LONG-TERM PERFORMANCE AND RELIABILITY ASSESSMENT OF 8 PV ARRAYS AT SANDIA NATIONAL LABORATORIES

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ABSTRACT

In the last decade, c-Si module degradation rates of <1%/year have been reported [1-3]. It is unclear if this degradation rate extends directly to the string level and what is the expected statistical spread of degradation rates. Nine photovoltaic (PV) arrays totaling nearly 100 kW at Standard Reporting Conditions are currently being used at Sandia National Laboratories (SNL) primarily for inverter testing. The measured power degradation of these arrays at the string level varied from no change over three years within measurement error to greater than 25% in three years. This paper outlines the methodology used to test the DC output, outlines analysis techniques used to evaluate the array performance, provides a current reliability assessment, presents the comparative data for up to five years of use and exposure, and discusses the methods used to track down the causes of unexpected string-level degradation.

INTRODUCTION

As the PV industry expands, the number and size of installations is growing rapidly. Measuring and predicting system-level performance, system reliability and system availability are becoming more important to installers, integrators, investors and owners. Monitoring and analyzing the performance and reliability of existing systems is essential to predicting the same for future systems. Feeding back issues and lessons learned to the PV community is vital to enhancing performance, reliability and availability of future systems, leading the way to high grid-penetration of PV.

Nine photovoltaic (PV) arrays are currently being used at the Distributed Energy Test Laboratory (DETL) at Sandia National Laboratories (SNL) primarily for outdoor test and characterization of inverters for PV installations. These arrays are used to stress the inverters and expose inverters to real-world power conditions. The arrays can be configured in multiple ways to achieve various current, voltage and power levels for inverter testing. See Figure 1. This test capability also provides an excellent testbed for long-term module and array exposure and reliability studies in the Albuquerque, NM climate.

Figure 1 Photo of six silicon-based PV arrays at Sandia's DETL

The first array was installed in 2002. A second array was installed in 2004. Four more arrays were installed in the summer of 2005, two arrays were installed in 2006, and most recently, a 50 kW array was installed in late 2008. Table 1 outlines the arrays by technology, nominal power, and year of installation. All except System #7 are flat-plate arrays installed at latitude tilt with minimal shadowing from obstructions. System #7 is a flat roof-mounted system. The modules in System #1 are known to degrade quickly, and therefore losses were not analyzed in depth. In addition, this module type is no longer sold and little is gained from further analysis. The arrays in use generate 93 kW of PV for use in inverter testing. The arrays will be discussed generically and the numbering scheme is chronological by year of installation.

As stated, these arrays provide a testbed for module degradation and reliability within a grid-tied system. Staff at the Photovoltaic System Evaluation Laboratory (PSEL) at SNL performed an outdoor DC performance test on each array in its installed configuration soon after installation. The arrays were retested in October 2008 when the most recent array was installed. This paper outlines the methodology used to test the arrays, outlines analysis techniques used to evaluate the array performance, provides a current reliability assessment, and presents the comparative data for up to five years of use and exposure in Albuquerque, NM.

Table 1: DETL Array Field Overview

Array #	Tech.	Strings	Modules /Str	Instl. Date	Name Plate Rating (kW)
1	a-Si	70	1	2002	3.06
2	c-Si	4	20	2004	6.00
3	mc-Si	4	22	2005	7.04
4	mc-Si	4	22	2005	7.04
5	c-Si	6	7	2005	9.31
6	c-Si	3	28	2005	7.04
7	a-Si	3	2	2006	3.26
8	c-Si	3	21	2006	7.92
9	c-Si	24	12	2008	50.50

TEST METHODOLOGY

Two or three modules from each array were subjected to full outdoor electrical performance measurements on a PSEL tracker, including thermal response and off-angle measurements, prior to installation. These modules were then analyzed according to the Sandia Photovoltaic Performance Model [4]. DC outdoor testing of the arrays was performed using a Daystar curve-tracer after disconnecting the arrays from the inverters. Thermocouples were placed on the backside of two modules in each array. Current-voltage (I-V) curves plus temperature and irradiance measurements were recorded approximately every 2 minutes over a mostly clear sky day. The arrays were measured during spring or autumn when solar incident angles would be less than 50 degrees during an air mass (AMa) of 1.5. Expected air mass is determined according to the method outlined in reference [5]. Two existing crystalline silicon reference cells in the array field mounted in the plane of array configuration were used to determine irradiance. One was cleaned and the other was read without cleaning to estimate power loss due to array soiling since the arrays were not cleaned prior to field testing. Figure 2 plots the ratio of the calculated illumination from the two reference cells.

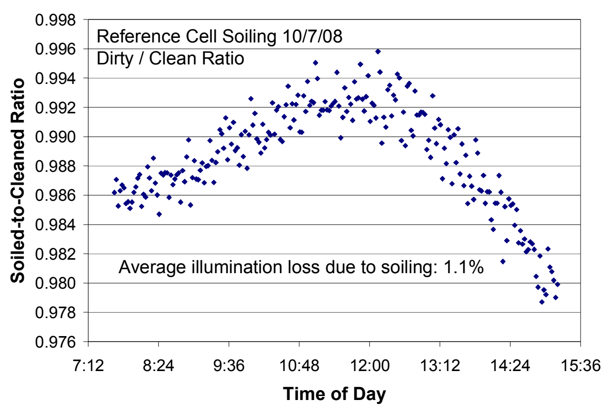

Figure 2 Effect of soiling on arrays

The shape of the curve demonstrates the increased loss at high air mass values early in the day and late in the day for the soiled reference cell due to increased scattering. The average illumination loss due to soiling is 1.1%.

Figure 3 plots the calculated illumination based on the response from the cleaned reference cell and an average module temperature. The average weather data recorded at the neighboring PSEL was occasionally used to corroborate the analyses. Based on the accuracy of the Daystar, thermocouple data logger, and reference cell degradation of ~0.1%/year, the estimated measurement error is +/- 2.5%.

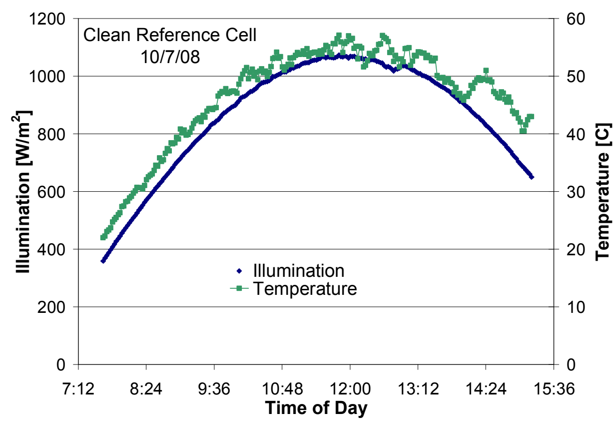

Figure 3 Illumination and module temperature during October 2008 testing

ARRAY DATA COMPARISON

Data were taken at ambient conditions and the results were translated to Standard Reporting Conditions (SRC) [6] using the Sandia PV Performance Model and the temperature coefficients measured in the initial module test. The average loss due to soiling was included in the translation. Table 2 summarizes the performance parameters at SRC and the change from the original measurement for all arrays. Since the arrays were not tested yearly, the calculated degradation was averaged over the time between measurements. An accepted degradation rate for c-Si and mc-Si modules is 0.5-1% in power per year [1-3].

Amorphous-Si System #7

The a-Si system #7 was not tested upon installation. It was tested for the first time in October 2008. After 2.5 years in the field, it has reached the name plate values to within measurement error. The stabilization of a-Si is expected within the first year, and therefore no additional degradation is being observed in the early years for this system. Note that the data have not been normalized for the expected seasonal variations for a-Si.

Systems #2, #4 and #6

System #2 is the oldest of the crystalline silicon systems, and was installed in mid 2004. This system has demonstrated consistent performance over nearly five

Table 2: Array performance data and % change from initial measurement before troubleshooting

Array	Test Date	Isc [A]	Imp [A]	Voc [V]	Vmp [V]	Pmp [W]	FF
System #2 c-Si, 5.42 kW 80 modules	6/16/2004	17.91	15.77	431	342	5401	0.70
	8/3/2005	18.24	16.23	428	337	5469	0.70
	% diff	+1.9	+2.9	-0.5	-1.6	+1.3	-0.1
	10/9/2008	18.28	16.01	427	335	5363	0.69
	% diff	+2.1	+1.5	-0.9	-2.1	-0.7	-1.8
	%/year	*+0.5*	*+0.4*	*-0.2*	*-0.5*	*-0.2*	*-0.4*
System #3 mc-Si, 6.87 kW 88 modules	9/26/2005	19.01	17.66	475	373	6593	0.73
	10/16/2008	14.33	13.27	464	370	4907	0.74
	% diff	-24.6	-24.9	-2.2	-1.0	-25.6	+1.0
	%/year	*-8.0*	*-8.1*	*-0.7*	*-0.3*	*-8.3*	*+0.3*
System #4 mc-Si, 7.00 kW 88 modules	10/3/2005	19.17	16.82	468	355	5974	0.67
	10/7/2008	18.80	16.52	473	357	5904	0.66
	% diff	-1.9	-1.8	+0.9	+0.6	-1.2	-0.1
	%/year	*-0.6*	*-0.6*	*+0.3*	*+0.2*	*-0.4*	*-0.0*
System #5 c-Si, 7.99 kW 42 modules	9/26/2005	22.49	20.19	479	382	7709	0.72
	10/27/2008	18.61	16.81	478	381	6397	0.72
	% diff	-17.2	-16.7	-0.2	-0.3	-17.0	+0.6
	%/year	*-5.6*	*-5.4*	*-0.1*	*-0.1*	*-5.5*	*+0.2*
System #6 c-Si, 6.93 kW 84 modules	10/5/2005	14.34	13.14	608	479	6292	0.72
	10/7/2008	14.29	12.88	607	468	6024	0.69
	% diff	-0.3	-2.0	-0.1	-2.3	-4.3	-3.8
	%/year	*-0.1*	*-0.7*	*-0.0*	*-0.8*	*-1.4*	*-1.3*
System #7 a-Si, 3.26 kW 6 modules	8/15/2006*	15.30	12.39	369	264	3264	0.58
	10/6/2008	14.91	12.43	365	265	3293	0.61
	% diff	-2.6	+0.4	-1.0	+0.3	+0.9	+4.3
	%/year	*-1.2*	*+0.2*	*-0.5*	*+0.1*	*+0.4*	*+2.0*
System #8 c-Si, 5.69 kW 63 modules	11/20/2006	17.20	15.67	444	359	5630	0.74
	10/15/2008	17.01	14.14	446	371	5240	0.69
	% diff	-1.1	-9.8	+0.4	+3.3	-6.9	-6.2
	%/year	*-0.5*	*-4.9*	*+0.2*	*+1.6*	*-3.5*	*-3.1*

* Name plate rating (array not tested)

years in the field, with no measurable change in parameters.

Likewise, Systems #4 and #6, both installed in October 2005, are showing little to no degradation within measurement error.

System #3, mc-Si, 6.87 kW

The losses in this system stood out immediately with 25% drop in power over a three year period. The investigation into the possible reasons for this loss began immediately upon data analysis.

Step 1: Visual inspection

A visual inspection of the system including each module, the interconnections, junction boxes, DC disconnect, and mechanical supports showed no obvious reasons for this loss. There were no cracked modules, no extensive discoloration of the glass or EVA, no disconnected or gnawed wires, and no missing junction box enclosures. This system appeared to be in excellent condition visually.

Step 2: Check the fuses and interconnects

System #3 is connected in four strings of 22 modules each; a 25% power loss could indicate the loss of one string. Each string is fed into a disconnect box with a fuse prior to tying into the array-level inverter. The fuse prevents over-current states in the string from tripping the inverter. The arrays were disconnected from the inverter and the fuse continuity was checked. All four fuses were in tact.

Similarly, the interconnect continuity was checked, and no connectors were loose or broken.

Step 3: Infrared imaging

A portable infrared camera is a valuable tool when diagnosing module losses. Infrared (IR) images were taken of the modules in pairs. Figure 4 is an example of the IR images from well-behaved modules in the center of the array. Using the scale from the IR images, the modules across this system were operating at a temperature of 32°C on average.

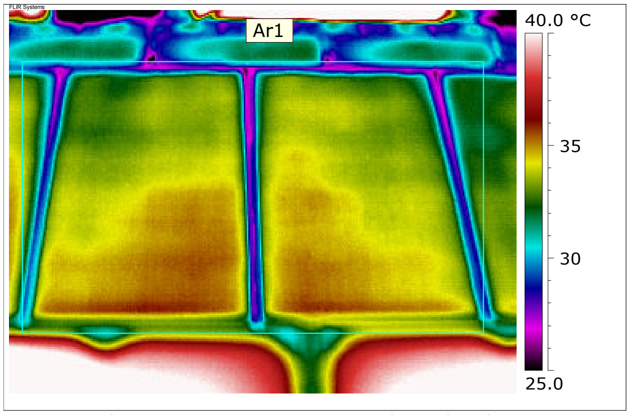

Figure 4 Sample IR images in the field for System #3

IR images can also demonstrate hot spots, open circuits in a string within a module, hot junction boxes, or non uniformities across a module. Figure 5 demonstrates two of these issues: a hot junction box on the top right and possible mismatch of two strings on the left module, observed as running cool.

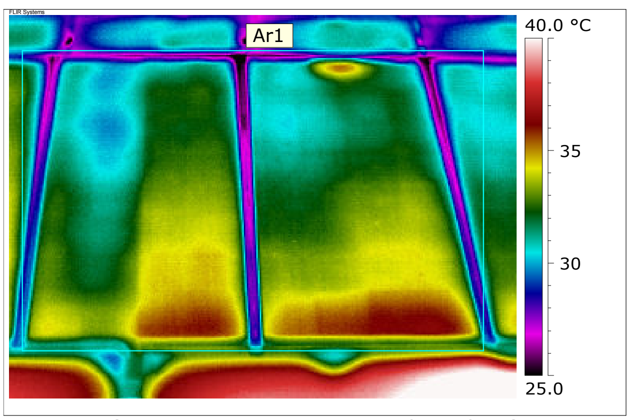

Figure 5 Sample IR images in the field for System #3 with issues observed; module on the left demonstrated intermittent response in IV check

Step 4: Voc check module by module

Following the IR images, the Voc was measured for each module. All the modules were disconnected from one another and individually tested with a handheld meter to check Voc. When no obvious issues were found in Voc, the Daystar was used to scan curve traces on each module. During this process, module number 51 of 88 was found to be intermittent. The curve traces on the 87 other modules were as expected. Module 51, shown in Figure 5 on the left, was removed from the string and replaced with a module of similar vintage from storage. The system was then retested with the Daystar; the performance parameters were within measurement error of the original performance measurement.

Step 5: Investigate "bad" module

The next step in the troubleshooting process is to understand what went wrong with this module. Figure 6 shows select power measurements as a function of time during a day-long performance test on Sandia's two-axis tracker. A companion module from the same array was measured for comparison. The power drop-outs occurred throughout the day, and did not correlate with insolation level or module temperature. When the module was responding, the performance was similar to the companion module (not shown).

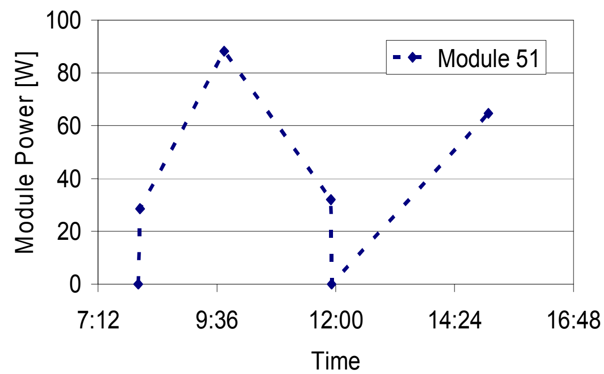

Figure 6 Power versus time for the intermittent module during day-long test on tracker

Dark IV curves were also measured on the intermittent module and analyzed [7]. A companion module from the same array was measured for comparison. See Figure 7. Module 51 demonstrated intermittency during dark IV measurements as well as during outdoor performance measurements, as observed in the dashed curve in Figure 7. However, the calculated module resistance values are similar between the modules, suggesting the problem is not in the solar cell material. It was possible to induce the intermittency by manipulating the pigtails, suggesting the failure mechanism is in the attachment of the pigtail to the circuit.

The remaining steps to prove this hypothesis include using non-destructive imaging techniques of the module to look for damage, and then finally to take the junction box apart. This process is currently underway.

Systems #5 and #8, c-Si

System #5 demonstrated a 17% loss in power, which corresponds to 1/6 of the power, or a likely drop out of one of the six strings. Steps 1-4 described above were also followed for this array, with no obvious single module standing out. At that point, the string connectors were checked, and the last of the six strings had been connected in reverse polarity following earlier maintenance. A retest after connecting the string correctly demonstrated the array was performing with no degradation to within measurement error.

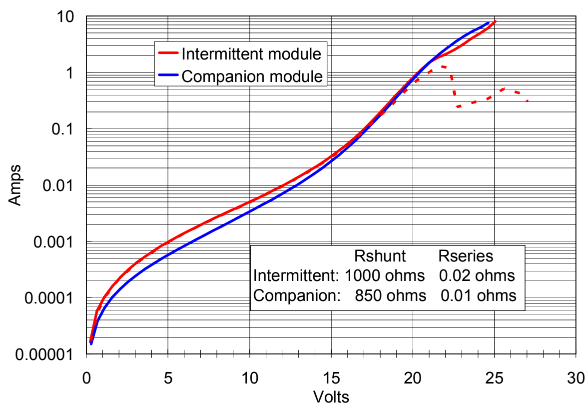

Figure 7 Dark IV and diode parameters for modules from System #3

System #8 after the first DC test in October 2008 showed 34% drop in power. A quick look at this array showed it had been placed on an inverter of the wrong polarity. Note that this technology requires a positive-ground inverter or it degrades, although it can recover. After one week on the correct inverter, the performance improved, but still demonstrated 6.9% loss in power from the installation data. The array was kept on the correct inverter and retested along with System #3 in February 2009, by which time the power had recovered to within measurement error of the installation level.

The array-level power losses for Systems #5 and #8 demonstrate how balance-of-systems losses can affect the output when a string is inadvertently rewired incorrectly or the wrong inverter is used for the system. In these cases, the arrays are being used primarily to stress the inverters, and therefore the strings are often reconfigured and inverters swapped out, increasing the likelihood of this mode of power loss.

Table 3 summarizes the performance characteristics of Systems #3, #5 and #8 after trouble-shooting and retesting the arrays.

RELIABILITY ASSESSMENT

The fielded arrays have been examined for reliability issues and/or potential for failure. Given the differences in age, technologies (a-Si, c-Si, and mc-Si), performance data and manufacturer, some issues directly tied to long-term reliability were expected. Of the reliability issues discovered, some are easily classified as failures, others may be considered failures based on aesthetics, and some are indicators of likely premature failure (before warranty is up). The following are issues observed in modules in these arrays that contribute to reduced reliability:

1. Performance loss >1% per year (System 6)
2. Encapsulant/backsheet discoloration (2 c-Si technologies)
3. Burn marks/arcing (2 c-Si technologies)
4. Backsheet delamination visible under visual inspection
5. Hot spots seen in IR images
6. Broken glass
7. Breakdown in polymer outer sheet
8. Corrosion of interconnect regions
9. Module interconnect intermittency

Manufacturers recognize these degradation modes and have taken steps to engineer out these problems. Without delving into the specific manufacturers and their processes it is difficult to understand whether these issues will continue to occur. In general, it appears that these systems have experienced more problems than would generally be expected.

NEXT STEPS

The next steps in assessing the observed and continued degradation of these systems include: 1) additional failure analysis of module 51 from System #3; 2) on-going yearly DC array measurements and trouble-shooting to document system-level degradation rates and to follow potential reliability issues; 3) investigate the AC data to look for patterns and early indicators of degradation; 4) remeasure modules from each system on the 2-axis tracker to document any module-level degradation; 5) further investigation of System #6, the only system to show degradation beyond measurement error.

SUMMARY

Of the seven arrays analyzed in detail, only System #6 showed true power degradation beyond experimental error at 4.3%±2.5%, averaging 1.4%±0.8% per year. In all other cases, the degradation rate was less than the experimental error.

The lessons learned from this study are that proper commissioning is essential to detect installation errors, and acceptance testing should also be performed following any maintenance work. Such acceptance testing and checking against the expected array output would have quickly caught the loss mechanisms for Systems #5 and #8.

Sufficiently sensitive monitoring at the string level might have detected the presence of a failed module through detecting string-level degradation. Peer to peer (string to string) monitoring at the string level would have certainly detected the specific string-level degradation due to the failed module. However, only module-level monitoring would automatically determine which module had failed.

Table 3: Array performance data and % change from initial measurement after troubleshooting

Array	Test Date	Isc [A]	Imp [A]	Voc [V]	Vmp [V]	Pmp [W]	FF
System #3 mc-Si, 6.87 kW 88 modules	9/26/2005	19.01	17.66	475	373	6593	0.73
	10/16/2008	14.33	13.27	464	370	4907	0.74
	% diff	-24.6	-24.9	-2.2	-1.0	-25.6	+1.0
	%/year	*-8.0*	*-8.1*	*-0.7*	*-0.3*	*-8.3*	*+0.3*
Retest after module replacement	2/27/2009	**19.13**	**17.71**	**481**	**380**	**6728**	**0.73**
	% diff	**+0.6**	**+0.3**	**+1.4**	**+1.8**	**+2.0**	**+0.0**
	%/year	***+0.2***	***+0.1***	***+0.5***	***+0.6***	***+0.7***	***+0.0***
System #5 mc-Si, 7.99 kW 42 modules	9/26/2005	22.49	20.19	479	382	7709	0.72
	10/27/2008	18.61	16.81	478	381	6397	0.72
	% diff	-17.2	-16.7	-0.2	-0.3	-17.0	+0.6
	%/year	*-5.6*	*-5.4*	*-0.1*	*-0.1*	*-5.5*	*+0.2*
Retest after string polarity change	3/24/2009	**22.35**	**20.20**	**481**	**381**	**7689**	**0.72**
	% diff	**-0.6**	**+0.0**	**+0.3**	**-0.3**	**-0.3**	**+0.1**
	%/year	***-0.2***	***+0.0***	***+0.1***	***-0.1***	***-0.1***	***+0.0***
System #8 c-Si, 5.69 kW 63 modules	11/20/2006	17.20	15.67	444	359	5630	0.74
	10/15/2008	17.01	14.14	446	371	5240	0.69
	% diff	-1.1	-9.8	+0.4	+3.3	-6.9	-6.2
	%/year	*-0.5*	*-4.9*	*+0.2*	*+1.6*	*-3.5*	*-3.1*
Retest after inverter change	2/26/2009	**16.57**	**15.09**	**451**	**364**	**5491**	**0.74**
	% diff	**-3.7**	**-3.7**	**+1.6**	**+1.2**	**-2.5**	**-0.3**
	%/year	***-1.8***	***-1.8***	***+0.8***	***+0.6***	***-1.2***	***-0.1***

Further analysis will continue to assess the degradation mechanism for System #6, as well as to look for patterns in the AC data which could be used to detect issues at either the module level or due to balance-of-systems losses as they occur. Annual or bi-annual DC testing will be performed on each of these systems to continue monitoring any long term degradation and to follow the progression of noted reliability concerns.

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REFERENCES

1. M.G. Thomas et al., "A Ten-Year Review of Photovoltaic Systems," *Proc. NREL Performance and Reliability Workshop,* NREUCP-411-7414,1994 pp 279-285.

2. D.L. King, M.A. Puintana. J.A. Kratochvil, DE. Ellibee, and B.R. Hansen, "Photovoltaic Module Performance and Durability Following Long-Term Field Exposure," *Progress in Photovoltaics Research and Applications,* July-August 2000. pp. 241-256

3. C.R. Osterwald. A. Anderberg. S Rummel. and L Onoson, "Degradation Analysis of Weathered Crystalline-Silicon PV Modules," *Proc. 29th IEEE PVSC*, New Orleans, 2002.

4. D. L. King et al., "Photovoltaic Array Performance Model," Sandia internal document SAND 2004-3535.

5. F. Kasten and A. T. Young, "Revised Optical Air Mass Tables and Approximation Formula," *Applied Optics,* Vol. 28, Issue 22, 1989.

6. ASTM E 1036, "Testing Electrical Performance of Nonconcentrator Photovoltaic Modules and Arrays Using Reference Cells."

7. D. L. King et al., "Dark Current-Voltage Measurements on Photovoltaic Modules as a Diagnostic or Manufacturing Tool," *Proc. 26th IEEE PVSC*, Anaheim, CA, 1997.