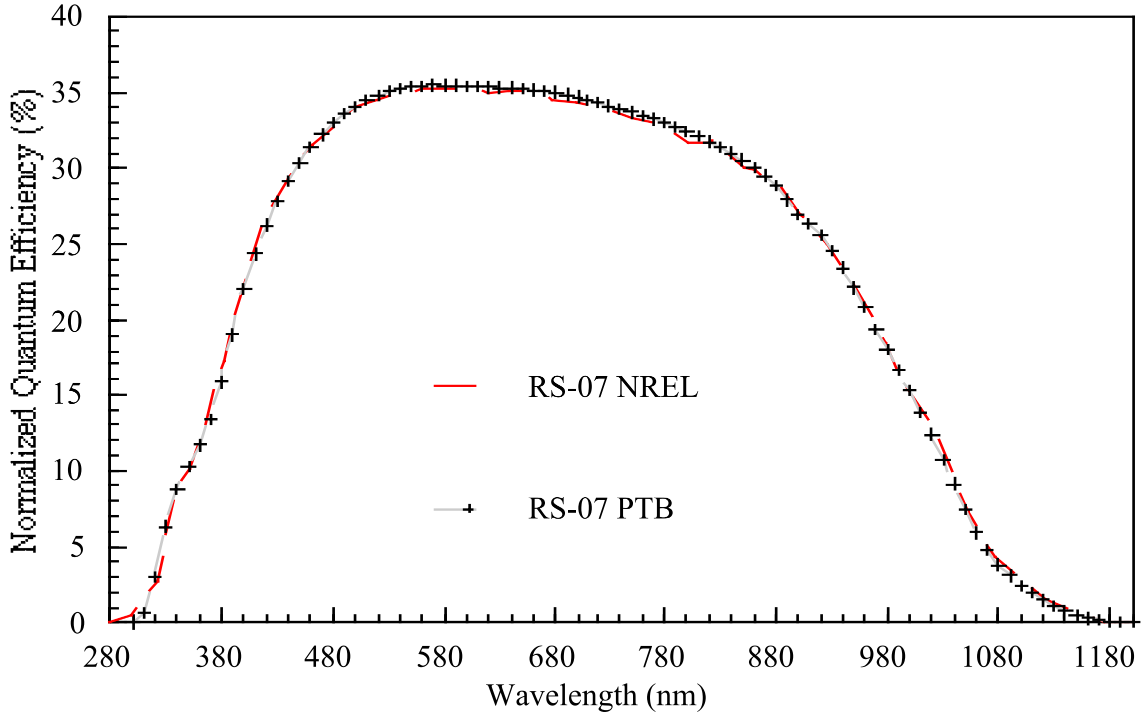

Figure 9. NREL and PTB QE on sample RS-07.

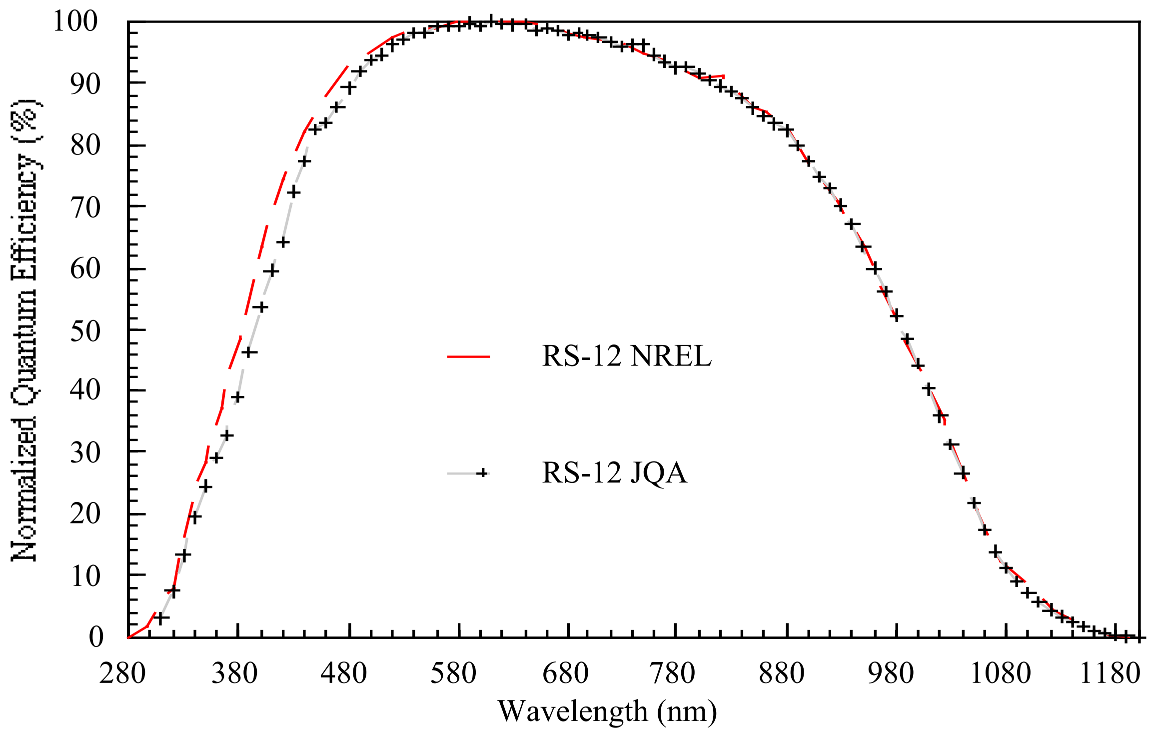

Figure 10. NREL and JQA QE on sample RS-12.

Table 5. New WPVS Candidates Using the Supplied Spectral Responsivity and Temperature Coefficient.

ID	Isc (mA)	σ (%)	# points	# days
930318-5	138.05	0.127	37	3
980512-1	122.34	0.352	34	3
980512-2	123.21	0.266	36	3
RS-06	124.86	0.186	31	3
RS-07	121.60	0.186	33	3
RS-12	118.71	0.042	26	3

Table 6. New WPVS Candidates Using Spectral Responsivity and Temperature Coefficients Measured at NREL.

ID	Isc (mA)	σ (%)	# points	# days
930318-5	138.58	0.126	37	3
980512-1	122.43	0.361	34	3
980512-2	123.38	0.337	36	3
RS-06	124.85	0.187	31	3
RS-07	121.61	0.192	33	3
RS-12	118.97	0.124	26	3

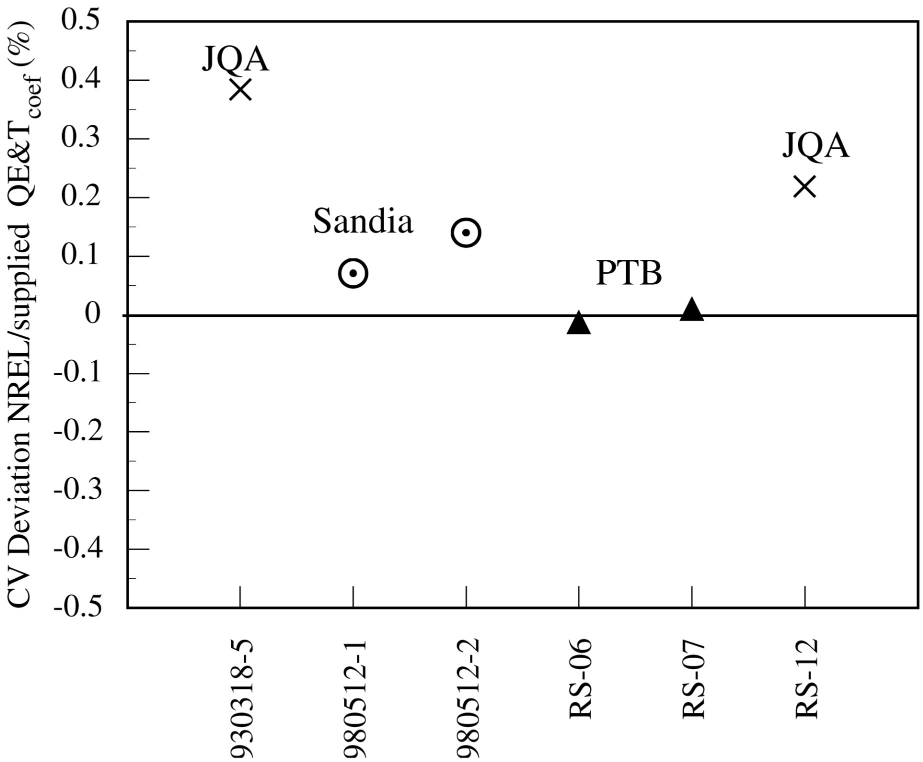

Figure 11. Percent variation in the calibration value using the NREL-measured versus supplied spectral response and temperature coefficients for the WPVS candidate cells. The differences are all due to variations in the spectral response.

5. Summary and Recommendations

The results of the first recalibration of WPVS reference cells have been presented. The WPVS calibration value was recomputed based upon the all of the valid WPVS calibration values shown in Table 3. The change in the WPVS value for the recalibrated cells varied from a 0.5% drop for NIM9351 to a 0.1% increase for TDC9305. The WPVS calibration values decreased by an average of 0.16%.

6. References

1. C.R. Osterwald, S. Anevsky, A.K. Barua, J. Dubard, K. Emery, D. King, J. Metzdorf, F. Nagamine, R. Shimokawa, N. Udayakumar, Y.X. Wang, W. Zaaiman, A. Zastrow, J. Zhang, "Results of the PEP 1993 Intercomparison of Reference Cell Calibrations and Newer Technology Performance Measurements," *Proc. 25th IEEE Photovoltaic Specialists Conf.*, Washington D.C., May 13-17, 1996, pp. 1263-1266, IEEE, New York, 1996.

2 C.R. Osterwald, S. Anevsky, A.K. Barua, J. Dubard, K. Emery, D. King, J. Metzdorf, F. Nagamine, R. Shimokawa, N. Udayakumar, Y.X. Wang, T. Wittchen, W. Zaaiman, A. Zastrow, and J. Zhang, "Results of the PEP'93 Intercomparison of Reference Cell Calibrations and Newer Technology Performance Measurements," Proc. 26th IEEE PVSC Conf., Aneheim, CA. Sept. 29-Oct. 2, 1997, pp. 1209-1212, IEEE, New York, 1997.

3. C.R. Osterwald, S. Anevsky, A.K. Barua, J. Dubard, K. Emery, D. King, J. Metzdorf, F. Nagamine, R. Shimokawa, N. Udayakumar, Y.X. Wang, W. Zaaiman, A. Zastrow, J. Zhang, "The Results of the PEP 1993 Intercomparison of Reference Cell Calibrations and Newer Technology Performance Measurements: Final Report," March 1998, NREL tech. rep. NREL/TP-520-23477.

4. C. R. Osterwald, K. Emery, D. Myers, and R. Hart, "Primary Reference Cell Calibrations at SERI: History and Methods," *Twenty-first IEEE PVSC*, 1990, pp. 1062-1067.

5. I. Reda, T. Stoffel, and J. Treadwell, "Results of NREL Pyrheliometer Comparisons," NPC October 5-16, 1998 (NREL report TP-560-28028) and October 4-15, 1999 (NREL report TP-560-28029).

6. H. Field and K. Emery, "An Uncertainty Analysis of the Spectral Correction Factor," *Proc. 23rd IEEE Photovoltaic Specialists Conf.*, Louisville, KY, May 10-14, 1993, pp. 1180-1187, IEEE, New York, 1993.

7. C. Wehrli, 1985: Extraterrestrial Solar Spectrum. Physikalish-Meterologisches Observatorium and World Radiation Center Pub. 615, 7 pp. [available at ftp://ftp.pmodwrc.ch/pub/publications/pmod615.asc].

8. C. Osterwald and K. Emery, "Spectroradiometric Sun Photometry," Journal of Atmospheric and Oceanic Technology, September 2000.