SUCCESSFUL TRANSFER OF SANDIA NATIONAL LABORATORIES' OUTDOOR TEST TECHNOLOGY TO TÜV RHEINLAND PHOTOVOLTAIC TESTING LABORATORY

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ABSTRACT

Sandia National Laboratories (Sandia) has observed an increased demand for high accuracy outdoor photovoltaic (PV) module characterization using Sandia's Photovoltaic Array Performance Model [1]. To meet this demand, Sandia entered into a competitively-bid agreement in May 2009 with TÜV Rheinland Photovoltaic Testing Laboratory (TÜV-PTL) to transfer Sandia's capability to fully characterize standard, commercial-scale PV modules. Sandia and TÜV-PTL worked closely on two round-robin experiments and months of subsequent work and discussions that resulted in module performance output calculations agreeing to within +/-2.5%.

INTRODUCTION

Designers and users need to understand performance characteristics of photovoltaic cells and modules under standard test conditions as well as various environmental conditions. Sandia has more than 20 years of experience characterizing module performance outdoors and has developed a method for modeling the output of modules under any climate condition [1]. Sandia publishes module parameters translated to Standard Reporting Conditions (SRC) and module modeling coefficients. This data set is currently being used in the Systems Advisor Model [2], Maui Solar PV Design Pro [3], and other photovoltaic systems design applications.

Demand has grown significantly in the last five years for module characterization and calculation of accompanying modeling coefficients by Sandia's Photovoltaic Systems Evaluation Laboratory (PSEL). The demand has come from start-up companies developing thin-film technologies and concentrating PV as well as from module manufacturers and integrators interested in characterizing established technologies such as crystalline silicon. To meet the demand, PSEL in conjunction with Department of Energy's Solar Energy Technologies Program (DOE SETP) transferred its outdoor PV module testing and characterization technology to the commercial test lab, TÜV-PTL. This will permit characterization of existing technologies, allow Sandia to focus on characterization of emerging technologies, and provide a U.S.-based test facility with a new business opportunity.

This paper documents the requirements, test methods, and results of Sandia's and TÜV-PTL's tests, which demonstrate that TUV-PTL is capable of testing, characterizing and modeling PV modules in accordance with Sandia's requirements.

METHOD

Contract Award

In May of 2009, Sandia selected TÜV-PTL out of four bidders based on the following criteria:

- Site and solar resource: Company has site that reaches Air Mass 1.5 at least 300 days per year
- Personnel: Company has specialists who are experienced in high-accuracy metrology and data analysis techniques
- Software: Company utilizes software capable of analyzing voltage-current (IV) curves on modules and calculating the modeling coefficients
- Hardware: Company employs two-axis tracker with +/-2° precision in elevation and azimuth; curve-sweeping capability for modules up to 400 Wp; thermal assessment; appropriate metrology station
- Business Plan: Company has a value proposition for DOE's investment that ensures the test method can be implemented and is self-sustaining at the end of the contract
- Project Management: Company ensures timely and efficient implementation of the contract

TÜV-PTL was selected from four bidders. The lab, formerly Arizona State University Photovoltaic Testing Laboratory, is an ISO 17025 accredited testing laboratory since 1997. TÜV-PTL's test site in Tempe, Arizona is ideally suited for PV testing per the Sandia method with more than 300 clear sky sunny days and a daily average insolation between 6.3 kWh/m^2 (winter) and 11.6 kWh/m^2 (summer) on a 2-axis tracker.

Round-Robin 1 (RR1): Instrumentation and Test Reproducibility

The first requirement of the contract was to ensure TÜV-PTL could accurately test modules according to Sandia's test methods. Sandia and TÜV-PTL chose and tested the following three modules at each lab for comparison:

- A triple-junction amorphous silicon module (SNL1660)
- A polycrystalline-Si module (SNL2490)
- A monocrystalline-Si module (SNL2491)

The modules were tested at Sandia in June and July, 2009 and at TÜV-PTL in October and November, 2009.

Testing at each laboratory included:

- Thermal testing: IV sweeps were taken over a 30- to 60-minute period as each module heated up during clear, stable sky conditions. Module temperature and irradiance were measured simultaneously and module temperature coefficients were calculated from these data sets
- At least one full day of clear sky testing: IV sweeps taken for a full day while simultaneously measuring module temperature and irradiance; full Air Mass range expected. Analysis included module performance parameters translated to standard reporting conditions and initial irradiance coefficients calculated
- At least a half-day of cloudy sky conditions: IV sweeps, module temperature and irradiance data were measured simultaneously; low irradiance data are used to refine the calculation of the irradiance coefficients and the diode factor

Sandia's Effort

Sandia personnel conducted multiple rounds of day-long performance measurements on the three modules using calibrated equipment. Each module was tested over an eight- to 10-day period, collecting more than 5,000 IV curves during clear and cloudy sky conditions. Individual modules were tested on different days. Sandia used its curve tracing system based on Agilent equipment. Each module was mounted on a 2-axis tracker and three thermocouples were attached to the back of the module with tape. Sandia used a four-point probe technique for the IV curves, sweeping from short-circuit current to open-circuit voltage every minute from sunrise to sunset. Each sweep took approximately 10 seconds and the module was held at maximum power between IV curves. Sandia measured module temperatures and plane-of-array irradiance simultaneously using a calibrated silicon reference cell and an Eppley PSP. Ambient temperature, wind speed and direction, direct normal irradiance, global horizontal irradiance, and global diffuse irradiance were measured every three seconds on Sandia's weather station located approximately 20 yards from the tracker. Figure 1 shows Sandia's weather station and Figure 2 shows Sandia's primary dual-axis tracker.

Thermal testing was performed under clear, stable sky conditions, typically within two hours of solar noon. The front of the module under test was covered and the module temperature is monitored until it reaches a stable temperature near ambient. The module was then uncovered and IV curves were swept every 10 to 20 seconds with simultaneous module temperature and irradiance measurements recorded until the module reached a stable temperature, typically resulting in 200 to 300 IV curves.

Fig. 1. Weather station at Sandia's PSEL

Fig. 2. Dual-axis tracker at Sandia's PSEL

Sandia's measurement uncertainty in maximum power is +/- 2.5% due primarily to uncertainty in the irradiance measurements.

TÜV-PTL's effort

TÜV-PTL personnel conducted two rounds of daylong performance measurements on the Sandia-supplied PV modules in accordance with Sandia's procedures and guidance using calibrated equipment. First-round measurements included sequential current-voltage (I-V) scans using a DayStar DS-100 curve tracer with multiple modules mounted on a 2-axis tracker and simultaneous measurements of solar irradiance — using reference cell and Eppley PSP — and module temperature in two locations. These daylong tests were performed on multiple days for each module to demonstrate the repeatability of the procedure. TÜV-PTL used a multiplex relay switch, controlled by a data acquisition system (DAS) to switch connections from one module to the next with the DS-100 tracer. As shown in Figure 3, TÜV-PTL used four-probe connections from the multiplexer to the Daystar and two-probe connections from the module to the multiplexer. The curves were collected continuously from sunrise to sunset every six minutes, leading to more than 100 curves per day per module.

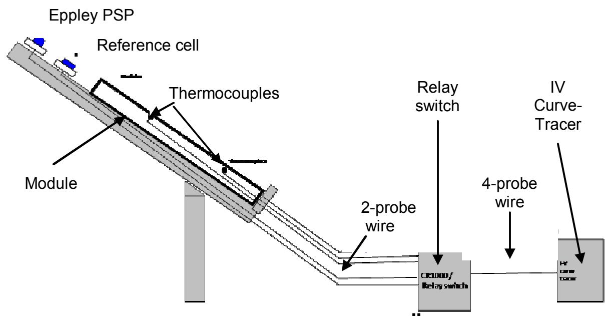

Fig. 3. Round Robin 1 Test Setup at TÜV-PTL

Table 1 provides results of the calculated module-scale temperature coefficients including Voc, Vmp, Isc and Imp and performance parameters at SRC (1000 W/m^2, 25°C, AMa 1.5). The temperature coefficients for the currents are normalized to the current values at SRC. Note that the values at SRC are calculated using the temperature coefficients. Any differences observed in these values will affect the comparisons at SRC. The percent difference is calculated using the Sandia value as the baseline.

The variation observed in the thermal characterization and in Imp and FF led to improvements in the test methods used at both locations. At Sandia, the thermal test method was improved by adding insulation to the back of modules during testing to maintain an even temperature distribution and expand the thermal range. For better measurement accuracy at TÜV-PTL, the round 2 test setup was improved and the measurements carried out with two-minute intervals using a Daystar DS3200 multi-curve tracer with four-probe connection (as opposed to two-probe connection in round 1) and three thermocouples (as opposed to two thermocouples in round 1). The temperature coefficients of the modules were obtained by cooling the module down below 20^{o}C and collecting ten I-V curves as the module warmed up uniformly under sunlight. The upper limit of module temperature was increased to more than 70^{o}C using an insulating pad on the backside of the test module. The temperature coefficients were determined through linear regression.

One item to note is the percent differences observed in αIsc and αImp. Although these differences appear large, they are actually differences in very small numbers and are statistically insignificant. The calculated values for αIsc and αImp from both labs fall within the historical range of calculated values for more than 50 measured crystalline silicon modules [4]. The voltage temperature coefficient plays the primary role in power changes with temperature, and uncertainty in βVmp has a greater impact on energy predictions than does αImp by nearly a factor of two [4].

The results of Round-Robin 1 provided good feedback for test method improvements and provided high confidence that the results of testing at both labs would overlap to within measurement error.

Table 1 Results of Round Robin 1

ID #	Area (m^2)	Site	βVoc (V/°C)	βVmp (V/°C)	αIsc (1/°C)	αImp (1/°C)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	FF	P_{mp} (W)
1660	1.29	SNL	-0.0940	-0.0616	0.00120	0.00164	4.59	23.46	3.65	17.05	0.579	62.3
a-Si		TÜV	-0.0959	-0.0609	0.00121	0.00290	4.59	23.76	3.46	16.55	0.524	57.2
		%diff	2.0%	-1.2%	1.4%	76%	0.0%	1.3%	-5.2%	-2.9%	-9.5%	-8.2%
2490	0.65	SNL	-0.0782	-0.0809	0.00043	-0.00044	4.96	21.89	4.56	17.22	0.724	78.5
poly-Si		TÜV	-0.0829	-0.0885	0.00060	-0.00116	4.90	22.00	4.20	17.00	0.673	71.7
		%diff	6.0%	9.4%	40%	167%	-1.2%	0.5%	-7.9%	-1.3%	-7.0%	-8.7%
2491	1.29	SNL	-0.1634	-0.1701	0.00046	-0.00033	5.21	44.94	4.86	36.27	0.753	176.4
mono-Si		TÜV	-0.1687	-0.1698	0.00030	-0.00069	5.18	45.14	4.86	35.76	0.743	173.9
		%diff	3.2%	-0.2%	-33%	107%	-0.6%	0.4%	0.0%	-1.4%	-1.3%	-1.4%
	95% CL						*1.90%*	*1.00%*	*2.00%*	*1.10%*	*1.00%*	*2.30%*

Round Robin 2: Modeling Coefficient Reproducibility

The second requirement of the contract was to ensure TÜV-PTL could accurately calculate the parameters and coefficients in the Sandia PV Array Performance Model [1]. Sandia and TÜV-PTL chose the following three modules to be tested at each location for this second comparison:

- A film silicon module (SNL2202)
- A polycrystalline-Si module (SNL0007)
- A monocrystalline-Si module (SNL0012)

The modules were tested at TÜV-PTL in March, 2010 and at Sandia in April and May, 2010.

Each module was tested following the procedures in RR1 with process changes implemented for TÜV-PTL as described. Sandia performed thermal testing and calculated temperature coefficients for both an insulated and non-insulated case for all of the modules. The performance parameters agree more closely when calculated using the temperature coefficients based on the insulated case.

When measuring temperature coefficients, Sandia has historically used the average temperature from three thermocouples distributed diagonally across the back of the module to estimate the average temperature of all the cells in the module. Infrared (IR) thermal imaging of modules during the test indicated the repeatability of temperature coefficient measurements using the historic procedure (with an open back surface) is too sensitive to variable wind conditions. Insulating the back surface during the test greatly reduces cell-to-cell temperature differences, extends the temperature range, and provides more repeatable results. These results are also more consistent with expectations based on laboratory testing of individual cells. The new procedure used at TÜV/PTL with modules mounted directly to a solid surface closely mimicked an insulated back surface and represented a good approach.

Table 2 provides the results of the calculated temperature coefficients for Voc, Vmp, Isc and Imp based on the insulated case, as well as the performance parameters at SRC (1000 W/m^2, 25°C, AMa 1.5) calculated using the temperature coefficients from the insulated case.

Although the differences observed in temperature coefficients remained high, particularly for the current values, those values again fall within the historical range and the resulting SRC parameters are much closer than in RR1, particularly for Imp, Vmp, FF and Pmp. The differences in the SRC results are within the measurement uncertainties. Note that the insulated case results for the monocrystalline-Si module did not differ from the non-insulated case due to a hot cell in the module that developed between test cases. Interestingly, even with this discrepancy, the resulting parameters at SRC agree to within +/- 2%.

Table 2 Results of Round Robin 2

ID #	Area (m^2)	Site	βVoc (V/°C)	βVmp (V/°C)	αIsc (1/°C)	αImp (1/°C)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	FF	P_{mp} (W)
2202	1.45	SNL	-0.0802	-0.0664	0.00086	0.00084	5.70	23.03	4.81	17.83	0.653	85.7
a-Si		TÜV	-0.0756	-0.064	0.00061	0.00059	5.76	22.85	4.89	17.74	0.659	86.8
		%diff	-5.7%	-3.6%	-30%	-29%	1.1%	-0.8%	1.7%	-0.5%	0.9%	1.3%
0007	1.61	SNL	-0.119	-0.1206	0.00037	-0.00033	8.20	36.88	7.53	28.83	0.718	217.0
poly-Si		TÜV	-0.1155	-0.1227	0.00051	-0.00023	8.01	36.96	7.40	29.04	0.726	215.3
		%diff	-2.9%	1.7%	39%	-31%	-2.3%	0.2%	-1.7%	0.7%	1.1%	-0.8%
0012	1.28	SNL	-0.226	-0.245	0.00039	0.00018	5.09	59.30	4.55	48.30	0.728	219.7
mono-Si		TÜV	-0.187	-0.2059	0.00038	0.00004	5.02	58.63	4.53	47.52	0.732	215.3
		%diff	-17%	-16%	-3.2%	-75%	-1.4%	-1.1%	-0.4%	-1.6%	0.5%	-2.0%
	95% CL						*1.90%*	*1.00%*	*2.00%*	*1.10%*	*1.00%*	*2.30%*

Performance parameters at various irradiance, temperature, wind speed and airmass conditions were calculated based on the coefficients developed according to Sandia's PV Array Performance Model. Sandia calculated the parameters for five conditions for each of the modules using the coefficients generated by each lab. In Figure 4, the parameters for Voc, Vmp, Isc, Imp and Pmp are shown as percent changes from the mean value for 1000 W/m^2 and 75°C, 1000 W/m^2 and 50°C, 800 W/m^2 and 50°C, 500 W/m^2 and 25°C, and 200 W/m^2 and 25°C. The differences in the voltages and the currents are within +/-1% and +/-1.5% respectively, with the exception of the low irradiance condition. This is likely due to the lack of data for irradiance less than 400 W/m^2 at TÜV-PTL.

The ultimate goal of generating modeling coefficients is to predict annual energy output from a PV system using a specified PV module. Sandia used its PVMOD program to calculate annual energy for Albuquerque, NM, for each module type based on the coefficients generated by each lab. Sandia assumed a flat-plate, latitude tilt design with a default derate factor of 0.9. The annual energy calculations shown in Table 3 agree to within 2.7%.

Table 3 Comparison of annual energy yield

	Mono-Si		Poly-Si		a-Si	
	SNL	TÜV	SNL	TÜV	SNL	TÜV
SRC Rating (Wp)	220	215	217	215	85.8	86.8
%diff	-2.3%		-0.9%		1.2%	
Annual DC (kWh)	472	467	476	471	187	192
%diff	-1.1%		-1.1%		2.7%	
Annual Yield (kWh/kWp)	2147	2170	2192	2191	2179	2209
%diff	1.1%		-0.05%		1.4%	

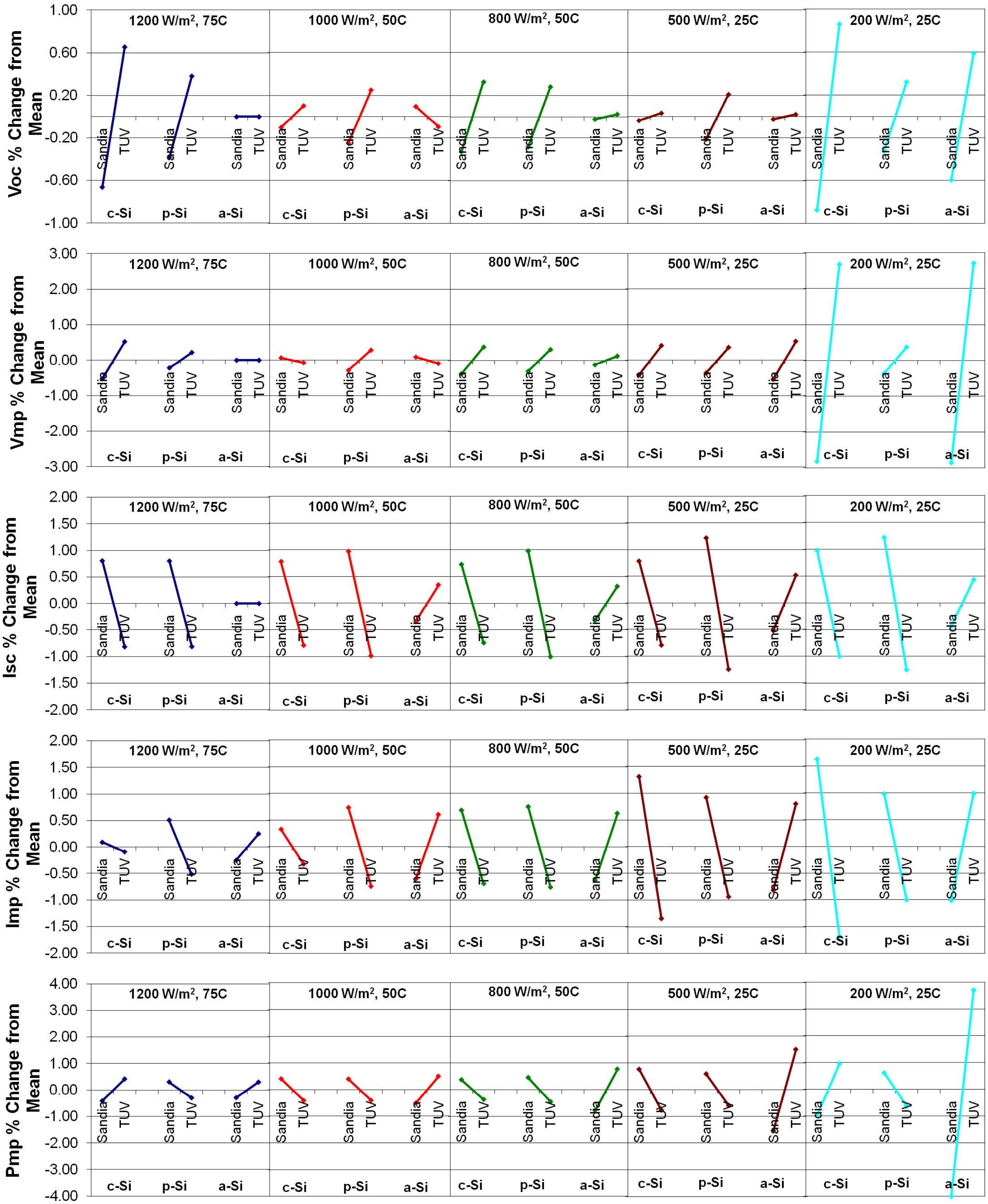

Fig. 4. Comparison of Parameters for Five Irradiance/Temperature Conditions. Top to bottom: Voc, Vmp, Isc, Imp, and Pmp.

Analysis Capability and Lessons Learned at TÜV-PTL

TÜV-PTL successfully implemented Sandia's outdoor PV module testing and characterization technology through the following steps:

- Consolidation of daylong I-V curves;
- Elimination of outliers due to inadvertent shading and other issues by charting two ratios (Imp/Isc and Vmp/Voc) and normalizing Isc for 1000 W/m^2 irradiance; and
- Incorporation of several other input parameters including temperature coefficients, module area, number of cells in series, and reference cell and PSP constants.

Sandia and TÜV-PTL determined that processed I-V data were identical using Sandia's conventional outdoor and daylong methods. Data obtained on multiple modules using the four-probe method with multi-curve tracer were determined to be more accurate than the data obtained using two-probe method with single-curve tracer. The experimental setup based on the multi-curve tracer was found to be less complicated and more accurate when a large number of modules were evaluated simultaneously. TÜV-PTL's data processing skills were greatly strengthened with added flexibility for actual airmass function rather than using a default airmass function. The day-to-day repeatability within TÜV-PTL and reproducibility between Sandia and TÜV-PTL has been established. If needed, additional low irradiance data may be obtained by using an appropriate mesh screen in front of the test module installed on 2-axis tracker or by moving the module away from the direct sun.

SUMMARY

Under guidance from the DOE SETP, Sandia successfully transferred its outdoor module test characterization and analysis technology to TÜV-PTL. Based on the results of two round-robin experiments, Sandia has high confidence in TÜV-PTL's capability to perform module testing and analyze test results according to the method detailed in the Sandia PV Array Performance Model. TÜV-PTL now offers to their customers Sandia's testing and analysis standards. Sandia continues to characterize and analyze modules of emerging technologies, expand the model, and work with other interested test facilities to transfer this technology.

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