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Metastable electrical characteristics of polycrystalline thin-film photovoltaic modules upon exposure and stabilization

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ABSTRACT

The significant features of a series of stabilization experiments conducted at the National Renewable Energy Laboratory (NREL) between May 2009 and the present are reported. These experiments evaluated a procedure to stabilize the measured performance of thin-film polycrystalline cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) thin-film photovoltaic (PV) modules. The current-voltage (I-V) characteristics of CdTe and CIGS thin-film PV devices and modules exhibit transitory changes in electrical performance after thermal exposure in the dark and/or bias and light exposures. We present the results of our case studies of module performance versus exposure: light-soaked at 65°C; exposed in the dark under forward bias at 65°C; and, finally, longer-term outdoor exposure. We find that stabilization can be achieved to varying degrees using either light-soaking or dark bias methods and that the existing IEC 61646 light-soaking interval may be appropriate for CdTe and CIGS modules with one caveat: it is likely that at least three exposure intervals are required for stabilization.

Keywords: Thin film, Photovoltaic, Transients, Metastability, CdTe, CIGS, IEC 61646

1. INTRODUCTION

Changes in the I-V parameters of polycrystalline thin-film PV devices have long been studied, particularly the reversible effect of light exposure and voltage bias on device efficiency[1]. Early on, it was recognized that the open-circuit voltage (V_{oc}) of CIGS and CdTe devices was affected by the prior voltage- and light-exposure history of the device[2,3]. Because voltage exposure near V_{mp} in the dark resulted in the same reversible increase in V_{oc} as light exposure at V_{mp} bias, it was suggested that these V_{oc} changes are driven by the bias history of the thin-film sample rather than its light exposure history. In all cases, dark storage returns the device's V_{oc} back to its original value. The shift has been ascribed to a continuum of trap states in the absorber junction, which depopulate when the cell is forward biased[2]. The time constant of this V_{oc} transient was on the order of minutes to hours, depending on the length of exposure to the voltage bias. We therefore categorize this V_{oc} effect as a short-term transient. An additional contributor to short-term reversible device performance change has been identified as persistent photoconductivity, yielding voltage and series resistance changes in response to light exposure[4,5]. The challenge of short-term transients is in measuring the performance of thin-film PV devices repeatably under standard test conditions (STC). A typical approach is to light-soak a particular module that has been stored in the dark prior to measurement. However, to ensure the module is at the requisite 25°C for the performance measurement, the module is typically allowed to cool in the dark for up to 1 hour, which may undo some of the performance changes produced by light-soaking.

Longer-term changes in the electrical characteristics of CIGS and CdTe modules have also been observed under illumination[6-10], occurring over time scales of 1000 hours of exposure at one-sun. Some of these longer-term exposure changes can be reversed when the modules are put into dark storage—defined as low-light-level conditions at room temperature—in periods of days to weeks. These reversible performance changes that arise after longer-term exposure (more than tens of hours) are termed metastable changes here. In CIGS modules, metastable changes have been attributed to persistent photoconductivity in the bulk CIGS[11], and charging-discharging of defect states at the CdS/CIGS

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interface[12,13]. In CdTe modules, an additional factor implicated in metastable performance changes is motion of ion species including copper. Copper inclusion in the back-side contact of CdTe modules can improve the ohmic connection with the high-work-function p-CdTe layer[14]. However, stability can be compromised in the process[7,15], possibly due to Cu diffusion from the back contact[16].

These longer-term metastable changes pose a challenge when trying to accurately gauge PV module performance following stress testing in module certification tests. The current certification standard for thin-film PV modules—IEC 61646[17] — requires successive light-soaking increments of 43 kWh/m^2 integrated irradiance until the relative changes in measured power are 2% or less. This procedure was designed to account for Staebler-Wronski changes in amorphous silicon modules and is quite likely not optimal for stabilizing polycrystalline CdTe or CIGS PV devices following stress test (damp heat under bias) exposure. For instance, high-temperature exposure typically produces temporary efficiency improvements in a-Si modules that are not replicated in CIGS or CdTe modules.

Our goal is to devise a set of procedures suitable for stabilizing the measured performance in CIGS and CdTe PV modules so that measurements made either after dark storage, manufacture, or certification will be reproducible to within allowable tolerance. Because there seem to be short- and long-term effects on measured performance, it may be useful to consider separate procedures: one for preconditioning, or removing the transient effects, plus a second that addresses stabilizing the module to its long-term performance measured when deployed outdoors. The latter task is described here (and in prior reports[18,19]), specifically as two possible stabilization paths: light-soaking at one-sun or forward-biasing in the dark, carried out at elevated temperatures as suggested in the literature[2,9,10].

2. EXPERIMENTAL STUDY PLAN

Our study plan to understand stabilization is based in part on procedures already available for standard performance testing. The details of this plan are depicted in Figure 1 and consist of a series of indoor and outdoor exposure sequences, with performance measurements (I-V and C-V) at STC following each exposure. The experimental procedure can be split into four phases: initial characterization and exposure, indoor light stabilization, indoor dark stabilization, and long-term outdoor light exposure.

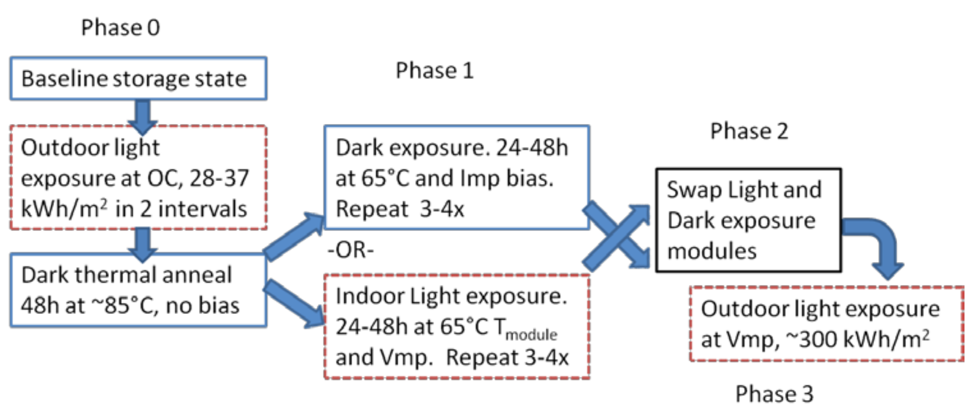


Figure 1. Study plan used to probe transitory electrical behavior in CdTe and CIGS modules. Only certain modules went through Phase 2, where light and dark indoor exposures were swapped. Performance measurements were taken after each interval in the process, including C-V measurement and dark and light I-V curves taken at STC.

The initial characterization and exposure phase (Phase 0) begins with natural outdoor light exposure for all modules, conducted at open circuit (OC) without temperature control. This exposure is conducted in two intervals totaling 28–37 kWh/m^2. The next step consists of a dark thermal (85°–90°C) anneal for 48 hours, nominal relative humidity (RH) (~30%), at OC (no bias), in an indoor thermal chamber. The importance and significance of the dark thermal anneal is that it emulates a shorter version of thermal stress tests encountered by modules in IEC certification (e.g., damp heat) which is known to alter performance—partly in a reversible manner. Indeed, in this experiment the dark thermal anneal exposure resulted in a large reduction in module performance that was partly recovered during subsequent stabilization exposures.

The next two phases of the experiment (Phases 1 and 2) consist of indoor stabilization through either light exposure under load or forward-biased dark exposure at elevated temperature. These two options were selected to identify metastable changes that are driven exclusively by light exposure as opposed to those driven equally by light or electrical bias. Making this distinction is important because dark current soaking has a number of advantages over light-soaking, including a lower cost, ease of use, and the ability to stabilize modules right up to the time of taking an STC measurement, since the bias could in theory be applied at room temperature. Additional details of these exposures are as follows: during exposure, module temperatures are maintained at a nominal 65°±10°C, and module bias is maintained between V_{mp} and V_{oc} using resistive loads (light-soaking) or power supplies (dark current soaking). Dark exposure durations range from 24 to 48 hours, and light exposures range from 24–48 kWh/m^2 at ~ one-sun intensity.

Following three or four such dark or light exposures, the modules were stored in the dark for 2 to 3 months, after which time Phase 2 began (for certain modules only). Details of Phase 2 are identical to Phase 1 except that modules which had previously been light-soaking are instead exposed in dark forward-bias, and vice versa. After about 120 hours of additional exposure, the modules are again put into dark storage for 4 months. The final exposure phase (Phase 3) consists of outdoor deployment for 6 to 8 weeks, for a total additional light exposure of ~300 $kW\text{-}h/m^2$. During the outdoor deployment phase, the modules are maintained at V_{mp} by fixed load resistors and peak-power-tracking power electronics. The outdoor exposure data are used to correlate and validate indoor versus outdoor behavior.

2.1 Modules used in the study

The modules used to probe transitory electrical behavior are described in Table 1 below, with details on module type by manufacturer or model number, whether dark- and light-exposed modules were swapped during Phase 2, quantity of each type, module construction, and previous exposures, if any.

Table 1. List of CdTe and CIGS modules investigated.

Module Type	Phase 2 Swap?	Quantity	Module Construction	Pre-Existing Exposure Conditions
CIGS A	Yes	3	Glass-substrate-glass laminate	Unexposed, three controls from 2003
CIGS B	Yes	2	Glass-flexible-substrate-glass laminate, solder bond interconnect	Unexposed, new
CIGS C	No	6	Glass-substrate-glass laminate	Unexposed, new
CdTe A	Yes	2	Glass-superstrate-glass laminate	Yes, outdoors 3 years
CdTe B	Yes	2	Glass-superstrate-glass laminate	Unexposed
CdTe C	Yes	1	Glass-superstrate-glass laminate	Yes, indoor light-soak, 1130 kWh in 2002
CdTe D	No	6	Glass-superstrate-glass laminate	Unexposed, new
CdTe E	No	6	Glass-superstrate-glass laminate	Unexposed, new

Not all of the modules finished all three phases in this study. Only half of the module types (CIGS A, B and CdTe A, B, and C) were intended to be swapped during Phase 2. For the remaining modules (CIGS C, CdTe D and E), sufficient quantities were available to dedicate half of the modules to indoor light exposure and the other half to indoor dark bias exposure. Additionally, some other modules failed to make it through the entire test: the two CdTe B modules failed during Phase 2 (open circuit), and one CdTe D and one CdTe E module were damaged by handling during Phase 1.

The pre-existing condition of the modules varied slightly, with some of the module types being brand new, some being older but unexposed, and some having been previously deployed outdoors. In particular, the CdTe A and CdTe C modules had prior light exposure history, which may have introduced variability in the results of this experiment, as will be discussed below.

3. RESULTS - CIGS MODULES

Changes in STC efficiency ($\Delta\eta_{STC}$) for the first two types of CIGS modules (A and B) are shown below in Figure 2. Figure 3 describes the η_{STC} changes for the third type of CIGS module (CIGS C). The η_{STC} efficiency values are plotted relative to their initial as-received "dark storage state," and show the $\Delta\eta_{STC}$ as a function of the cumulative exposure in kWh/m^2. Since both light and dark exposures are plotted in the same chart, a 1:1 relationship is assumed between hours of dark exposure and kWh/m^2 of light exposure for the purpose of these charts. Modules receiving indoor light-soaking in Phase 1 are plotted with a dashed line, while modules receiving dark forward-bias are plotted with a solid line. During Phase 2, the light-soaked and dark-soaked modules of CIGS A and CIGS B are switched, which is reflected in the chart.

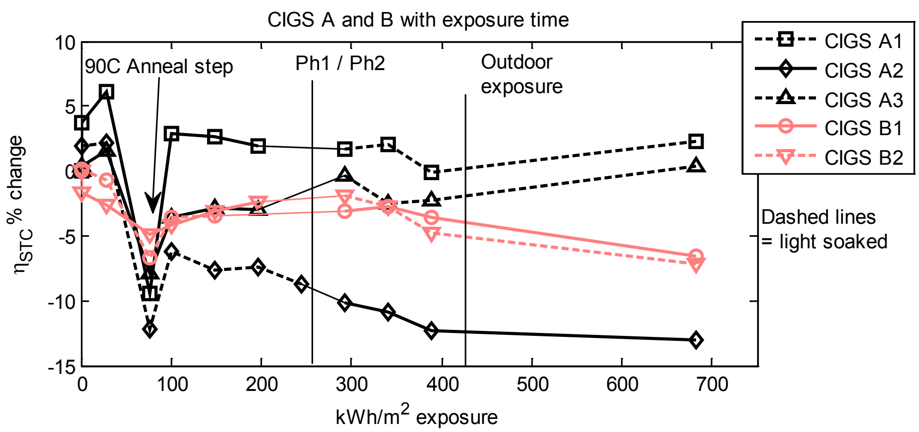


Figure 2. Efficiency changes for CIGS A and CIGS B modules, relative to initial baseline exposure.

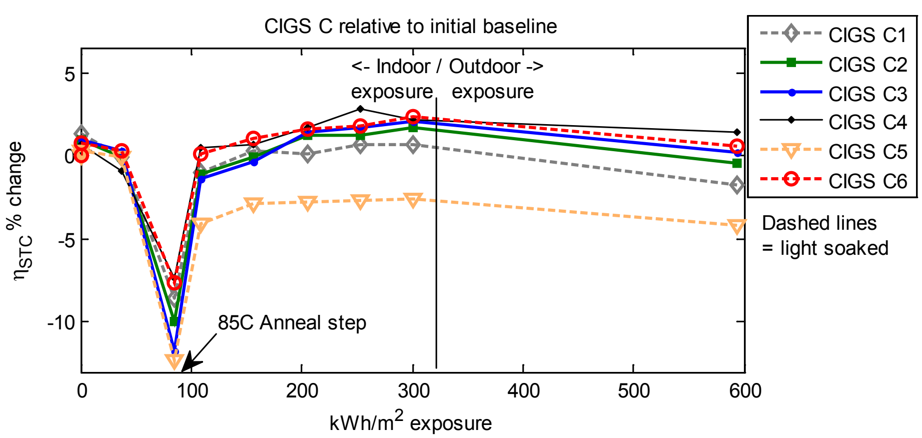


Figure 3. Efficiency changes for CIGS C modules, relative to initial baseline exposure.

The salient features of the exposures are described here: During the initial preconditioning light-soak from 0 to 36 kWh/m^2 cumulative exposure, all of the CIGS A modules' performance improves by roughly 2%–6%, while that for CIGS B modules declines by 1%–2%. These changes are predominantly driven by changes in fill factor (FF), followed by changes in short-circuit current (I_{sc}) in order of importance. CIGS C module η_{STC} remains roughly the same (within 1%–2%). The following dark thermal anneal executed at 90°C depresses η_{STC} of all CIGS modules by 5%–12% relative to baseline, driven largely by FF losses and then V_{oc} losses in importance, while the I_{sc} values remain relatively unchanged. Again, the purpose of this thermal anneal is to begin our stabilization test with metastable changes that may be encountered in a longer-duration damp heat stress test through IEC 61646.

An immediate recovery of some or all of the efficiency loss of the dark thermal anneal is produced by the first 24-hour stabilization exposure (concluding at 100 kWh of total exposure) regardless of whether the exposure involved light-soaking or dark current soaking. According to the technical criteria of the IEC 61646 standard, all CIGS modules shown in Figures 2 and 3 would be considered "stable" following the second exposure (concluding with 150 kWh total exposure) because two successive exposures had a $\Delta\eta_{STC}$ less than 2%. Indeed, aside from module CIGS A2, which continued a slow decline throughout all exposure steps, the other CIGS modules remained within 3% of their first post-anneal measurement throughout the entire remaining 500–600 kWh/m^2 exposure. It can be stated generally that for these CIGS modules, indoor light-soaking and current-biasing in the dark are equally effective in delivering performance stability, and a majority of the post-anneal stabilization occurs within the first 24 hours of light or dark exposure.

Following indoor exposure, the modules were all exposed to ~300 kWh of outdoor light-soaking at P_{mp} to insure that the indoor stabilized conditions are representative of outdoor, field-stabilized conditions. The effect of outdoor exposure was different on different module types, with CIGS A modules all experiencing an efficiency improvement (+2.5%) and module types CIGS B and CIGS C experiencing a reduction in η_{STC} following outdoor exposure (-3% for CIGS B, -1.5% for CIGS C).

3.1 I-V parameter details

Changes in η_{STC} are driven by the three I-V parameters: V_{oc}, J_{sc}, and FF. The trends described here were consistent across all CIGS modules, with typical behavior shown for CIGS C modules in Figure 4. J_{sc} was the smallest contributor to $\Delta\eta_{STC}$, with a slight increase in J_{sc} (3%) seen during the dark thermal anneal. After this increase, J_{sc} remains relatively constant throughout indoor exposure, regardless of whether the module is light- or dark-soaked. A final increase in J_{sc} of ~1% was seen in most modules during the outdoor exposure increment. In general, J_{sc} was negatively correlated with η_{STC} changes. The main drivers of $\Delta\eta_{STC}$ were FF and V_{oc}, which trended after each other. In the case of the CIGS C modules, V_{oc} changes were of the largest magnitude, while ΔFF dominated efficiency changes in CIGS A and CIGS B modules. In particular, η_{STC} improvements in the CIGS A modules during the initial light preconditioning (prior to dark thermal anneal, visible in Figure 2) were driven by FF increases. In all CIGS modules, FF and V_{oc} decreased during dark anneal, slowly recovering during subsequent exposures, regardless of light or dark exposure path. During the final outdoor exposure increment, each module type behaved differently, but again, no difference was apparent between modules on the dark or light exposure path. In CIGS A modules, all I-V parameters improved by ~1% during outdoor light-soaking. In CIGS B modules, $\Delta\eta_{STC}$ was dominated by a 3% drop in FF. In CIGS C modules, V_{oc} and FF each drop by 1%–1.5%. Additional details on the I-V parameters of each of the module types is shown below in Table 2 at four points in the exposure experiment: following the dark thermal anneal, at the conclusion of indoor exposure in Phases 1 and 2, and after the ~300 kWh/m^2 outdoor exposure in Phase 3.

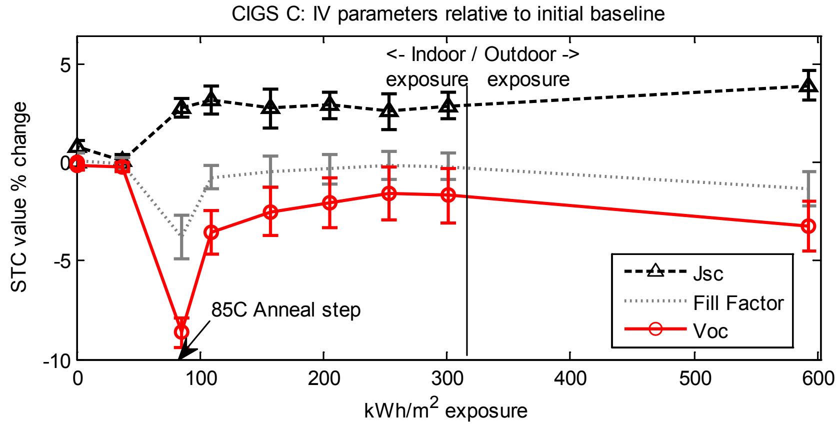


Figure 4. Changes in I-V parameters for CIGS C modules, relative to the first post-anneal exposure.

Table 2. I-V parameter STC values (relative to initial baseline) at four exposure conditions.

Module/Value	Anneal (%)	Last Ph1 (%)	Last Ph2 (%)	Outdoor (%)
CIGS A J_{sc} *	2.9	2.0	0.8	1.9
CIGS A FF*	-9.3	-2.3	-1.6	-0.8
CIGS A V_{oc} *	-2.0	-0.3	-0.3	0.2
CIGS B J_{sc}	0.5	0.7	-1.1	-0.5
CIGS B FF	-3.7	-1.6	-0.9	-4.1
CIGS B V_{oc}	-2.7	-2.0	-2.3	-2.4
CIGS C J_{sc}	2.8	2.9	NA	3.9
CIGS C FF	-3.8	-0.2	NA	-1.3
CIGS C V_{oc}	-8.6	-1.7	NA	-3.2

***Excluding CIGS A2, which had irregular stability following thermal anneal**

Additional investigation was made into FF changes to determine the major driver for these changes: series resistance (R_s), shunt conductance (G_{sh}), or diode quality factor (a). In all of the CIGS modules, the best correlation to ΔFF could be traced back to diode quality factor a changes. Correlation coefficients of -0.85 or better were found for all modules between ΔFF and Δa. The only other significant correlations were found in CIGS module A2, which experienced significant FF loss after the dark anneal step, primarily in a (-0.99 correlation) and R_s (-0.73 correlation). Additionally, CIGS C modules showed a correlation (-0.5±0.2) between ΔFF and ΔG_{sh}.

4. RESULTS - CDTE MODULES

4.1 CdTe A – CdTe C modules

Changes in STC efficiency ($\Delta\eta_{STC}$) for the first three types of CdTe modules (A through C) are shown in Figure 5. The η_{STC} efficiency values are plotted relative to their "dark storage state" at the beginning of the experiment and show their $\Delta\eta_{STC}$ as a function of the cumulative exposure in hours of dark exposure or kWh/m^2 of light exposure. As above, modules receiving indoor light-soaking in Phase 1 are plotted with a dashed line, while modules receiving dark forward-bias are plotted with a solid line. During Phase 2, the light-soaked and dark-soaked modules of CdTe A and CdTe C are switched, which is reflected in the chart.

During the exposure process, module CdTe B1 developed an unexpected loss in FF following the dark anneal step. Subsequent exposures brought back some of its performance, but module CdTe B2 meanwhile began to experience reduced FF as well. The FF losses of both modules are correlated with increased R_s and subsequently attributed to contact problems with the bus-bars as evidenced by IR images. Both CdTe B modules eventually failed in an OC condition during Phase 2—an irreversible change. The CdTe B modules will therefore not be considered further for this experiment.

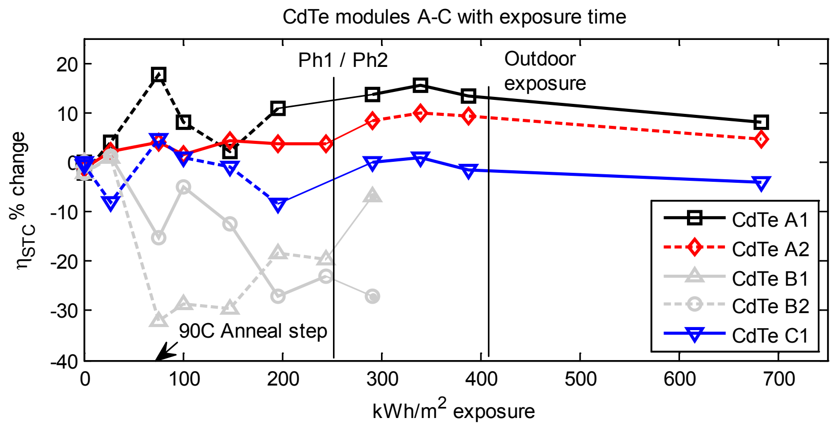


Figure 5. Efficiency changes for CdTe A, CdTe B, and CdTe C modules, relative to initial baseline exposure. Both CdTe B modules failed midway through Phase 2.

With the failure of the CdTe B modules, the sample pool was greatly reduced for the remaining CdTe modules in this exposure sequence. However, some general comments can be made about the behavior of these modules during exposure. Unlike the CIGS modules discussed above, the CdTe A and C modules responded to the dark thermal anneal exposure by an increase in η_{STC}, to values in some cases 10% above the starting baseline condition. A simple explanation may be suggested for this apparent anomalous behavior. As noted in Table 1, the CdTe A modules had a prior exposure history and when new had η_{STC} 5%–17% higher than their starting value in this experiment. As part of these modules' prior exposure history, they were deployed in a hot, humid climate, leading to substantial decline in η_{STC}, close to the baseline value measured here in this experiment. Table 1 also notes that the C1 module had been light-soaked (~1130 kW-h/m^2) several years earlier and was stored in the dark since. Module CdTe C1's prior η_{STC} was about 5% higher than what was measured for its reference baseline here. The improvement in η_{STC} for these CdTe modules following the 90°C dark anneal exposure can thus be thought of as returning some amount of pre-existing metastable performance to these modules as well as undoing some of the metastable η_{STC} loss that was experienced from prior exposure.

With the small sample size, it is difficult to determine whether performance changes are driven differently by light-soaking versus current-soaking after the dark anneal step. It is certain that by the end of Phase 2, after accumulating ~200 hours of either indoor light or current exposure, each of the modules (A1, A2, and C1) have stabilized within 2% $\Delta\eta_{STC}$. It is also true that module A2 stabilized earlier in the exposure sequence, following several dark current soaks by the end of Phase 1, and modules A1 and C1 only stabilized in Phase 2 after they had gone through several dark current exposure increments. However, this does not necessarily indicate that dark current exposure will stabilize any given CdTe module any better or faster than indoor light-soaking.

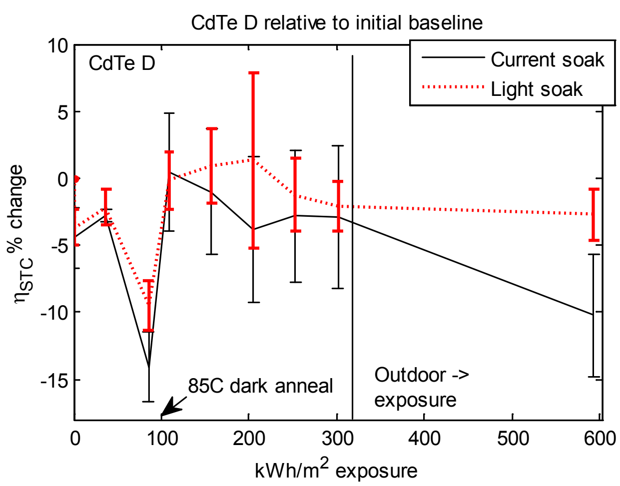
Following the indoor light and dark exposure increments, the CdTe modules were deployed outdoors for ~300 kWh/m^2 light exposure, as with the CIGS modules above. Also like the CIGS B and CIGS C modules, a subsequent reduction in η_{STC} resulted from the outdoor exposure. Relative to the final indoor exposure in Phase 2, η_{STC} for A1 and A2 drops by 5%, while that for C1 drops by 2%.

A comment on the I-V parameters driving η_{STC} changes in CdTe A and C modules can also be made here. For all three modules, V_{oc} remained the most constant, reaching a stabilized value early in the experiment after the initial 30 kWh/m^2 light-exposure preconditioning. The other two parameters—FF and J_{sc}—varied widely through the first half of the experiment and were responsible for most of the variations in η_{STC} for CdTe A and C modules. The values did not always move in the same direction from exposure to exposure, either; a decrease in one exposure step could be followed by an increase in the following step. By the end of Phase 2 exposure, FF in all three modules had stabilized at a value 2%–5% above the initial baseline value. J_{sc} had also stabilized back around the original baseline level by the end of Phase 2 for CdTe A1 and C1, and much earlier for CdTe A2. Following the final 300 kWh/m^2 outdoor exposure, J_{sc} increased by 1% in all modules, while FF declined by 3%–5%. V_{oc} also declined slightly. A full summary of these I-V parameter changes is available in a prior report[18].

4.2 CdTe D and CdTe E modules

Figures 6 and 7 display the η_{STC} changes for CdTe D and CdTe E modules. The main features of η_{STC} changes are similar across these two module types, so they will be discussed together. Unlike the CdTe A and CdTe C modules, these modules have had no prior exposure history, so they are all starting from the same nascent condition. As a result, most of the stabilization changes are monotonic—there are less of the random up and down movements that were seen in the CdTe A and CdTe C data, presumably caused by differences in their initial starting condition. It should be noted that one of the modules in each of group CdTe D and CdTe E were lost due to breakage in mishandling. The damage had nothing to do with the exposure steps, so their data up to the point of failure are included in this analysis.

The η_{STC} changes are plotted separately for the modules exposed to indoor light-soaking and those exposed to dark bias. Although there are slight variations between the two exposure tracks, it is difficult to say that the variations are caused by anything beyond module-to-module variation as opposed to the exposure type itself. For instance, the spread in module response within each exposure type is greater than the difference between the two different types of exposure. The one possible area where there may be a discernable difference between light-exposed and dark-exposed η_{STC} is at the final outdoor exposure. For CdTe D, the indoor light-exposed modules did not experience additional power loss following outdoor deployment, while the indoor dark-current modules had $\Delta\eta_{STC}$ = -7%. A full description of exposure results are provided below.



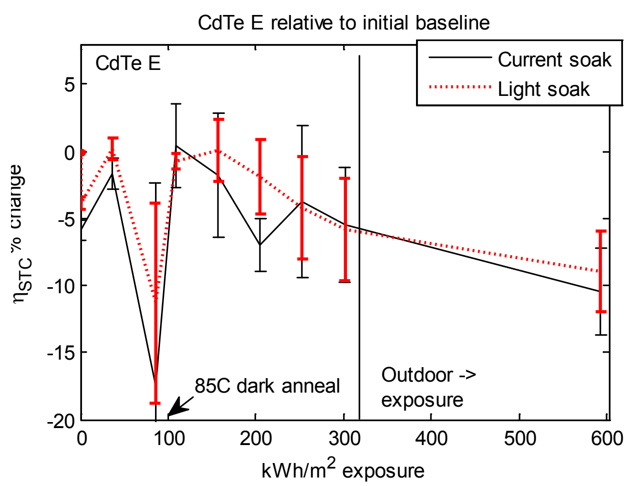
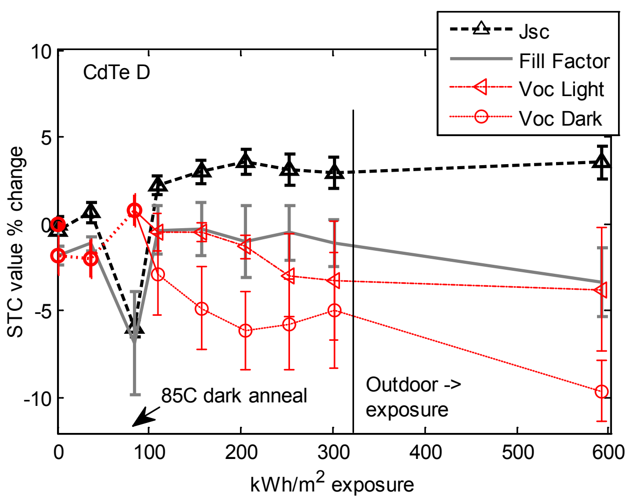


Figure 6 (left). Efficiency changes for CdTe D modules, relative to initial baseline exposure. The current-soaked modules experienced an efficiency drop during final outdoor exposure, but the light-soaked modules did not.

Figure 7 (right). Efficiency changes for CdTe E modules, relative to initial baseline exposure. Little apparent difference is visible between the light-soaked and current-soaked modules.

During the first two pre-conditioning steps (1.2 and 36 kWh/m^2 outdoor exposure) there is an initial ~5% decrease in η_{STC} after the first hour that is largely recovered during the remaining light-soak. A look at the I-V parameter changes in Figures 8 and 9 can provide some insight. The initial 5% drop coincides with loss in FF and V_{oc} in all modules, followed by a recovery of FF and an increase in J_{sc} through the second outdoor light-soak increment. The dark thermal anneal step causes degradation in η_{STC} for all modules, to varying degrees. The FF is primarily affected, being reduced by an average of -6% for both CdTe D and CdTe E modules. J_{sc} is also similarly affected, with a similar -6% change on average for D and E modules during the dark anneal step. This situation is different from that of CdTe A and CdTe C modules, where J_{sc} remained unchanged during the dark anneal step. The changes seen in V_{oc} during dark anneal differ slightly between CdTe D and CdTe E modules. For the CdTe D modules, there is a uniform increase in V_{oc} of ~2% on average. This follows similar behavior of CdTe A and CdTe C modules, where V_{oc} increases slightly during dark anneal. With the CdTe E modules, the response varies from module to module, with roughly half showing a 2% increase in V_{oc} and the other half showing a 2% decrease in V_{oc}. Interestingly, in subsequent exposure steps, those modules that had an increase in V_{oc} gave up some of those increases, while modules that had lost V_{oc} during dark anneal had a subsequent improvement. It appears that the dark anneal is driving metastable V_{oc} changes in opposite directions for different modules, which are subsequently stabilized during indoor light or current exposure. More detailed plots of these modules are given in Appendix A.

The losses sustained during the dark anneal step are reversed during subsequent indoor exposures. After 24 hours of either light or current exposures, most CdTe D and CdTe E modules' η_{STC} were within 4% of baseline values. Although module efficiency trended lower for all modules throughout the remaining exposure steps, on an individual module basis, all of the modules had stabilized by the end of the indoor exposure sequence, according to the IEC 61646 criterion, to within 2%. However, while there were 48-hour increments in which $\Delta\eta_{STC}$ was less than 2% for each of the modules, there were also many increments in which the module $\Delta\eta_{STC}$ was equal or greater than 2% in 48 hours, sometimes after the module would have been deemed "stable" based on IEC 61646. The CdTe D and CdTe E modules never achieved the same level of stability as the CIGS C modules or other CdTe modules through this exposure procedure. Some additional short-term transients that were not controlled for in the experiment may be contributing to this apparent instability.



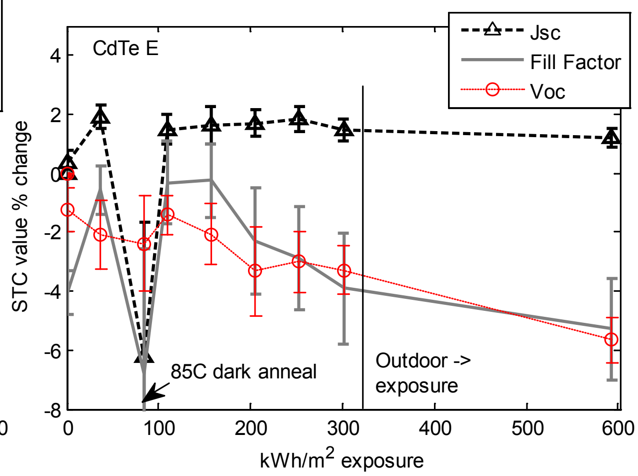


Figure 8 (left). I-V parameter changes for CdTe D modules, relative to initial baseline exposure. There was an apparent difference between V_{oc} in current-soaked modules and light-soaked modules, so these values are plotted separately.

Figure 9 (right). I-V parameter changes for CdTe E modules, relative to initial baseline exposure.

Following the indoor light and dark exposure increments, the CdTe D and CdTe E modules were deployed outdoors for ~300 kWh/m^2 light exposure. A slight difference was found between the light-soaked and dark-soaked CdTe modules. In particular, modules that had previously been exposed to indoor dark bias experienced a greater loss in η_{STC} during outdoor exposure. In the case of CdTe D, the dark-soaked modules lost around -7% η_{STC} while the light-soaked modules lost only -0.5% η_{STC}. For CdTe E modules, the difference is less stark, with dark-soaked modules having $\Delta\eta_{STC}$ of -5% and light-soaked modules having $\Delta\eta_{STC}$ ~ -3.5%. Examination of Figure 8 indicates that the difference between light-exposed and current-exposed modules rests primarily in the difference in V_{oc}, which decreased significantly in the dark-exposed modules following final outdoor exposure, but remained the same in light-exposed modules.

5. DISCUSSION

5.1 IEC 61646 light-soaking recommendations

A primary purpose of this exposure experiment was to investigate the IEC 61646 qualification procedure as written and to determine if it contains an appropriate-duration light-soaking regimen following a CdTe or CIGS module's exposure to indoor accelerated stress. For almost every module tested here, whatever η_{STC} changes were produced by our "dark anneal" indoor exposure were largely reversed by the very first 24-hour increment of exposure. The reversal occurred whether either light-soaking or dark bias at 65°C was employed as the exposure condition. Aside from a slight difference in V_{oc} for CdTe D modules following outdoor deployment, there was hardly any discernable difference between an indoor light-soaked module and a module exposed to 65°C in the dark with module bias at I_{mp} in this experiment. And the largest $\Delta\eta_{STC}$ recovery following the dark anneal step occurs in the first 24-hour exposure.

However, the metastable performance changes in this experiment were not completely realized in the first 24-hour exposure. Additional stabilization intervals resulted in additional incremental changes—within the 2% IEC 61646 limit for some modules, and greater than 2% for other modules. It is difficult to determine to what extent these changes are metastable effects relaxing to their "true" value through additional stabilization, as compared to long-term irreversible changes that may be occurring simultaneously. For obtaining stabilized performance at the 2% level or better, our data show that the CIGS modules in some cases required greater than 100 hours of exposure using either light-soaked or biased exposures at 65°C indoors. There did not appear to be any additional simultaneous instability or long-term degradation in these modules (aside from CIGS A2, which experienced R_s degradation).

For CdTe modules, our tests involved a total of 200 hours of exposure, and it is difficult to say that module stability improved to wtihin 2% during this exposure interval. In particular, CdTe D and E modules experienced V_{oc} and FF loss throughout the exposure sequence, possibly as a result of the additional "stabilization" exposures. There is also the issue of inherent instability in some of the CdTe modules. As opposed to the CIGS modules, which showed relatively little change from stabilization step to stabilization step, the CdTe modules could vary widely from step to step—sometimes losing >5% η_{STC} in one exposure step to regain it in the next. This inherent variation coupled with a decreasing trend in η_{STC} suggests that such modules with inherent variation may never meet the IEC requirement of $\Delta\eta_{STC} < 2\%$—and may also be exposed to unrelated stress through the stabilization process.

Two points are therefore identified for the light-soaking requirement as stated in IEC 61646, Section 10.19. First of all, it is pointed out that while some modules may have reached a "stable" condition (η_{STC} within 2% between subsequent measurements) after two 43 kWh/m^2 exposure increments, we have identified continued monotonic increases that may result in a final stabilized value several percentage points higher (or lower) than the value at 86 kWh if the module were to be further light-soaked. Depending on the accuracy required for the measurement, a minimum light exposure of 100–120 kWh/m^2 may be required to completely drive out metastable changes in the module.

Additionally, it is acknowledged that certain modules may display apparent instability from measurement to measurement in a non-monotonic fashion. This may be caused by short-term transient behavior that is not accounted for in the exposure or measurement process and may prevent the module from being declared stable when in fact most long-term reversible changes have already occurred. To account for this possible measurement issue, it is suggested that two adjacent 43kWh/m^2 measurements be averaged if they can be considered non-monotonic and then compared with the third 43kWh/m^2 measurement. To illustrate, consider P1, P2, and P3, each a module power measurement following a 43 kWh/m^2 exposure increment. If P2 < P1 but P3 > P2, then P2 and P3 would be averaged, and P1 would be compared with the average of (P2,P3) in the equation: $2*(P_{max} - P_{min})/(P_{max}+P_{min}) < 2\%$. This should provide some allowance for transient effects in η_{STC} measurements likely tied to extrinsic factors rather than effects intrinsic to the semiconductor.

5.2 Difference between indoor and outdoor stabilized condition, and dark and light bias

Regarding the effective difference between indoor light-soaking at V_{mp} and dark exposure at 65°C with module bias between V_{mp} and V_{oc}, this experiment has shown little difference between the two conditions in recovering initial dark anneal η_{STC} loss. Particularly in regards to recovering losses from the dark anneal step, both 24 hours of light-soaking and 24 hours of dark bias exposure appeared equally effective. It may therefore be appropriate to suggest dark exposure at I_{mp} forward bias and module temperature between 40°–60°C (to mirror existing IEC 61646 rules) as an appropriate alternative to indoor light exposure for CdTe and CIGS modules. One possible mitigating factor with this suggestion is the fact that differences in V_{oc} were evident in light- versus dark-exposed modules following outdoor exposure. Particularly for CdTe D and E modules, the indoor light-exposed modules stabilized more closely to outdoor final values of η_{STC}. There may therefore be some value in indoor light exposure, especially if the module has a known sensitivity to light exposure in particular (versus a metastability equally driven by light or by forward bias).

5.3 Instability of polycrystalline thin-film measurements

Transient changes in CIGS modules appear more reversible and predictable than in CdTe modules. Our C-V data showed that for CIGS modules, carrier concentrations decline by factors of 5 to 20 after dark thermal anneal. but these are reversed in subsequent exposures lasting ~100 kWh. The V_{oc} and FF losses in CIGS observed after dark thermal anneal or exposures also appear consistent with theoretical models that indicate a correlation between larger depletion width and a lowering of V_{oc} and FF[20].

More variation is apparent when some of the CdTe modules' η_{STC} is measured. It may be the case that CdTe modules have more intrinsic variability, and a larger sample set is required. Some of the variation may also be related to short-term V_{oc} and FF transients, which were found in some CdTe modules on time scales of ~1 hour following light-soaking[21]. If this is the case, short-term transients may introduce random uncertainty in STC measurements as modules are allowed to relax in the dark to different extents following light-soaking or dark bias exposure. Some suggestions may be given to possibly address this issue. Applying forward bias to the module right up to the point of I-V measurement could possibly reduce measurement uncertainty for these CdTe modules; so could applying strict requirements on the amount of time lag allowed between the indoor light-soaking increment and the indoor STC performance measurement. A third option is low-level light-soaking while the module cools to STC temperature. Additional research on this point may provide verification of these recommendations.

5.4 Module pre-conditioning

Our test plan also included simple outdoor pre-conditioning—similar to that currently used at NREL and other test labs—but ours comprised two steps of short and longer durations. Our pre-conditioning tests and data suggest that transients are still occurring and/or not saturated until well after 1 kW-h/m^2. This is shown in both CIGS and CdTe modules by the surprisingly large difference (up to 8%) in η_{STC} and I-V parameters between data points at 1 kWh/m^2 and 30 kWh/m^2. A more satisfactory amount of pre-conditioning would accrue up to 20–30 kW-h/m^2 to remove these metastable effects, but this is likely not feasible in a majority of test laboratories. This further highlights the difficulty of accurate η_{STC} measurements for thin-film modules.

6. CONCLUSION

We developed and executed a test plan to probe transitory electrical behavior and performance in CdTe and CIGS modules and applied it to several groups of modules, numbering a total of 28. Our initial goal as stated was to develop a set of procedures that will stabilize the measured performance of polycrystalline CdTe and CIGS PV modules, specifically targeting methods that improve upon the current thin-film stabilization standard—IEC 61646—as noted in the introduction.

Our data indicate that thermal exposures temporarily degraded performance by substantial amounts, but most of these losses were truly metastable phenomena and largely recoverable after ~24–72 hours in most cases, using either light-soaking or dark exposure with forward-bias currents near I_{mp}, while at elevated temperatures (65°±10°C). This represents a very positive result with regard to reversing metastable losses.

As a result of our series of tests, it became clear that certain modules (notably CIGS and certain CdTe) stabilized quickly, within the first two exposure steps. Other CdTe modules required additional time to be considered "stabilized" as per the IEC 61646 guidelines. A persistent loss in FF and V_{oc} coupled with possible short-term transient effects made measurement within 2% difficult for some CdTe modules. This difficulty could possibly be mitigated by further investigation and control of short-term V_{oc} changes, along with a shorter IEC 61646 light-soaking interval for CIGS and CdTe modules. An alternative stabilization method involving indoor dark exposure at 65°C with module bias between V_{mp} and V_{oc} was compared with the traditional indoor light-soaking. The indoor dark exposure was found to cause similar metastable changes in all I-V parameters for both CIGS and CdTe modules. Some difference was evident in V_{oc} changes in CdTe D modules between the light and dark exposure segment, but this was not the case for other modules.

7. ACKNOWLEDGEMENTS

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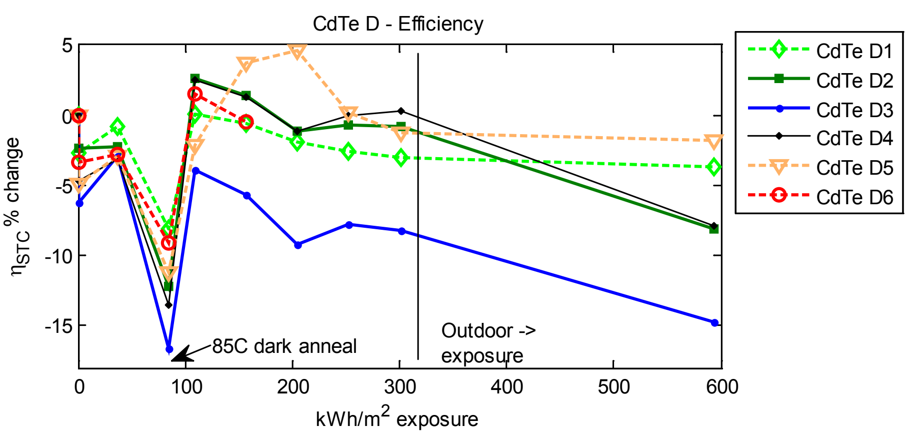
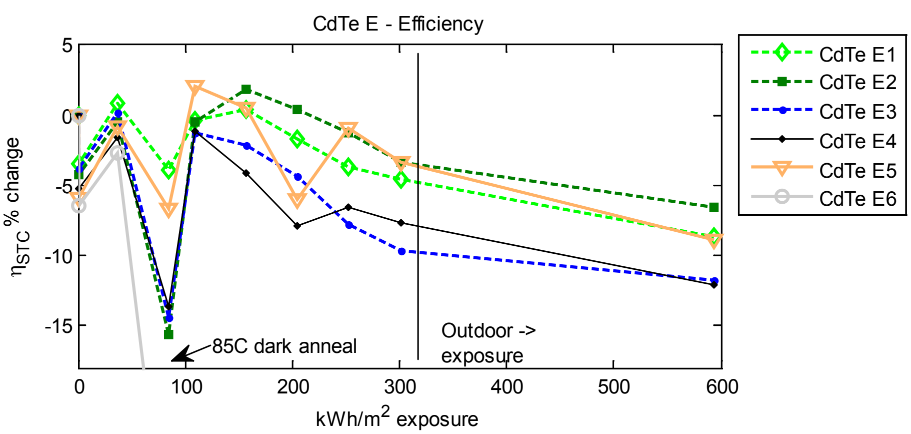
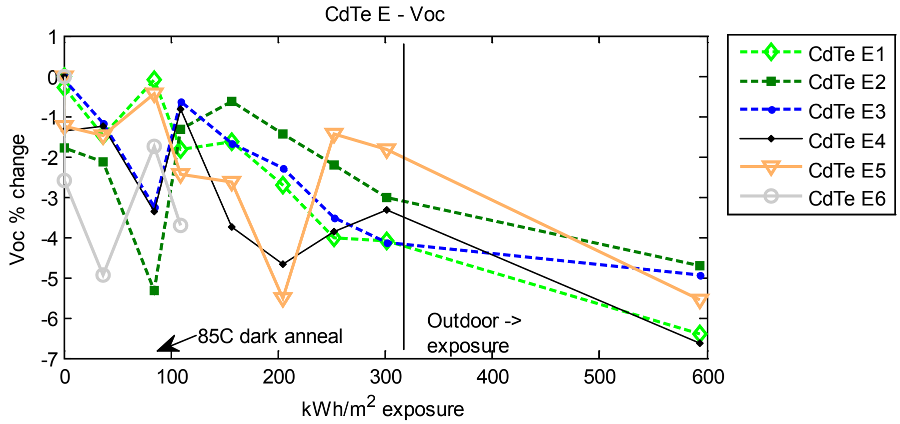
APPENDIX: ADDITIONAL RAW DATA PLOTS







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