The accurate measurement of PV module temperature is important for tasks ranging from the determination of normal operating cell temperature (as performed by testing laboratories and manufacturers) to the performance analysis of utility-scale generation plants. Module temperature is a key input to performance models and is essential for the translation of I-V curve data to standard test conditions (STC). Unfortunately, this measurement is difficult to complete with accuracy and is highly dependent on the method by which the measurement probe is attached to the module.

In this article, we present results from a series of empirical tests at the National Renewable Energy Laboratory (NREL) that focused on the method used to attach back-of-module temperature measurement devices to a simulated PV module. The results from this evaluation provide suggested best practices for system installers and operators to successfully monitor module temperatures and to understand the implications of various attachment methods.

**NEED FOR ACCURATE MEASUREMENTS**

Why do module temperature measurements matter, and why should anyone be concerned with the method of attachment? The temperature of the module—specifically, the temperature of the solar cell junction—impacts the energy production of the module. Temperature coefficients are
usually stated by module manufacturers in terms of the effect of temperature on short-circuit current ($\alpha$), open-circuit voltage ($\beta$) and power ($\gamma$), and may be listed in either absolute terms (amperes, volts or watts per °C) or relative terms (% per °C). As the parameter most applicable to system performance analysis, typical values of the relative temperature coefficients of power for various module technologies are listed in Table 1.

Translation equations provide you with a working knowledge of how a module behaves in differing thermal environments. Beyond that, they include temperature coefficients that are used to calculate a module’s electrical characteristics at an arbitrary temperature condition using data measured at a different temperature, such as at a standard reference condition. Standard translation equations are as follows:

Using absolute temperature coefficients:

\[
\begin{align*}
I_{SC,\text{corr}} &= I_{SC} + \alpha(T_2 - T_1) \\
V_{OC,\text{corr}} &= V_{OC} + \beta(T_2 - T_1) \\
P_{\text{MAX,corr}} &= P_{\text{MAX}} + \gamma(T_2 - T_1)
\end{align*}
\]

Using relative temperature coefficients:

\[
\begin{align*}
I_{SC,\text{corr}} &= I_{SC} \times [1 + \alpha(T_2 - T_1)] \\
V_{OC,\text{corr}} &= V_{OC} \times [1 + \beta(T_2 - T_1)] \\
P_{\text{MAX,corr}} &= P_{\text{MAX}} \times [1 + \gamma(T_2 - T_1)]
\end{align*}
\]

where $I_{SC}$ is the short-circuit current measured at temperature $T_1$ and $I_{SC,\text{corr}}$ is the short-circuit current translated to temperature $T_2$ (see References 1 and 2). Similar definitions apply to $V_{OC}, V_{\text{OC,corr}}, P_{\text{MAX}}$ and $P_{\text{MAX,corr}}$.

For accurate performance monitoring, modeling and assessment of warranty claims, it is important to know the module temperature coefficients and the appropriate translation of measured temperatures. System operators often use module temperature measurements, in addition to electrical and meteorological data, to commission the system and to predict the output of large-scale systems. An inaccurate measurement of module temperature, which is typically low as compared to reality, results in an overprediction of expected power output. This is due to the negative value of $\gamma$, the temperature coefficient of power, which indicates that an increase in temperature results in a decrease in power. For instance, as shown in Figure 1, a measurement that is low by 5°C may result in an overprediction of expected dc power by about 2.25%, a significant amount for large systems.

Beyond performance monitoring, module temperature may be used in degradation rate calculations for systems and modules. An erroneously low temperature measurement during the review of module I-V traces for analysis or warranty claims could trigger an unnecessary module replacement.

Temperature Coefficients

<table>
<thead>
<tr>
<th>Technology</th>
<th>TC of Power, $\gamma$ (%/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si</td>
<td>-0.45</td>
</tr>
<tr>
<td>SiC-Si</td>
<td>-0.44</td>
</tr>
<tr>
<td>a-Si (1-, 2- and 3-junction)</td>
<td>-0.24</td>
</tr>
<tr>
<td>CdTe</td>
<td>-0.29</td>
</tr>
<tr>
<td>CIGS</td>
<td>-0.47</td>
</tr>
</tbody>
</table>

Table 1 Typical relative temperature coefficients (TC) of power for various module technologies are published on manufacturer data sheets. Negative values indicate that power decreases as temperature increases.

![Normalized Parameter vs Temperature Deviation](image)

**Figure 1** This plot shows the normalized, expected outputs for a system of monocrystalline silicon modules as a function of the deviation of the back-of-module temperature from reality. A low measurement results in an overprediction of power output and Voc and an underprediction of Isc. Typical relative temperature coefficients of power, current and voltage for a monocrystalline silicon module of -0.45, 0.048 and -0.36 %/°C, respectively, are assumed.
or impact other analyses. This is because comparisons are made against module STC parameters (reported at 1,000 W/m² irradiance, AM1.5 spectrum and 25°C module temperature) that necessitate translation of the I-V curves from the measured field conditions. Temperatures that are under-reported lead to errors in calculated power when translating back to STC, potentially yielding a lower power rating.

TYPICAL ATTACHMENT METHODS
Several methods exist to measure the temperature of a module, but not all are practical for use in the field. First, an accurate measure of the average junction temperature can be obtained by measuring the open-circuit voltage of a fielded reference module. This method requires knowledge of the open-circuit voltage thermal coefficients of the cells within the module. It is arguably the most reliable method, because it represents the average junction temperature across a whole module as compared to other methods that rely on discrete measurement locations. Also, a temperature probe can be installed on the back surface of a cell prior to module encapsulation. Finally, a measurement taken on the back surface of the module can act as a proxy for the cell junction temperature. Other quantitative methods, such as the use of infrared thermography, are relegated mostly to laboratory settings and rarely make it into the field for long-term monitoring.

Unfortunately, commercially available modules generally do not offer the capability to measure the junction temperature using built-in measurement devices, and the use of fielded reference modules maintained at $V_{oc}$ is not common. The vast majority of applications require the attachment of a measurement device to the backsheet or substrate of the module. It is important to note that module backsheet measurements are generally lower than the actual junction temperature. This is because of the insulating properties of the encapsulant, which is often EVA, and the backsheet, often composed of multilayer polyesters. Researchers studying module nominal operating cell temperatures (NOCT) have calculated a temperature drop of between 1° and 2°C between the junction and the substrate (see Reference 3).

We conducted a survey of utility- and commercial-scale system installers and operators to gain insight into some of the typical methods for attaching temperature measurement probes to the backs of modules. Common methods include the use of beaded or thin-film thermocouples attached with polyimide or polyester tape, or a quick-setting adhesive such as epoxy or silicone. When installers were asked if they followed specific attachment procedures, including surface preparation, the general consensus was “no,” which became the impetus for this work. In the case of polyimide tape, the quality of the attachment can significantly degrade after only a few years of field exposure. Epoxies continued on page 94
can embrittle due to UV exposure, and silicones can detach if the attachment surface is not adequately cleaned.

Poor attachment at the beginning of monitoring, such as during commissioning, may result in a lower power rating. However, poor surface preparation coupled with a less-than-ideal attachment method can pose longer-term problems, including drift and range spread. Drift becomes a concern when analyses that use present-day measurements are compared against historical measurements or analyses. The performance of a system may be viewed as excessively degraded when in reality the apparent degradation is caused by an attachment-induced measurement drift. In addition to drift, range spread may be seen in analyses as inconsistent results. This is due to the increased influence of wind and local environmental parameters on measurement devices with poor thermal contact to the module backsheet.

In an ideal circumstance, heat is primarily conducted from the module to the measurement device. The two other heat transfer mechanisms that have an influence on the measurement—radiation and convection—are significantly outweighed by conduction. However, when the sensor is in poor thermal contact with the module, conduction is inhibited and convective cooling becomes significant. This results in a spread in the range of measurements. Even lower apparent temperatures are recorded when wind velocities increase. In addition, the presence of insulation around the sensor and/or a difference in the emissivity of the sensor and the module can change the module temperature. In that case, the sensor may give an accurate measurement of the actual localized temperature of that module, but it does not represent the average temperature of modules that do not have the sensor applied. (These effects are beyond the scope of this article.)

**PROBE ATTACHMENT TESTS AT NREL**

The focus of this test series was to review attachment methods, not to evaluate the use of different sensor technologies such as thermocouples, thermistors and resistance temperature detection. For this work, we used only type-T thermocouples.

To determine if common attachment methods are adequate for the measurement of back-of-module temperatures, an 18-by-18-by-0.5-inch aluminum plate was prepared with a black anodized front surface and an EVA/polyester lamination on the rear surface. We used type-T thermocouple probes, installed at half of the plate thickness on all four sides, to determine the average bulk-plate temperature throughout the study. The plate was thermally isolated from the mounting frame during testing. The completed test setup was mounted at 180° azimuth with a 40° tilt angle (see photo on p. 90).

Two rounds of tests were conducted, accounting for a total of 20 different attachment/thermocouple combinations. Three attachments from Round 1 were continued in Round 2. The details of both rounds continued on page 100.
### Temperature Measurement Methods

#### Table 2: Round 1 Test Results

<table>
<thead>
<tr>
<th>Position</th>
<th>Details</th>
<th>R/P*</th>
<th>Distribution 750–1,050 W/m² (ºC)</th>
<th>$\Delta T_{sensor}$ (ºC)</th>
<th>$\sigma_{\Delta T_{sensor}}$ (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Thin-film thermocouple, type-T; thin silicone adhesive with round polyester tape overlay</td>
<td>R</td>
<td><img src="image1" alt="Histogram" /></td>
<td>-1.18</td>
<td>0.47</td>
</tr>
<tr>
<td>B1</td>
<td>Twisted and soldered thermocouple, type-T; silicone adhesive with tip of thermocouple pressed against backsheet during cure</td>
<td>R</td>
<td><img src="image2" alt="Histogram" /></td>
<td>-2.63</td>
<td>0.67</td>
</tr>
</tbody>
</table>
| B2       | Twisted and soldered thermocouple, type-T; silicone adhesive with tip of thermocouple pressed against backsheet during cure*  
*Intentional 80% delamination from backsheet after cure | R    | ![Histogram](image3)            | -5.90                    | 1.52                             |
| B3       | Twisted and soldered thermocouple, type-T; two-part unfilled epoxy adhesive with tip of thermocouple pressed against backsheet during cure (cure time ~5 minutes) | P    | ![Histogram](image4)            | -2.33                    | 0.81                             |
| C        | Thin-film thermocouple, type-T; round polyester tape overlay attachment with no adhesive | R    | ![Histogram](image5)            | -1.16                    | 0.54                             |
| D        | Thin-film thermocouple, type-T; thin silicone adhesive with no additional overlay | R    | ![Histogram](image6)            | -1.13                    | 0.48                             |
| E        | Thin-film thermocouple, type-T; thick silicone adhesive (~4 mm) with no additional overlay | R    | ![Histogram](image7)            | -2.47                    | 0.70                             |
| F        | Thin-film thermocouple, type-T; round polyester tape overlay attachment with thermal compound | R    | ![Histogram](image8)            | -1.87                    | 0.63                             |
| G        | Thin-film thermocouple, type-T; thin silicone adhesive with thick (~4 mm) silicone overlay | R    | ![Histogram](image9)            | -1.06                    | 0.39                             |
| H        | Thin-film thermocouple, type-T; thin, two-part thermally conductive epoxy adhesive with no overlay (cure time ~48 hours) | P    | ![Histogram](image10)           | -0.64                    | 0.30                             |
| I        | Thin-film thermocouple, type-T; 0.85 mm closed-cell foam tape overlay with no adhesive | R    | ![Histogram](image11)           | -1.46                    | 0.39                             |

* R= removable attachment method; P= permanent attachment method
### Temperature Measurement Methods

#### Table 3: Round 2 Test Results

<table>
<thead>
<tr>
<th>Position</th>
<th>Details</th>
<th>R/P*</th>
<th>Distribution 750–1,050 W/m² (ºC)</th>
<th>( \Delta T_{\text{sensor}} ) (ºC)</th>
<th>( \sigma_{\Delta T_{\text{sensor}}} ) (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>Thin-film thermocouple, type-T; moderate-thickness silicone adhesive with no overlay</td>
<td>R</td>
<td><img src="chart1" alt="Graph" /></td>
<td>-1.41</td>
<td>0.55</td>
</tr>
<tr>
<td>K1</td>
<td>Twisted and soldered thermocouple, type-T; steel-filled, two-part semi-solid epoxy with tip of thermocouple pressed against backsheet during cure (cure time ~15 minutes)</td>
<td>P</td>
<td><img src="chart2" alt="Graph" /></td>
<td>-1.70</td>
<td>0.58</td>
</tr>
<tr>
<td>K2</td>
<td>Twisted and soldered thermocouple, type-T; metal-filled, two-part liquid epoxy with tip of thermocouple pressed against backsheet during cure (cure time ~60 minutes)</td>
<td>P</td>
<td><img src="chart3" alt="Graph" /></td>
<td>-2.15</td>
<td>0.70</td>
</tr>
<tr>
<td>K4</td>
<td>Twisted and soldered thermocouple, type-T; two-part thermally conductive epoxy adhesive (cure time ~48 hours)</td>
<td>P</td>
<td><img src="chart4" alt="Graph" /></td>
<td>-2.58</td>
<td>0.73</td>
</tr>
<tr>
<td>K5</td>
<td>Crimped bead thermocouple, type-T; two-part thermally conductive epoxy adhesive (cure time ~48 hours)</td>
<td>P</td>
<td><img src="chart5" alt="Graph" /></td>
<td>-4.79</td>
<td>1.33</td>
</tr>
<tr>
<td>L</td>
<td>Thin-film thermocouple, type-T, trimmed to within 2 mm of tip; round polyester tape overlay attachment with no adhesive</td>
<td>R</td>
<td><img src="chart6" alt="Graph" /></td>
<td>-1.32</td>
<td>0.63</td>
</tr>
<tr>
<td>N</td>
<td>Thin-film thermocouple, type-T, trimmed to within 2 mm of tip; thin silicone adhesive with no additional overlay</td>
<td>R</td>
<td><img src="chart7" alt="Graph" /></td>
<td>-1.04</td>
<td>0.43</td>
</tr>
<tr>
<td>O</td>
<td>Thin-film thermocouple, type-T, trimmed to within 2 mm of tip; round polyester tape overlay attachment with thermal compound</td>
<td>R</td>
<td><img src="chart8" alt="Graph" /></td>
<td>-1.06</td>
<td>0.53</td>
</tr>
<tr>
<td>P</td>
<td>Thin-film thermocouple, type-T; round polyester tape overlay attachment with thermal compound*</td>
<td>R</td>
<td><img src="chart9" alt="Graph" /></td>
<td>-1.70</td>
<td>0.66</td>
</tr>
<tr>
<td>R</td>
<td>Thin-film thermocouple, type-T; 1.7 mm closed-cell foam tape overlay with no adhesive</td>
<td>R</td>
<td><img src="chart10" alt="Graph" /></td>
<td>-1.29</td>
<td>0.33</td>
</tr>
</tbody>
</table>

* R= removable attachment method; P= permanent attachment method

---

*Courtesy NREL*
of tests, including the removable or permanent nature of the attachment method, are described in Table 2 (p. 96) and Table 3 (p. 98). The backsheets were cleaned with 70% isopropyl alcohol on lint-free wipes and dried before attaching the test devices. Unless noted otherwise in the tables, the thermocouples were mounted in the as-received condition from the manufacturer. We attempted to replicate both effective and poor mounting practices during testing. Poor attachment methods have a significantly detrimental effect on the measurement of module backsheet temperatures.

Before each round of testing, the test plate was installed outdoors on the test rack and temperatures were monitored for each test sensor and for the four bulk-plate measurement probes. Because of the inherent variation in measurements from type-T thermocouples (as received, a probe is usually ±1°C), offsets were applied iteratively to each sensor within the datalogger code to minimize the variation between sensors during calm, nighttime conditions (2am to 4am, wind velocity <1 m/s, no measurable irradiance). This method effectively acts as a field calibration. Through four iterations of this process, the variation between the four bulk-plate temperature measurements was limited to <0.3°C, and the variation between the test sensors was <0.8°C.

Round 1 was completed in April 2011, and Round 2 was completed in June 2011. Measurements of the test sensor temperatures and environmental parameters were captured every 5 seconds, 24 hours per day, for 14 continuous days in each round of testing. This resulted in over 480,000 measurements from which to perform analyses. Over the course of testing, wind speeds reached up to 16 m/s and ambient temperatures ranged from –1°C to 35°C. Bulk-plate temperatures ranged between –1°C and 55°C.

TEST RESULTS

The most appropriate way to review the results was to limit the data set to daytime conditions (plane-of-array irradiance >5 W/m²) when the range in the bulk-plate temperature was small (<1°C), eliminating times of rapid heating or cooling. We then calculated the deviation of each instantaneous measurement from the average bulk-plate temperature as follows:

$$\Delta T_{sensor} = T_{sensor} - T_{bulk\ plate}$$

Negative values of $\Delta T_{sensor}$ indicate that a sensor measured a lower temperature than the bulk plate average. In the following discussion, the results of this simple calculation are referred to as deviations.

A review of the distribution of the deviations for measurements taken above 5 W/m² reveals...
that the shapes of the distributions of $\Delta T_{\text{sensor}}$ vary significantly from test to test. Temperature measurements on modules, however, are of increased significance when the incident irradiance is above 800 W/m² because of NOCT and STC rating conditions. Figure 4 (p. 100) shows the effect of removing deviations for irradiances below 800 W/m². The full-range distributions (>5 W/m²) for three example attachments have drastically different shapes, but all tend towards normal distributions when the irradiance is limited by this lower threshold. This is the case across all tested attachment methods. As the threshold increases to higher irradiances, the mean deviation for most attachments stabilizes near 1° to 2°C loss, as expected from heat transfer calculations.

To maintain consistency with NOCT and STC rating conditions, data was limited to measurements captured at irradiances between 750 and 1,050 W/m². In describing what is desired in an attachment method, a measurement should be as close to the actual junction temperature as possible and, more importantly, track closely with changes in the junction temperature.

So what metrics should be used to make a judgment between attachment methods, given the stated criteria? The mean deviation from the bulk-plate temperature, $\Delta T_{\text{sensor}}$, describes the average temperature difference between the bulk-plate temperature and the sensor. The standard deviation of the distribution, $\sigma_{\Delta T_{\text{sensor}}}$, describes the variation of the measurements from the distribution’s mean. A low standard deviation describes a distribution for which more of the $\Delta T_{\text{sensor}}$ values are close to the mean deviation, whereas a high standard deviation describes a wider distribution with points spread over a larger range of $\Delta T_{\text{sensor}}$ values. Combined, the mean and standard deviations provide sufficient information from which to begin evaluating attachment methods by general characteristics such as adhesion method, insulation thickness and thermocouple style, as shown in Figure 5.

In addition, Tables 2 and 3 include the values of $\Delta T_{\text{sensor}}$ and $\sigma_{\Delta T_{\text{sensor}}}$ for each attachment method.

We can make several key observations from Figure 5. First, as a general rule, thin-film style thermocouples perform better than beaded thermocouples. The worst performance was for the partially detached (B2) and high-surface-area beaded thermocouples using thermal epoxy (K5). This is indicated by the high $\Delta T_{\text{sensor}}$ and high $\sigma_{\Delta T_{\text{sensor}}}$ values for these attachments and emphasizes the importance of effective adhesion and clean installation methods. If it is necessary to employ a beaded thermocouple, then the use of a metal-filled epoxy yields the best performance. Second, the adhesion method and insulation thickness are equally important in building a successful attachment. In the case of thin-film thermocouples, attachment H appears to have the lowest mean deviation and standard deviation. This may be an artifact—it remains a good attachment method but may show a systematic error of up to 1°C. The addition of insulation does show an improvement over uninsulated sensors, with the thick (1.7 mm) layers exhibiting slightly lower $\Delta T_{\text{sensor}}$ and high $\sigma_{\Delta T_{\text{sensor}}}$ values as compared to moderate and thin insulation attachments. However, adhesion with a thin layer of silicone produces high-quality

**Figure 5** Mean deviation from bulk-plate temperature, $\Delta T_{\text{sensor}}$, versus the standard deviation of $\Delta T_{\text{sensor}}$ for plane-of-array irradiances between 750 and 1,050 W/m² are shown. Symbol shapes denote thermocouple adhesion method and symbol color corresponds to the level of insulation.
results regardless of the level of insulation. The use of a thicker adhesion layer (attachment G) results in decreased performance. In general, the use of thermal compound with thin insulation does not provide results as good as using either thin silicone or no adhesion layer. Not all attachment methods were included in these tests, such as substantially thicker insulation layers or combinations of adhesions and methods were included in these tests, such as substantially thicker insulation layers or combinations of adhesions and insulation thicknesses, but it is our intention to explore these attachments in the future.

**BEST PRACTICES**

Based on the experience of the NREL PV Reliability Group and the results of the described tests, we recommend the following best practices.

**During planning, deployment and commissioning:**

- Minimize the surface area of attachments and choose attachment methods that minimize the mean deviation.
- Install multiple temperature measurement probes using the same attachment method. This consistency allows for comparisons between sensors and can help differentiate results from a drifting or failing sensor from actual system performance degradation. The mounting locations should be similar.
- Plan to use the calm, zero-irradiance technique to develop offsets for the sensors. This reduces the uncertainty between the sensors and allows for improved comparisons. However, since a reference temperature from which to make adjustments is not always available, be careful when applying any offsets greater than 0.5°C. If a more accurate measurement set is desired, then the laboratory calibration of at least one of the sensors before installation is recommended; the offsets would therefore be applied to the uncalibrated sensor(s).

**During attachment:**

- Before attaching any sensor, clean and dry the module backsheet with a solvent that does not leave a residue. In our experience, 70% isopropyl alcohol on lint-free wipes is effective. Even small amounts of dirt or dust decrease the effectiveness of any attachment method.
- Keep all adhesive layers as thin as possible to improve thermal contact with the module backsheet. Do not allow adhesives to spread beyond the surface area of thin-film devices. This is especially important for thermal epoxies.
- Permanent attachments are most appropriate when modules are to be deployed long-term in the field. If using thermally conductive epoxies, you must be fully cognizant of their cure times. Secure the sensor and allow the attachment to cure for a few days to prevent movement.
- Reasonable levels of insulation may improve measurement performance, but the effect of excessive insulation is not yet characterized.
- Provide strain relief near the sensor attachment point to limit pulling on the sensor element.

**During maintenance:**

- Inspect temperature sensor attachments during routine maintenance. This is especially important for nonpermanent attachments that may pull loose or degrade over time.
- Replace removable sensor attachments (primarily tape) periodically and check for damage to sensing elements.

We intend to continue this work and expand on the attachment types and experiment durations. Please contact us with suggestions for additional experiments to benefit the photovoltaic community at large.

We would like to thank Dirk Jordan for discussions surrounding this project, Adam Stokes for assistance in summarizing manufacturer data sheets, and L. Li, J. Wohlgemuth and C. Deline for reviewing this article. This work was supported by the U.S. Department of Energy under Contact No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory.

**CONTACT**

Ryan M. Smith / National Renewable Energy Laboratory / Golden, CO / ryan.smith@nrel.gov / nrel.gov
Sarah Kurtz / National Renewable Energy Laboratory / Golden, CO / sarah.kurtz@nrel.gov / nrel.gov
Bill Sekulic / National Renewable Energy Laboratory / Golden, CO / bill.sekulic@nrel.gov / nrel.gov

**References**