RESULTS OF THE PEP'93 INTERCOMPARISON OF REFERENCE CELL CALIBRATIONS AND NEWER TECHNOLOGY PERFORMANCE MEASUREMENTS

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ABSTRACT

This paper presents the results of an international intercomparison of photovoltaic (PV) performance measurements and calibrations. The intercomparison, which was organized and operated by a group of experts representing national laboratories from across the globe (i.e., the authors of this paper), was accomplished by circulating two sample sets. One set consisted of twenty silicon reference cells that would, hopefully, form the basis of an international PV reference scale. A qualification procedure applied to the calibration results gave average calibration numbers with an overall standard deviation of less than 2% for the entire set. The second set was assembled from a wide range of newer technologies that present unique problems for PV measurements. As might be expected, these results showed much larger differences among laboratories. Methods were then identified that should be used to measure such devices, along with problems to avoid.

INTRODUCTION

Under the auspices of the seven-nation Photovoltaic Energy Project (PEP), an international round-robin of reference cell calibrations and performance measurements of Newer Technology (NT) PV devices was initiated in 1993. The round-robin was preceded by two other PEP-sponsored projects in 1984 [1] and 1987 [2]. The objectives of the intercomparison were threefold: (1) establish the World PV Scale (WPVS) by comparing primary reference cell calibrations traceable to national metrology programs, (2) identify problems with emerging technology measurements and propose recommendations for suitable measurement procedures to be considered by standardization organizations, and (3) recommend methods of qualifying calibration data in publications. Thirteen laboratories from eight nations participated in the intercomparison, which required more than two years to complete.

WPVS SAMPLE SET

A major recommendation of the PEP'87 intercomparison was that a single primary calibration method should not be adopted for international standardization, but rather, the total uncertainty of acceptable reference cell calibrations should be less than ±2% [2]. The WPVS sample set, which required the participants to calibrate 20 2×2 cm packaged silicon devices using the best method available to them that is traceable to national standards, was an attempt to act on this recommendation. Each participant provided at least one reference cell to the sample set that was returned at the conclusion of the intercomparison.

A number of calibration methods were used by the participating laboratories, including: outdoor primary calibration against a cavity radiometer (A), indoor primary with absolute simulator spectral irradiance (C), differential spectral responsivity with variable bias light (D1), differential spectral responsivity with no bias light (D2), indoor primary with a standard irradiance lamp (L), absolute spectral responsivity (R), and secondary calibration against a primary reference cell (S). All of these methods involve spectral corrections of some kind to the standard global air mass 1.5 spectral irradiance [3]. The letter codes, similar to those used in reference [2], identify the methods used in the plot of the normalized short-circuit current calibration results from ten laboratories, Fig. 1. For this data set, the overall 2σ standard deviation is 7.3%, a large value.

We adopted the following procedure to qualify the WPVS calibrations. First, it was decided that only primary calibration methods should be allowed to contribute to the WPVS. Thus, laboratories 1, 9, and 10 were removed as these were secondary calibrations. Second, any laboratories with 50% or more of their data points in Fig. 1 outside of 1.0 ± 0.02 were excluded. This criterion resulted in the removal of laboratories 3, 5, and 7. The normalized short-circuit currents were then recalculated, and individual points that exceeded 1.0 ± 0.02 were removed. The remaining data were averaged to obtain the final WPVS short-circuit current values. These results are presented in Fig. 2, where the overall 2σ standard deviation is now 1.9%. Although space does not allow presentation here, qualified spectral responsivity and short-circuit current temperature coefficients are also included as part of the World PV Scale.

The WPVS effort revealed several drawbacks to implementing such a program in its current state. First, the length of time needed to circulate all the cells among all laboratories traceable to the WPVS is excessive. The first attempt

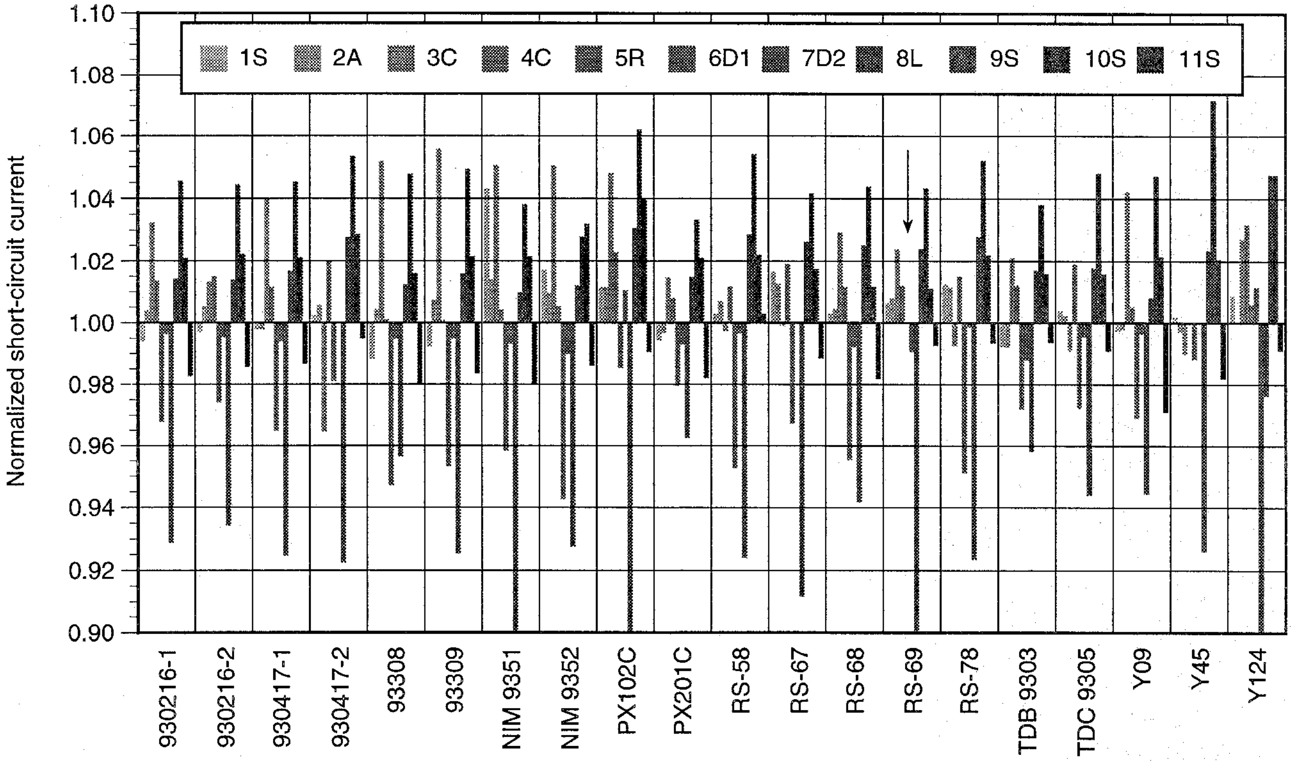

Fig. 1. Normalized 2×2 cm Si reference cell calibration results for the WPVS sample set. The 2σ standard deviation is 7.3%. The laboratory designations indicate the order in which the samples were circulated and the calibration methods used (see text). The vertical arrow marks a missing data point.

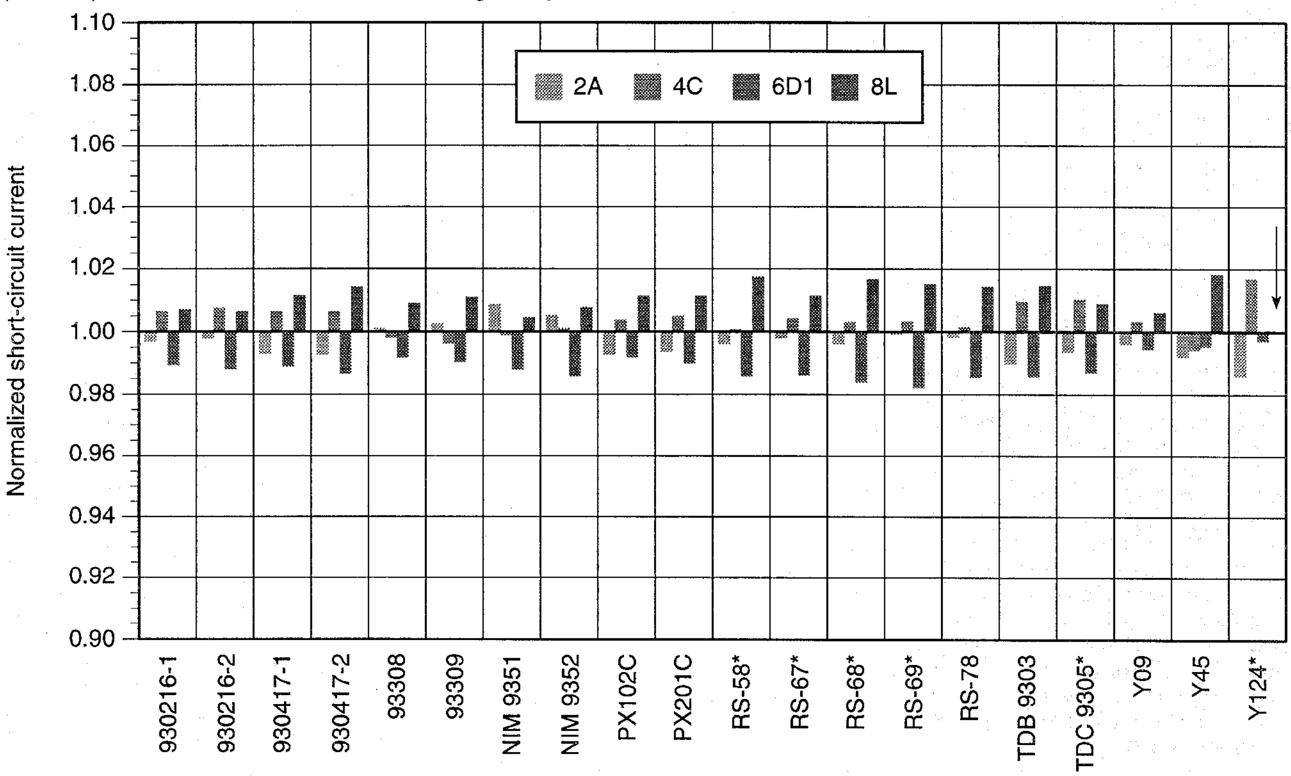

Fig. 2. Normalized reference cell calibration results for the WPVS sample set following removal of secondary calibrations (1, 9, and 10) and laboratories with 50% or more data points exceeding 1.0 ± 0.02 (3, 5, and 7). The 2σ standard deviation is 1.9%. The point marked with a vertical arrow was removed as an outlier. Cells indicated with a (*) had defects that may affect the calibration uncertainty.

required almost 3 years. During this time, the cells are unavailable and thus cannot be used as reference cells. Also, the risk of losing the entire set at once in shipment between laboratories is unacceptably high. Second, the cells currently in the WPVS are themselves problematic. The only restriction placed on the cells was that they meet the requirements of reference [4], which are fairly minimal. Several cells developed bubbles in encapsulation, and the cover windows of three cells were cracked during the calibrations. Moreover, the twenty WPVS cells represent a total of seven different package designs with a wide variety of temperature sensors, cables and connectors, and physical sizes. This variety caused logistical problems for the participants during the calibrations. Third, procedures for adding new cells to the WPVS set must be developed.

NT SERIES SAMPLE SET

The NT sample set consisted of two cells from each of the following categories: ESTI sensor, $CuIn(Ga)Se_2$, CdTe, a-Si bi-cell (two-cell minimodule), low-pass (300-800 nm) filtered Si, high-pass (600-1200 nm) filtered Si, GaAs, 10×10 cm bare Si, a-Si two-terminal tandem, and a two-cell GaAs concentrator module with fixed optics. All of the devices were packaged as reference cells except for the large-area silicon cells. Because of the objective to identify measurement problems, the participants were free to measure these samples by whatever methods they chose. The majority of the measurements were performed in solar simulators against reference cells, using spectral corrections to the global spectral irradiance. A notable exception was the GaAs concentrator module which several laboratories measured outdoors against blackbody detectors.

Overall, the nature of the NT series samples posed problems for all the laboratories. Also, no instructions were provided about how to measure the devices, except for necessary information about contacts and connectors. For example, the ESTI sensors consist of two 50-cm^2 silicon cells inside a module-laminated package. One cell is loaded with a 20-mΩ resistance for short-circuit current measurement, and the other cell is intended as a temperature sensor using the cell's open-circuit voltage. Because they are not intended to be operated at maximum power, a four-wire connection is not provided to the temperature cell. Most of the laboratories did not know how to calibrate these devices and measured the current-voltage curve of the open cell. Therefore, the ESTI sensor data are not reported.

Fig. 3 presents the normalized maximum-power results for the NT series. Maximum-power data were used for the comparison instead of efficiency because maximum-power is independent of cell area and because some laboratories did not measure cell areas. After the reported data were normalized, individual points that exceeded 1.0 ± 0.08 were removed and the normalization factors recalculated. The 2σ standard deviation of the remaining data is 5.7%, which is probably about what might be expected from such a diverse group of samples. The outlying data points were also re-normalized and appear in Fig. 3, even though most exceed the plot vertical limits.

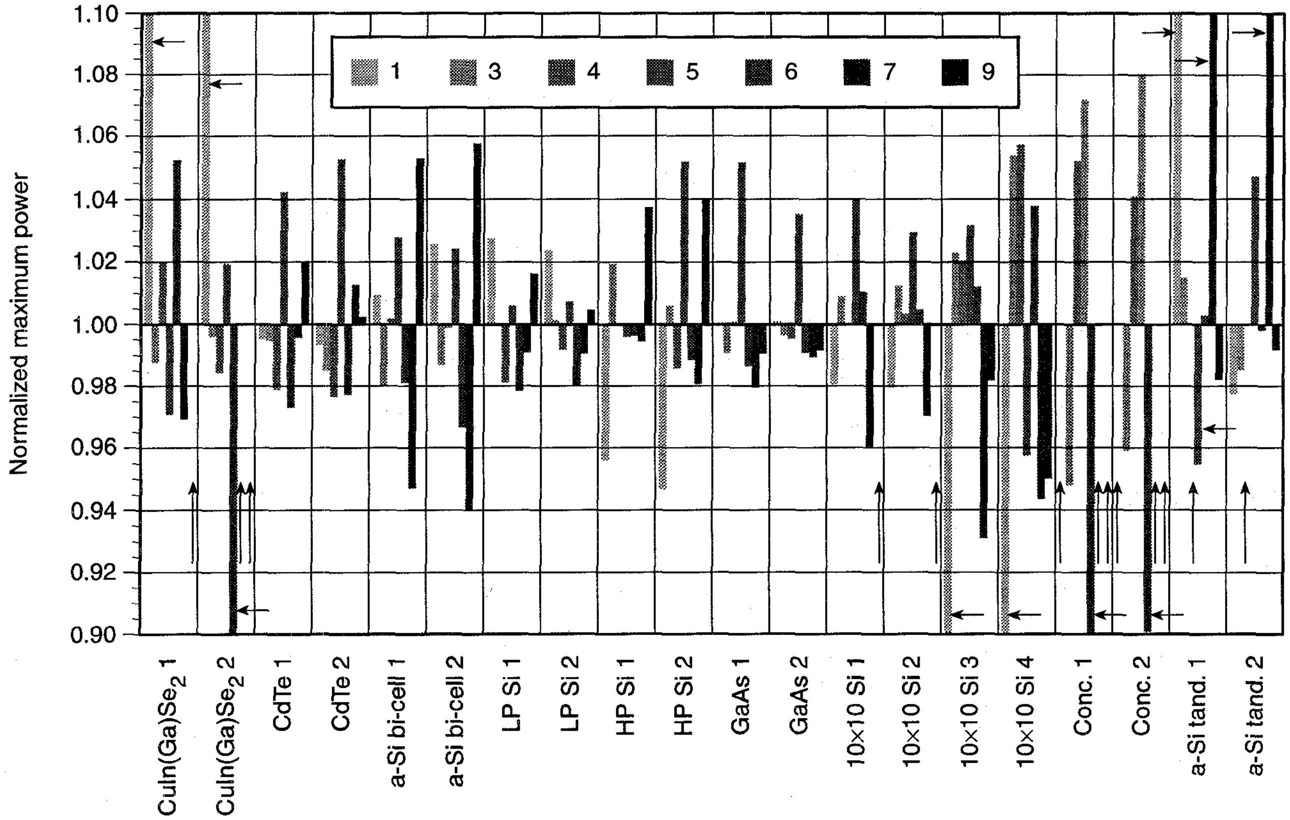

Fig. 3. Normalized maximum-power results for the NT series sample set. The 2σ standard deviation is 5.7%. The vertical arrows mark missing data points, and the horizontal arrows indicate data points that exceeded 1.0 ± 0.08. All but one of these points exceeded 1.0 ± 0.1 and were clipped to the plot edges. These outliers were not used to calculate the overall standard deviation.

Subsequent analysis and discussion of the results revealed a number of problems encountered by the participating laboratories. Contacting problems were uncovered by the large-area Si cell samples, two of which had four-terminal connector blocks provided (1 and 2), and two that had only two sockets for connections (3 and 4). Cells 3 and 4 therefore show more deviation caused by fill factor differences. The results for the $CuIn(Ga)Se_2$ devices indicate there is a strong possibility that the contacts of these devices degraded during the intercomparison. Laboratory 5 determined from the WPVS results that the reference cell used for this laboratory's measurements was out of calibration (about 4% high), which resulted in correspondingly higher values. The large-area devices caused temperature control problems for several laboratories. Laboratory 1 allowed large-area cells 3 and 4 to reach temperatures of approximately 40°C. Only three laboratories used multiple-source simulator measurement techniques on the a-Si tandem cells. A major problem was spectral response measurements of these cells. Half the participants did not attempt to measure the subcells individually, thus producing a composite spectral response. One laboratory could not measure the maximum power of the tandem cells because the higher open-circuit voltage of these devices exceeded the maximum limits of the instrumentation. Spatial non-uniformities may be responsible for the higher differences observed for the a-Si minimodules.

The analysis showed that differences in short-circuit current (not reported here) are not accounted for by differences in spectral response measurements. These differences must therefore be caused by reference cell calibrations or spectral calibration of simulators.

RECOMMENDATIONS

A number of recommendations for performance measurements of newer technology devices were made. First, tandem-cell measurements are difficult, especially spectral response, and need to be done with multijunction techniques. Second, problems inherent with newer technology devices that can cause unexpected errors should be carefully considered. These include (a) area measurement, (b) temperature measurement and control, (c) device stability, (d) contacting and wiring, (e) pulsed light versus steady-state measurements, and (f) sweep speed of the current-voltage measurements. Third, reference cell calibration is vitally important, and adoption of the World PV Scale should help reduce differences.

After spending a great deal of time discussing the problems with the WPVS identified above, the following recommendations for future WPVS calibrations were made. First, circulation of the entire set among all the laboratories traceable to WPVS will no longer be performed. Intercomparisons will be replaced with recalibration at a single laboratory. The recalibration events should take place every 1 ½ to 2 years at different laboratories. Laboratories eligible for recalibration events will initially be those whose data were selected for the final WPVS average (laboratories 2, 4, 6, and 8 in Fig. 2). Second, new cells must undergo an extensive series of acceptance tests prior to being qualified for subsequent calibration. These acceptance tests include (a) meeting physical requirements, (b) light soaking, (c) current-voltage characteristics, (d) visual inspection, (e) temperature sensor integrity, and (f) temporal stability. Third, new cells that have passed the acceptance tests are circulated informally among several laboratories traceable to WPVS prior to the next calibration event. The new cells may then be brought to the next event for calibration with the other WPVS cells. Fourth, following the calibration event, the results of the recalibration and data from any new cells are considered and analyzed by the participating laboratories at a post-calibration meeting. The new qualified average for each cell is determined at this time. Also, laboratories that have improved their calibrations are considered for admittance to the recalibration group at this time. Finally, a new reference cell package design that should minimize logistical problems that can occur when calibrating a large number of devices from around the world was developed.

CONCLUSIONS

For the first time, a group of worldwide national laboratories have agreed on a single scale for PV reference cell calibrations. The 2σ standard deviation of the normalized short-circuit currents from four laboratories for 20 2×2 cm Si reference cells was 1.9%. Although each of the laboratories have different bias and random errors, this result appears to achieve the recommendation of the previous PEP'87 round-robin, that the total uncertainty for primary calibrations should be ±2%. Procedures for maintenance and recalibration for the World PV Scale have also been recommended.

A second sample set of newer technology PV devices circulated worldwide gave a 2σ standard deviation of 5.7% for the normalized maximum power, after removal of obvious outliers. This study has shown a number of problems associated with these measurements that must be dealt with if this uncertainty is to be reduced in the future.

ACKNOWLEDGMENT

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REFERENCES

[1] H. Ossenbrink, R. Van Steenwinkel, K. Krebs, "The Results of the 1984/1985 Round-Robin Calibration of Reference Solar Cells for the Summit Working Group on Technology, Growth, and Employment," Joint Research Centre, Ispra Establishment, PREPRINT EUR 10613 EN, April 1986.

[2] J. Metzdorf, T. Wittchen, K. Heidler, K. Dehne, R. Shimokawa, F. Nagamine, H. Ossenbrink, L. Fornarini, C. Goodbody, M. Davies, K. Emery, R. DeBlasio, "Objectives and Results of the PEP'87 Round-Robin Calibration of Reference Solar Cells and Modules," *Proc. 21st IEEE PV Spec. Conf.*, Kissiminee, FL, 1990, pp. 952-959. See also "The Results of the PEP'87 Round Robin Calibration of Reference Solar Cells and Modules -Final Report-," *PTB report PTB-Opt-31*, ISBN 3-89429-067-6, Braunschweig, 1990, 174 p.

[3] "Photovoltaic Devices—Part 3: Measurement Principles for Terrestrial Photovoltaic (PV) Solar Devices with Reference Spectral Irradiance Data," *International Electrotechnical Commission Standard 904-3*, Geneva, Switzerland, 1989.

[4] "Photovoltaic Devices—Part 2: Requirements for Reference Solar Cells," *International Electrotechnical Commission Standard 904-2*, Geneva, Switzerland, 1989.