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Preprint

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Presented at the 37th IEEE Photovoltaic Specialists Conference (PVSC 37)
Seattle, Washington
June 19-24, 2011

Conference Paper
NREL/CP-5200-50744
July 2011

Contract No. DE-AC36-08GO28308

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TRANSIENT RESPONSE OF CADMIUM TELLURIDE MODULES TO LIGHT EXPOSURE

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ABSTRACT

Commercial cadmium telluride (CdTe) photovoltaic (PV) modules from three different manufacturers were monitored for performance changes during indoor and outdoor light-exposure. Short-term transients in V_{oc} were recorded on some modules, with characteristic times of ~1.1 hours. Outdoor performance data shows a similar drop in V_{oc} after early morning light exposure. Preliminary analysis of *FF* changes show light-induced changes on multiple time scales, including a long time scale.

Multiple methods of measuring β_{Voc} resulted in a range of values on the same CdTe PV module between -0.25%/C and -0.4%/C, possibly due to concurrent light-induced V_{oc} transients and temperature changes. This paper highlights the need for rapid performance measurement of PV samples following light exposure and the possibility of incorrect results when using outdoor light exposure to collect values of β_{Voc} for CdTe modules.

INTRODUCTION

Polycrystalline thin-film photovoltaic (PV) modules, including those incorporating cadmium telluride (CdTe) materials, are rapidly gaining market share [1]. Given the growth in thin-film PV installations, it is imperative that accurate standards and measurement methods be developed to allow accurate performance assessment. Prior experiments have shown that measurement issues arise from the indoor testing of polycrystalline thin-film modules, including spectral mismatch, capacitance in high-speed current versus voltage (*I-V*) measurement, and light exposure effects [2,3,4,5]. This last measurement effect – light exposure – is the focus of this paper.

The light exposure history of a thin-film PV module has been shown to affect performance characteristics on two time scales: short-term transients, which decay in a matter of hours [6,7], and longer-term effects, which may persist longer and may or may not be reversible [8, 9, 10, 11,12]. While both effects may influence performance measurement, the presence of short time-scale transients may affect the repeatability of qualification testing to e.g. IEC 61646 [13]. For instance, the IEC 61646 qualification standard calls for light-soaking in 43-kW-hour increments yet does not specify how soon after exposure the module must be measured for power. Transients occurring on the order of minutes to hours may or may not be recorded during performance measurement, resulting in variability in the result. Additionally, the measurement of the temperature coefficient of V_{oc} (β_{voc}) using outdoor measurement techniques after prolonged storage in the dark (IEC 61646) may result in light-induced open-circuit voltage (V_{oc}) transients being captured along with temperature-related effects.

Experiments were conducted with CdTe PV modules from three different manufacturers. Both indoor and outdoor exposure experiments were conducted with these modules, particularly emphasizing short-term transients in measured V_{oc} and fill factor (*FF*). For all experiments, periodic *I-V* curves are taken with the module maintained at its maximum power point voltage (V_{mp}) in between *I-V* curves. For the indoor light/dark exposure experiment, the module was alternately light-exposed for 24–200 kWh and stored in the dark at room-temperature for 24–100 hours. For the outdoor exposure of the modules, the module is deployed outdoors in a fixed-tilt configuration.

METHOD

A full description of experimental methods is provided in [14]. A total of nine CdTe modules from three manufacturers were used in this experiment, with prior exposure details shown in Table 1. The modules were divided between an indoor light/dark exposure experiment and an outdoor exposure experiment. Modules from manufacturer **A** had no prior outdoor exposure but were allowed to light-soak for a short period of time (~1 kWh) to collect initial performance and temperature coefficient data, according to IEC 61646. Modules from manufacturer **B** were control modules left over from certification testing and had some prior outdoor exposure. The module from manufacturer **C** has been continuously exposed outdoors for a period of more than two years.

Table 1 CdTe modules used for this experiment

Mfr.	Indoor modules	Outdoor modules	Pre- experiment condition
CdTe **A**	2	2	~1 kWh exposure
CdTe **B**	2	2	> 1 kWh exposure
CdTe **C**	0	1	Continuous exposure > 2 yrs

Initial performance characteristics and β_{voc} were measured for each of the CdTe modules. β_{voc} measurements were taken outdoors (after several days of dark/indoor storage) in natural sunlight for all modules as the modules warmed naturally. β_{voc} measurements were also taken using a Spire 4600 pulsed solar simulator as the modules cooled from approximately 60°C indoors. This second method provided more accurate β_{voc} measurements that were more closely aligned with steady-state outdoor values

(>24 hours outdoor exposure) given that light-induced V_{oc} transients are not included with the temperature coefficient measurement. The results of these three temperature coefficient collection methods are provided in Table 2 and labeled as methods 61646 Outdoor, Indoor Flash, and Steady-State (outdoor), respectively.

Table 2 Measured β_{voc} for the modules under test

Module, β_{voc} method	β_{voc} measured*
CdTe **A**, 61646 Outdoor	-0.43%/C
CdTe **A**, Indoor Flash	-0.21%/C
CdTe **A**, Steady-State	-0.24%/C
CdTe **B**, 61646 Outdoor	-0.39%/C
CdTe **B**, Indoor Flash	-0.25%/C
CdTe **B**, Steady-State	-0.25%/C
CdTe **C**, Steady-State	-0.25%/C

*Measurement uncertainty = 0.04%/C

An illustration of why the IEC 61646 outdoor procedure resulted in higher β_{voc} values is shown in Figure 1. This plot shows V_{oc} versus temperature data for module CdTe **A** during its initial light exposure. Data are plotted for three different time scales: the initial two hours of exposure, a middle period of exposure up to 15 hours, and steady-state conditions up to 100 hours. The V_{oc} value during initial light exposure has poor linear dependence on temperature, probably due to an initial V_{oc} transient. The middle time interval, while showing good linearity with temperature, provided a value that is much greater (β_{voc} = -0.34%) than the steady-state value reached after 15 hours of light exposure (β_{Voc} = -0.24%).

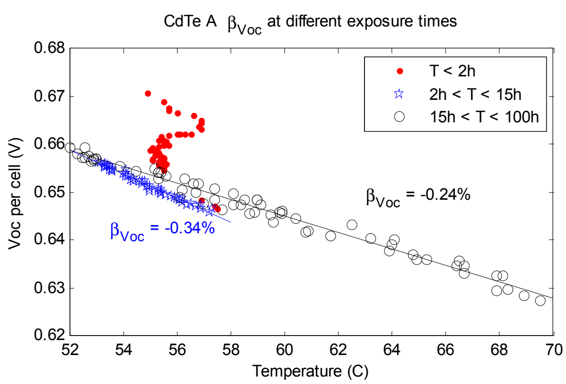

Figure 1 Module CdTe A- V_{oc} vs. Temperature showing β_{Voc} temperature coefficients changing over time. Measured β_{Voc} (dV_{oc}/dT_{mod}) stabilizes during light-soaking to -0.24% following 15 hours light exposure.

Indoor light exposure of a subset of PV modules was then conducted in a Class C Iwasaki large-area Xenon arc lamp solar simulator. *I-V* curves were collected on a five-minute basis during light exposure using a Daystar RD-1200 multi-tracer. Between successive *I-V* curves, the module is kept loaded at its peak power point. Spectral mismatch effects and temporal variation of the Class C simulator may lead to variation in the recorded short-circuit current (I_{sc}) and *FF* of the modules under test. Spatial and spectral mismatch should not affect the measurement of V_{oc} reported here, however.

Temperature measurements are recorded on the front and back of the module with T-type thermocouples. Module temperature during light exposure remained at 50°–60°C. The light intensity was generally constant throughout the exposure, but depending on the position of the module, the light intensity ranged from 650 W/m^2 to 1,050 W/m^2.

Light exposure of the CdTe modules is provided in increments ranging from 24 kWh to 200 kWh. Following light exposure, rather than disconnecting the module and removing it from the solar simulator, the module remains inside the solar simulator, but enshrouded to eliminate light exposure. The same temperature and voltage monitoring equipment is used during dark exposure to eliminate different monitoring equipment as a source of systematic error. The V_{oc} and other performance parameters of the module are periodically measured by quickly removing the dark shroud, taking an *I-V* sweep, and replacing the dark shroud. In a given indoor exposure experiment, a module will be exposed to two cycles of light and dark exposure of 24–200 hours each.

Outdoor exposure data was also collected for modules from each of the CdTe manufacturers. Modules of a similar vintage to those used for indoor light exposure tests are used, with similar exposure history. The outdoor exposure is conducted at a fixed latitude tilt under natural light. A Raydec Multitracer MT-5 unit is used to take *I-V* curves every five minutes with the modules loaded at V_{mp} in between measurements. Plane-of-array irradiance is collected with a Kipp & Zonen CMP-11 pyranometer, and backside module temperature is collected with a T-type thermocouple. The outdoor data considered here was taken following at least two weeks of outdoor exposure, allowing the module to achieve some level of stabilization.

Correction of V_{oc} data back to standard test conditions of 25°C and 1,000 W/m^2 (STC) is important when comparing module performance at different exposure conditions. King et al. has proposed the following translation equation for V_{oc} [15]:

$$V_{oc,0} = V_{oc,meas} - \beta_{Voc}(T_{cell} - T_0) - N_s \frac{nkT}{q} \ln\left(\frac{E}{E_0}\right) \quad (1)$$

where $V_{oc,0}$ is V_{oc} at STC conditions; $V_{oc,meas}$ and T_{cell} are the measured V_{oc} and cell temperature, respectively; T_0 is the temperature at STC (25°C); and β_{Voc} is the temperature coefficient of V_{oc}, reported for the module in units V/C. For glass-glass module construction, the cell temperature is generally considered to be 3°C greater than module temperature at STC [13]. The second subtractive term in Equation 1 corrects the measured V_{oc} for changes in irradiance. Here, N_s is the number of series cells in the module, n is the diode quality factor, k is Boltzmann's constant, and q is the elementary charge. For diode quality factor = 1, nkT/q = 26 mV. E/E_o is the incident irradiance divided by 1,000 W/m^2. Although uncertainty exists in the value for diode quality factor in polycrystalline thin-film modules, typically reported values range from 1.5 to 2 [16]. Note that error due to uncertainty in *n* goes to zero at 1,000 W/m^2. In this analysis, a constant value *n* = 1.5 is assumed for CdTe modules, and *n* = 1.2 is assumed for c-Si modules.

ANALYSIS

Indoor V_{oc} Transients

With knowledge of the effect of temperature on module V_{oc}, it is possible to plot the time series of data to show the transient effect of light-soaking on module V_{oc}.
The temperature-corrected time series for CdTe **A** is shown in Figure 3. Light exposure introduces a suppression of V_{oc} that stabilizes after a few hours. Removing the module from light restores the initial V_{oc} value in a similar period of time. This phenomenon was repeatable and consistent across all modules tested from manufacturer **A**. A constant temperature coefficient of -0.24%/C ± 0.02%/C is determined for both light and dark exposure data. Slight adjustments in the assumed β_{Voc} do not affect this V_{oc} transient. A close-up view of the V_{oc} transient shows an exponential decrease with a time constant of τ = 1.1 hours. The total magnitude change of V_{oc} is 7%–8%.

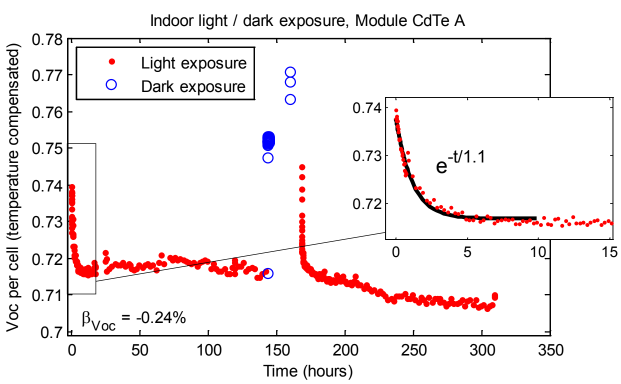

Figure 2 Module CdTe A: Temperature-corrected V_{oc} data showing negative voltage transient during light exposure with exp(-t/τ) time constant of τ = 1.1 hours.

The second module type tested, CdTe **B**, does not show a strong negative voltage transient when exposed to light. In fact, this module type shows a slight improvement in V_{oc} during light exposure on the order of 2%–3%. Again, this behavior was repeatable and consistent over all modules tested from this manufacturer. The V_{oc} increase at the start of light exposure #2 is also exponential in time with a constant of τ = 1.1 hours. However, there is not a similar exponential decrease in V_{oc} once the module is removed from light exposure; the decay in voltage seems to occur gradually over time, at a rate of less than 1% per day.

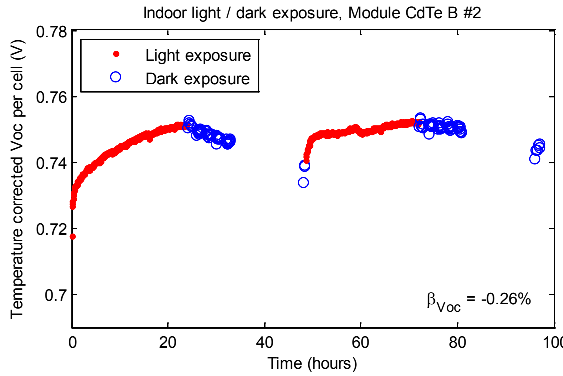

Figure 3 Module CdTe B: Temperature-corrected V_{oc} data showing positive voltage transient during light exposure.

Indoor Fill Factor Transients

In addition to changes in V_{oc}, the impact of light exposure on *FF* was also monitored during indoor light/dark exposure. One complication of assessing any change in *FF* is that it has a dependence on both temperature and irradiance (γ_{FF}), which is difficult to know *a priori* [17]. However, for the indoor light exposure experiments considered here, irradiance is kept at a constant value, simplifying assessment of the *FF* coefficient γ_{FF}.

For almost all modules considered here, a temperature dependence of γ_{FF} = -0.16%/C ± 0.05%/C was determined by a best linear fit through *FF* data at constant irradiance. The best linearity (R^2 = 0.65–0.73) was found during the dark exposure portions of the experiment for reasons that will be explained shortly. A temperature correction was applied to all *FF* data, which are presented in Figure 4 for a CdTe **A** module and in Figure 5 for a CdTe **B** module.

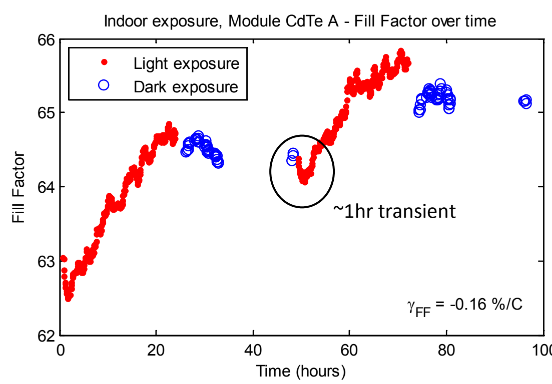

Figure 4 Indoor exposure showing *FF* changes of module CdTe A. Temperature sensitivity analysis shows correlation with *FF* (R^2 = 0.73 for γ_{FF} = -0.16%/C).

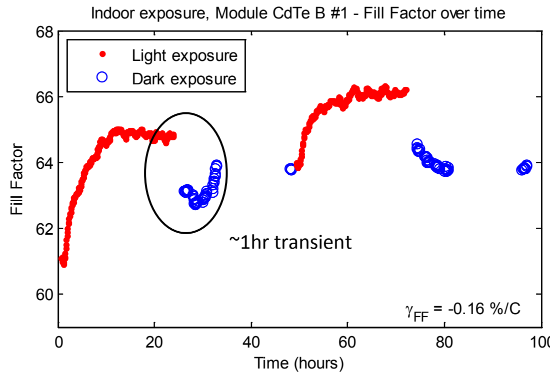

Figure 5 Indoor exposure showing *FF* changes of module CdTe B (#1). Temperature sensitivity analysis shows correlation with *FF* (R^2 = 0.65 for γ_{FF} = -0.16%/C).

The plots of *FF* show several interesting behaviors. First, an increase in *FF* begins with the start of light exposure, with module *FF* increasing by 4%–9% for both indoor-tested module types. The amount of *FF* increase is relatively unaffected by the value of γ_{FF} applied in the temperature correction. This increase in *FF* occurs primarily during light exposure. Because the modules had little light exposure prior to this experiment, it is possible that the *FF* increase is a one-time transient due to improved ohmic contact between the back-side contact (possibly incorporating copper) and the high-work-function p-CdTe layer [10,11].

The strong increase in *FF* during light exposure occurred with no correlation to temperature (R^2 < 0.1). This is why γ_{FF} could only be determined during the dark exposure increment of the modules—otherwise the transient in *FF* due to light exposure would outweigh any temperature dependence of *FF*.

In addition to a strong increase in *FF* that occurs on a time scale of 10–24 hours, there is also the possibility of a transient decrease in *FF* with a time scale closer to one hour, identified in Figures 4 and 5. The magnitude of this decrease is less than 1% for module CdTe **A** and around 3% for module CdTe **B.** However, it is difficult to determine any details about this transient due to the action of the much stronger *FF* increase. It is also possible that this is a temperature-related transient, which could be related to uncertainty in the value of γ_{FF}. In this experiment, measurements of R_s (*dV*/*dI* near V_{oc}) showed similar transients to the overall plots of *FF*.

One of the modules under test showed a different *FF* response to indoor light/dark exposure. Figure 6 shows the change in *FF* for the second of two CdTe **B** modules tested indoors. Rather than the transient light/dark behavior seen in Figures 4 and 5, this CdTe **B** module shows a constant increase in *FF* even when the module is enshrouded in the dark. In addition, the temperature dependence of *FF* is negligible for this module (R^2 < 0.05) during both light and dark exposure. One explanation for this different behavior is the possibility that the module was insufficiently shrouded during the dark exposure, and some light was still able to get through to the module. Even a small amount of light would provide a light-induced bias that could be responsible for a continuous increase in *FF*. This would further explain the low correlation between *FF* and temperature during dark exposure, as the small temperature-dependent *FF* change is outweighed by a much stronger light-induced *FF* improvement.

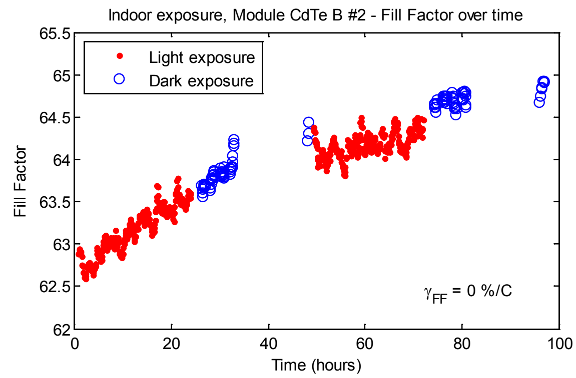

Figure 6 Indoor exposure showing *FF* changes of module CdTe B (#2). Temperature sensitivity analysis shows no correlation with *FF* (R^2 < 0.05 for any γ_{FF}). This module may have been insufficiently shrouded during dark exposure.

Outdoor Exposure Experiments

Indoor light exposure experiments show V_{oc} transient behavior for different CdTe modules; the next step was to see if this V_{oc} transient was evident in outdoor exposed modules as well. (*FF* was not assessed due to complicated irradiance-dependent γ_{FF}). If a module experiences V_{oc} reduction due to light exposure, one would expect that this behavior would show up as a reduction in V_{oc} throughout the day once the sun was high enough to begin light-soaking the module. V_{oc} transients with a time constant on the order of one hour should be visible within the diurnal cycle. Figure 7 shows outdoor exposure data for three CdTe module manufacturers and also a crystalline Silicon (c-Si) module for comparison (BP 485J). Note that we have multiplied the c-Si cell voltage by 1.32x to plot it on the same scale as the higher-cell-voltage CdTe modules. In order to account for differences in temperature and irradiance throughout this single, cloud-free day, Equation 1 is used to correct V_{oc} data back to STC conditions.

As is visible in Figure 7, both modules CdTe **B** and the c-Si reference module show a relatively symmetric corrected V_{oc} profile throughout the day. However, CdTe **A** and CdTe **C** both show a noticeable droop in V_{oc} after 8 AM. The reduction in V_{oc} for CdTe **A** is around -6% at noon relative to both its own peak at 8 AM and relative to module CdTe **B** at noon. This change in V_{oc} is consistent both in magnitude and time scale with the indoor V_{oc} transients for module CdTe **A** shown in Figure 2. Likewise, module CdTe **C** at noon shows reduced V_{oc} of -1.5% and -4% relative to its own maximum and relative to module CdTe **B** at noon, respectively. This is consistent with the fact that CdTe **A** had a much larger V_{oc} transient during indoor light/dark exposure than CdTe **B**.

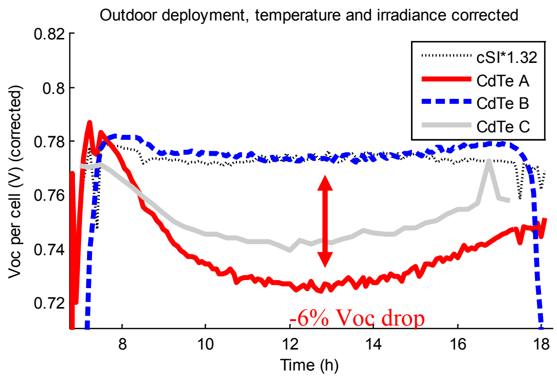

Figure 7 Outdoor deployed modules, temperature, and irradiance corrected by Equation 1. Note a constant *V_{oc}* profile through the day for CdTe B and the cSi module, while CdTe A and CdTe C have an early morning reduction in *V_{oc}*, consistent with light-induced *V_{oc}* degradation.

The data in Figure 7 depend in part on the assumed value of n = 1.5 for CdTe modules. A higher value of n in this case was tried, but resulted in an over-correction of the data, leading to a greater apparent V_{oc} drop for module CdTe **A.**

SUMMARY

Light exposure experiments were conducted for CdTe modules from three different manufacturers. Transients in V_{oc} have been identified that occur within the first hour of light-soaking, and, if unaccounted for, can cause errors by convolution with the measurement of a module's β_{Voc} temperature coefficient. This problem is seen during the IEC 61646 outdoor β_{Voc} method but not during the indoor flash testing β_{Voc} method. The estimation of a module's STC performance can also be affected because instantaneous module performance is dependent on its light exposure history. Evidence of a diurnal V_{oc} transient has been identified in outdoor performance data from multiple CdTe manufacturers and is consistent in magnitude and time scale with those seen in indoor exposure experiments on similar vintage modules.

ACKNOWLEDGEMENT

The authors would like to thank those companies who supplied modules for testing and TUV Rheinland PTL for allowing us to perform testing at their facility. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

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