

Meta-stability of Crystalline
Thin-Film Photovoltaic Modules

by

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ABSTRACT

Given the growing market in solar energy, specifically by the thin-film technologies, it is imperative that adequate and accurate standards be developed for these newer photovoltaic devices. Cadmium Telluride, CdTe, one of the major players in the thin-film PV industry is currently rated and certified using standards that have been developed under the context of older technologies. The behavior of CdTe has been shown to be unique enough to suggesting that standards be revised. In this research, methods built on previous industry and independent studies are used to identify these unique behaviors. As well new methods are developed to further characterize CdTe modules in the context of current standards. Clear transient and meta-stable behavior is identified across modules from four different commercial manufacturers. Conclusions drawn from this study show illumination and temperature hysteresis effects on module ratings. Furthermore, suggestions for further study are given that could be used to define parameters for any reexamination of module standards.

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CHAPTER 1

INTRODUCTION

1.1 General Overview:

Solar energy technology has grown significantly in recent years and with this growth comes a need to understand the behavior of each new technology. Some knowledge of previous Photovoltaic (PV) technologies can be carried over, but there are characteristics unique to emerging materials that require further research to appropriately integrate them into the marketplace. Previous standards may now be reviewed based on research such as that presented in this paper and similar papers.

PV is the conversion of light energy directly to electrical energy, and the technology shares much of its scientific fundamentals with that of general semiconductor electronics. As such, the PV industry, which grew up in the mid-twentieth century, is based around silicon technology and continues to use it to a large extent. This means that most of the research into PV applications and standards thus far has focused around the material characteristics of silicon. This is evident from a general survey of PV standards publications such as: IEC 611215, IEC 61646, [1]. Since the former pertain specifically to mono- and poly-crystalline silicon technologies, the latter is intended to encompass these newer thin-film technologies but is still not designed to their material characteristics.

Recently, these novel materials have become more prevalent and have opened a new area in the PV industry associated with what is called thin-film technology. Polycrystalline thin film technologies such as Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS) have high absorption coefficients [2] and differ from crystalline-silicon because this material characteristic allows the PV devices to be made thinner. Amorphous silicon (a-Si) has for a relatively long time now been used to create thin-film modules, but has characteristics significantly different from CdTe and CIGS. This fundamental difference in new materials means there is a large potential for growth in this sector of PV.

The materials used in these PV technologies have been known to be able to harness the power of the sun for many years, but only recently have they become developed enough for consumer and commercial application. As early as the 1960's, PV devices made using a material called cadmium telluride (CdTe) were being explored in laboratory settings. Commercial modules using this technology have been available since the 1990s. Recently, one CdTe module manufacturer has claimed that they have developed a photovoltaic power plant that provides energy at a cost comparable to the current market rate [3] (this is a reference to the original report by Mark Bachman of Pacific Crest). This could mark a huge milestone in the cost savings that drive the thin-film industry. Of the emerging PV materials, only Cadmium Telluride will be covered in the scope of this paper though it should be noted the many of the general module behaviors between CdTe and CIGS are similar.

1.2 Issues with New Technology:

Presently the standards that outline PV module rating seem to be falling short when applied to newer thin film modules. Firstly, amorphous silicon thin-film modules have significant initial degradation that requires a stabilization process before they can receive certification testing. Other thin film materials also require a stabilization procedure; however, the current amorphous silicon based procedure does not seem to have the same effect on the newer materials. Amorphous silicon's behavior is almost solely dependent on two factors: its irradiation and temperature history. On the other hand, CdTe modules have degradation trends that show signs of being sensitive to recent irradiation and temperature treatment as well as other significant variables such as time and temperature in dark storage.

1.3 Primary Purpose:

It is the purpose of this research to explore the meta-stable and transient behavior seen in CdTe photovoltaic devices. Further knowledge in this area is hoped to yield alternative procedures that can be performed on these types of modules to effectively stabilize their performance characterization and pragmatically rate PV devices.

Furthermore, it would be of added benefit if these new procedures allowed the certification process to be streamlined.

The technology will be characterized using techniques used by manufacturers and researchers alike [4], [5]. In this regard, the results of this exploration will be comparable and repeatable for future work. From this base it is hoped that new methods developed here will also be comparable, repeatable and seriously considered for further advancement of knowledge of CdTe PV devices.

CHAPTER 2

LITERATURE REVIEW

2.1 General:

Though the materials differ between PV module technologies, the semiconductor physics is relatively consistent. The material covered in this paper, CdTe, is a polycrystalline structure which is similar to the more common polycrystalline silicon (polySi) modules in this respect. However, Cadmium Telluride can be made as a thin-film, like amorphous crystalline silicon (a-Si) another common type of solar module. Because CdTe modules inhabit the space between the general characteristics of c-Si and a-Si, the standards of certification for CdTe modules may need to be modified from those currently used – which were “really meant for a-Si” [1].. This paper is a continuation of a study pertaining to the unique CdTe and CIGS behaviors , relative to a-Si, forming new models of the material dynamics and, possibly, new procedures for certification at the module level.

2.2 Journal Findings:

2.2.1 PN-Junctions and diode modeling

The pn-junction is a most fundamental concept in semiconductor physics as it relates many of the PV technologies as well as many other technologies common today [6]. Though this paper is concerned only with the PV applications of semiconductors it is important to keep in mind that the following treatment of PV devices is mature and accepted in the semiconductor industry for pn-junctions analysis.

To begin, single PV cells can be modeled by a single and double diode circuits. The equations from these models are then used to describe the current-voltage characteristics of the device. A model for a PV device as seen as a two diode equivalent circuit is given below in equations 1 and 2. It is assumed that the first diode quality factor is 1 in this model. The listed parameters are commonly empirically cross-checked to complete the model analysis.

$$I = I_{01}\{e^{qV_j/kT} - 1\} - I_{02}\{e^{qV_j/n_2kT} - 1\} - V_j/R_{sh} \quad (1)$$

$$V_j = V - IR_s \quad (2)$$

where, I_{01} is the reverse saturation current,
 R_{sh} is the shunt resistance,
 R_s is the series resistance,
 n_2 is the diode quality factor.

There have been several papers published specifically on the behavior of CdTe and its parameters within these model equations, two of which are given in references [7] and [8]. It is demonstrated that CdTe is not typically well-behaved and modifications to the parameters must take into account many factors not seen in crystalline silicon or even amorphous silicon devices. In practice it is suspected that all the parameters could be voltage and/or light dependent in thin-films solar cells, which is a major source of complication in their analysis [8].

Hegedus reports that, “methods developed for characterization of crystalline semiconductor solar cells either do not apply or must be modified for valid application to [CdTe]” [8]. This follows a four point analysis of CdTe behavior with respect to a single diode equation and relative to a-Si behavior under the same analysis. However, one stable parameter of the model revealed that the temperature behavior V_{oc} in CdTe is strictly linear and would in fact extrapolate to the value of the accepted bandgap as shown in Figure 1 [8].

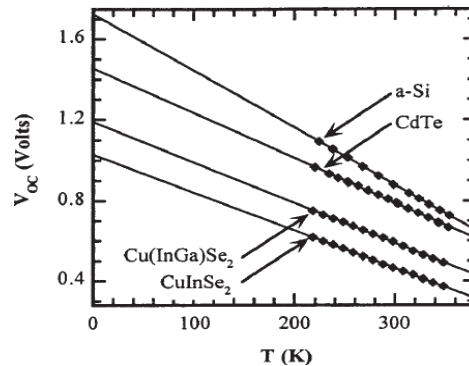


Figure 1: V_{oc} Temperature dependence on four different thin-film technologies, in each case as the $V_{oc} \rightarrow E_{bandgap}$ as $T \rightarrow 0$

The temperature analysis in the figure above corresponds well to the findings presented later in this paper in terms of linearity of V_{oc} with temperature. However beyond temperature, Hegedus's analysis is concerned with issues outside of the scope of this paper.

The other study mentioned, published through NREL, used the standard two diode model modified by another diode circuit which had been shown empirically capable of matching current-voltage characteristics. The rationale behind this modification stems from the known non-ideal conditions that exist in the material near the pn-junction - such as the presence of impurities and structural defects [7]. It is these two studies that fundamentally show the differences in between CdTe and other PV technologies which are held the standards.

PN-junction devices are manufactured in various ways and configurations depending on the application. CdTe cells are typically manufactured using a vapor transport deposition (VTD) process in which a pure source of the element is evaporated in a vacuum chamber and allowed to settle on a given substrate [9]. Though given the name CdTe technology, PV modules using this material are actually composed of a CdTe p-type layer and a CdS n-type layer. A recent analysis of manufacturing parameters gives more details into the forming of the junction in CdTe devices and yet another analysis tool [10]. As such the fabrication of the device which involves selection of back contact, deposition times, post fabrication annealing and chemical treatments, all play role in determining the impurities and structural integrity of the junction.

2.2.2 Meta-stability in Light I-V Measurements

Meta-stable behavior can be described as behavior in which the measured parameter trends in one direction for a short period of time (i.e. on an hour time scale) but follows a different trend pattern for the remaining duration. An example of this type of behavior was found in CdTe cells exposed to 1-sun irradiance at select temperatures for stress durations of over 700 hours as seen in Figure 2 and Figure 3 [7].

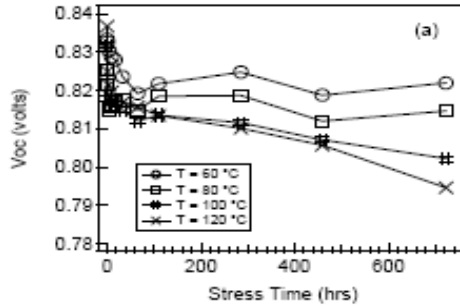


Figure 2: Change in V_{oc} as a function of time and stress temperature

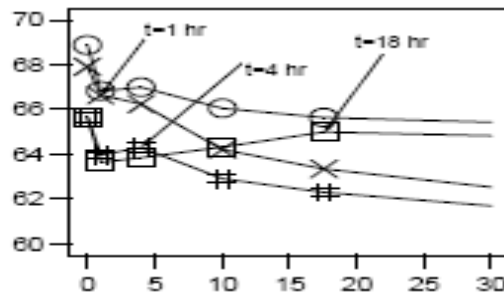


Figure 3: Non-monotonic change in cell Fill Factor observed during initial stress (FF vs. Stress Time)

It should be noted that the measurements taken in the figures above were done after the module had been removed from light exposure and held in dark storage for 12-24hr. Thus these are not real-time measurements of the module in continuous exposure.

Other research tracking CdTe module performance has also revealed non-monotonic behavior in many of the rated parameters such as open circuit voltage, short circuit current and fill factor. An earlier 2000 study and the NREL report after which this current research is based both show meta-stable behavior of module parameters under extended light exposure and/or cycling [11], [12]. Dobson et al. compares parameter trends under various voltage biases as a method of exploring degradation characteristics related to junction degradation and back contact degradation. Their findings show an initial increase in V_{oc} , as opposed to the sharp initial drop seen in the previous figures, but Fill Factor behavior remains consistent between both studies.

The del Cueto et al. report shows both meta-stable behaviors seen in the previous two papers, though in this case the behavior is seen on the module level [12].

Light cycling produced improvements in some module parameters for part of the sample pool and degradation in the other. Here again it is proposed that the junction's structural defects and back contact degradation hold the key to the abnormal behavior of CdTe.

Indeed, long-term field exposure data on CdTe arrays has shown mixed performance on the module level. In the report, the array had an output drop of 3.3% over 5.5 years (similar to crystalline-Si based PV technology), yet individual module performance varied between 15% degradation and 20% improvement [13]. Though this type of extreme result not completely consistent with manufacturer reports, various CdTe manufacturers have reported some meta-stable behavior [4], [14].

As one very consistent theme running through all these reports is the connection between the choice of back contact and meta-stability. The use of Cu to form a better contact has also introduced mobile ion impurities into the PV material. It is believed that Cu ions move from the back contact to the junction area for even small amounts of Cu in the back contact [15]. This Cu mobility has been quantitatively shown to effect performance, ostensibly by creating recombination sites in the junction area and narrowing the junction field region [16]. It is thought, however, that this ion mobility effect is reversible and techniques to stabilize CdTe devices are being explored.

2.2.3 Voc and Transients

Also of particular interest in this study are the open circuit voltage transient characteristics of CdTe solar cells. The transient behavior introduced here is that which dominates during a shorter period of time than the meta-stable behavior described earlier. This type of characteristic can be seen strongly in open circuit voltage as most transients are related to energy band gap traps [17]. In fact the behavior illustrated in Figure 3 is an example of a transient as it last only over a few hours and then the cell is dominated by stabilization effects.

A measurement program consisting of real time measurements of modules under light exposure could reveal the transient beyond just the cell level and illuminate trapping dynamics in CdTe modules. Traps at mid-bandgap energies have been explored

extensively but only on CdTe cells [18]. It is hoped that by tracking a Voc transient in modules trap energies can be determined through the discovery of a predictable transient time. The transient is likely to be illumination as well as temperature dependant, but, returning to the diode modeling, at constant temperature the illumination effects on the diode quality factor could be extracted. This hinges on the dependence of the diode factor on the energies of the dominant trap states [8].

2.3 Thin-film Standard:

The current standards call for a specific treatment of thin-film modules for certain test sequences. Because performance rating can be significantly affected by unstable behavior from thin film modules certification requires a light soaking. These are outlined in standards such as IEC 61646 [19]. Light soaking is one of the procedures involved in stabilizing modules for performance testing based mainly on the illumination induced stabilization effects in a-Si [12].

This standard, however, does not restrict continuous light exposure for light soaking, thus accommodating outdoor light soaking. In light of this, stabilization calculations measuring across a period of dark storage are currently acceptable and no requirement is given to such dark durations. It is plausible that cycling parameters could affect module stability in CdTe based devices and periodic transients could also result in comparability issues between data points. As an example, a strong transient coupled with longer-term meta-stable characteristics, as seen in some of the references above, could cause wide variations in measured performance if the timing of the measurements is not strictly defined.

Also under-addressed in the currently accepted standards are procedures for baseline and temperature coefficient measurements. Temperature coefficients (Tcoef) can be dependent on the irradiance and temperature history of module at the time of measurement. A hysteresis is known to exist between Tcoefs taken while the module heats up versus cools down. A procedure to supplement IEC 60891 and IEC 60904-10 may be of value as new technologies penetrate the PV market.

CHAPTER 3

METHODOLOGY

3.1 Introduction to process:

The goal of these procedures was to catch light induced meta-stable behavior by cycling CdTe modules through periods of light exposure and dark storage. Environment and stress were the two control factors and various techniques were attempted to account for them throughout the experiment. The measurements taken during the sequences were full light voltage-current (I-V) sweeps, though the major focus of this experiment was open circuit voltage (Voc). Temperature measurement techniques also adapted during the course of the research to accommodate new equipment.

3.2 I-V Curve Measurements:

Though this research is concerned primarily with Voc behavior, full current-voltage curves were taken to have as much data as possible at the conclusion of the experiment for future students. It was decided that only light I-Vs would be performed because light induced current paths are different than those induced by electronic load. As literature suggests, this difference influences parts of the performance curves and could possibly influence the transient behavior of the semiconductor material if it is illumination dependent [20].

Current-Voltage curves were taken by two different machines during the course of the experiment. The first is the Daystar DS-100C Photovoltaic I-V Curve Tracer and the second is the Spire Sun Simulator 4600SLP. Both of these machines are capacitive load measurement devices that perform sweeps from Isc to Voc. Each is a four probe device with a trace time of 60 ms-2s. Calibration and cross-checks were performed before each measurement each day.

Cycling consisted of exposing modules in a solar simulator for a specified duration while taking a sequence of I-V measurements, then storing the modules in the dark while again taking a sequence of measurements. The measurement frequency during all cycling was broken down in the following manner: curves were taken every 2-3

minutes for 3 hours immediately after transitions, every 15min for the next 8 hours, and then every few hours over the rest of the cycle duration. One cycle consists of one light sequence and one dark sequence. Once Voc behavior patterns were established the measurement intervals were adjusted accordingly so that test equipment would be free for other projects. Module and ambient temperatures were taken concurrently with I-V measurements as described in the following section.

Further into this research a new curve tracer, the PERT1, became available and was from this point used exclusively for the remainder of the experiment. The PERT1 is a programmable multi-curve tracer with 15 data collection ports and is also an electronic load. Therefore data collection and module loading were automated for module set "D".

3.3 Temperature measurements:

The accuracy of temperature measurements is of primary importance to the scope of this experiment. As such, careful procedures have been developed to assure that temperature is taken with as little error as possible. With this accomplished it is hoped that temperature effects can be accurately tracked and the true Voc transient can be revealed.

Temperature measurements on the "A" module set were made almost exclusively with K-type thermocouples attached to the top center of the module back side during light soaking. Later in the research T-type thermocouple measurements were taken to compliment the K-type. T-type measurements were also used to provide complimentary data for the temperature coefficient calculations during the novel Tcoef procedures. During the flash measurements of the dark storage sequence temperature was measured using an IR thermometer integrated into the Spire unit. The placement of the IR thermometer was over the same spot that the thermocouples were attached, the thermocouples were removed at this time.

In the later phases of the experiment, when the PERT1 unit was used, all temperature measurements were made using T-type thermocouples only. The PERT1 collected this data and automatically associated it with the proper input channel.

Placement of the thermocouples was also changed. Three thermocouples were used on each module with the following locations: the front center, front upper corner, and back upper center (for comparison to original temperature measurements). This placement required exploring several combinations of attachment techniques. The considerations for this are: attachment method and path to location.

The attachment of the Tcoef junction to the module was explored using semi-transparent thermal tape and a combination of thermal tape and foil tape processes. It was thought that shading the junction would protect it from direct heating from the sun or other irradiance source. In both cases the size of the tape was made as small as possible while still securely attaching the thermocouple to the module. A photo of these methods is given in Figure 4.

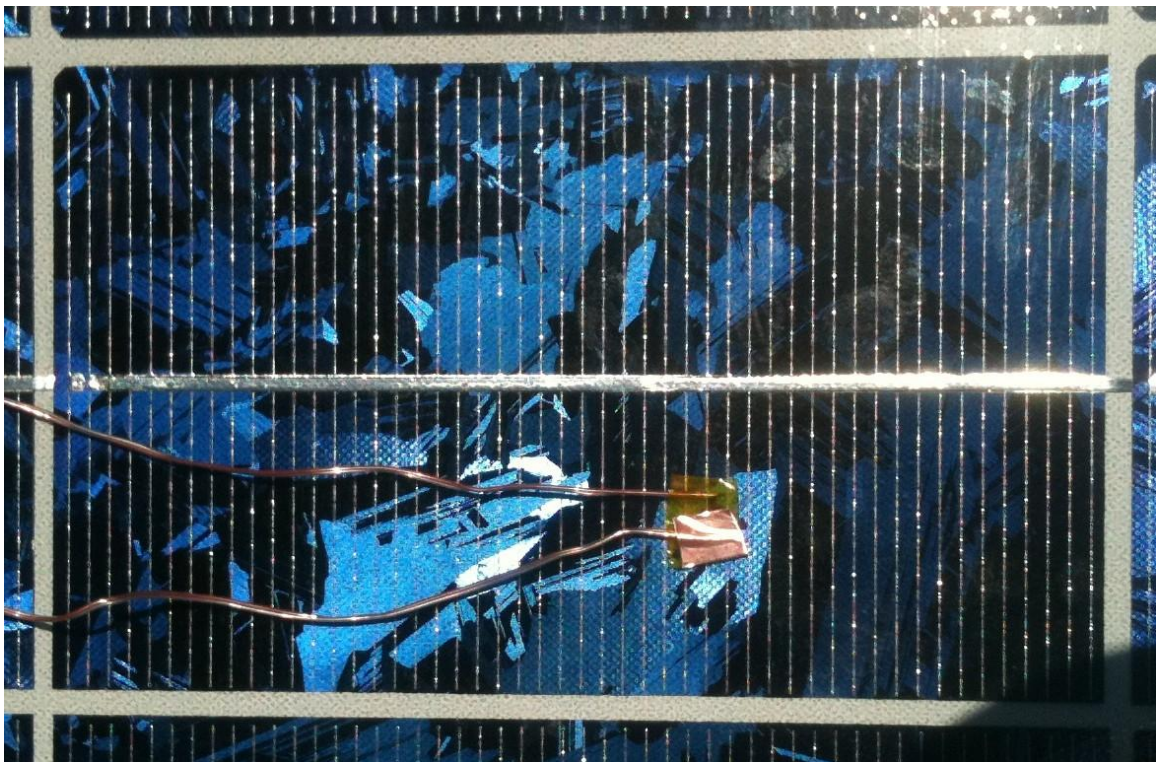


Figure 4: Photograph showing test of thermocouple attachment test set-up on dummy module.

Using an IR camera the thermocouple attached with thermal tape alone gave a reading consistent with the overall cell temperature. The foil tape seems to retain heat on the thermocouple resulting in a temperature measurement approximately 5°C above that

of the thermocouple not covered with foil. These temperature tests were conducted using T-type thermocouples, a Fluke 52 II thermometer, and a Fluke IR camera.

With regards to the path of the thermocouple along the face of the module, shading must be reduced to an absolute minimum. Currently available thermocouples have a 10 mil wire diameter, with a total thermocouple dimension (two insulated wires together) of 25mil X 40mil. One method split the individual thermocouple wires and then the 10mil thin wires were run in between the cells of the module. A second option was to run the wire perpendicular to the cells which should have little effect since the thermocouple width is around 0.08% of the total cell length. Anchoring the wire was definitely the most difficult aspect using the split wire procedure since attachments can only be made at the very edge of the module and at the TC junction. Therefore, it was not guaranteed that the wires did not shift over and cover a long length of the cell.

Testing of the effect on I_{sc} and V_{oc} which these two paths had on the measurements was done on the flash simulator. The results of which showed that the split wire method had a larger effect on I_{sc} , and thus received irradiance, than running the complete thermocouple perpendicular to the cells.

3.4 Temperature Coefficients:

These measurements were in all cases taken in accordance to the standard IEC61646 [21], however exposure and temperature control methods varied. Linearity was determined by MS Excel as outlined in IEC 60904-10 [22].

Natural light with a spectral profile matching the ASTM G173-03 reference spectra was used to standardize any spectral effects that may be present. The spectral measurements are given in Figure 5 and Table 1 which show that natural light matches the reference spectrum within 2.5% over the CdTe spectral response range [15], [23], though the solar simulator clearly does not (Figure 6). A GaAs and a crystalline-Si (when possible) reference cell were used to measure the irradiance during the measurements, each being allowed to thermally stabilize beforehand.

Table 1: Comparison of natural light in Tempe, AZ to ASTM reference spectra.

ASTM G173-03 Reference Spectra Derived from SMARTS v. 2.9.2

Reference Irradiance for 100 nm band width (%)	Measured Irradiance for 100 nm band width (%)	Deviation from reference spectrum (%)	Bandwidth (nm)
18.70	18.50	-1.1%	400-500
20.27	20.67	2.0%	500-600
18.70	18.39	-1.7%	600-700
15.20	14.95	-1.7%	700-800
12.71	12.40	-2.4%	800-900
14.23	14.92	4.8%	900-1100

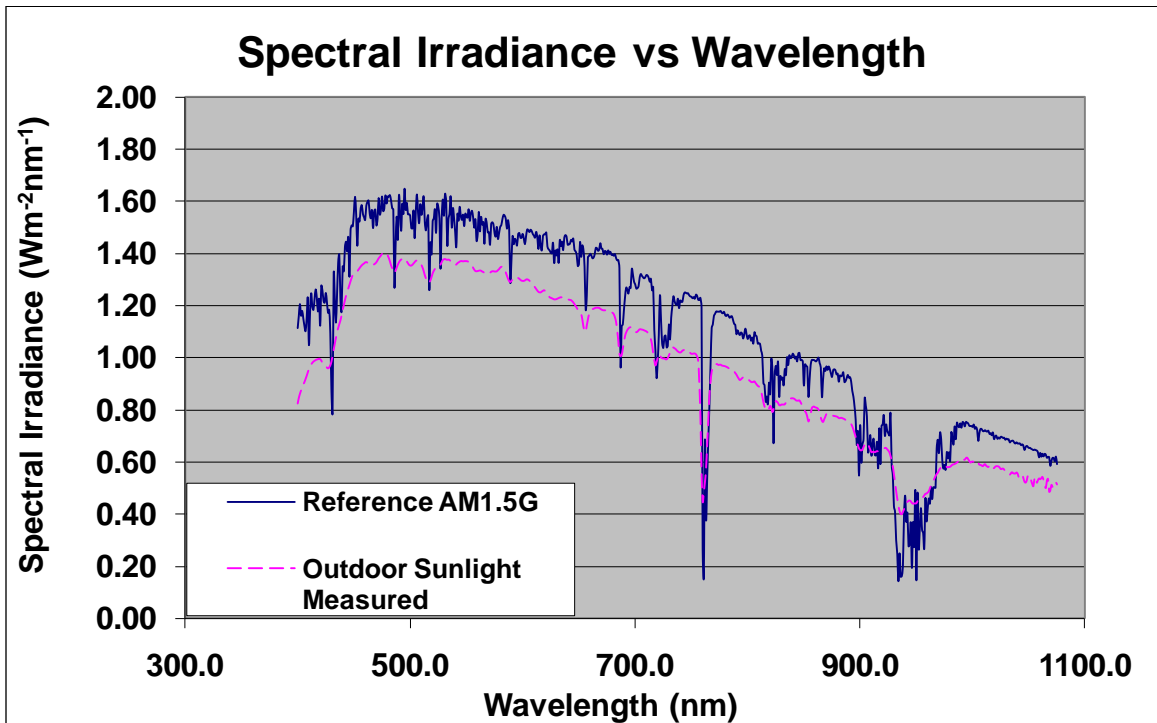


Figure 5: Measured natural light spectrum Tempe, AZ vs. ASTM reference spectrum. Another temperature coefficient was taken on the modules not using natural light for the purpose of matching a coefficient to the Spire Flash Solar Simulator. In this case the spectrum has been unable to be measured but the simulator is listed class “A”, therefore it is assumed there is no significant spectral variance that would result in misleading data. Monocrystalline silicon reference cells were built into the simulator and thus no match was able to be made with the CdTe technology.

The procedure for calculating temperature coefficients was to measure the performance of the modules as they heated up or, in the case of the temperature coefficient taken using the flash simulator, cooled down. A discussion of the temperature measurement methods is found later in this chapter. Modules were held in a dark “cool box” until the module temperature was near 20°C and then taken, while covered, to an outdoor I-V table. Here the face of the module was maintained normal to the sun and I-V traces were taken as the module’s temperature increased from approximately 25°C to 60°C. In the case of the coefficients taken on the simulator, the modules were heated in a dark air convection oven to approximately 60°C and I-Vs were taken as the module cooled down on the simulator. These two temperature coefficients are referred to as the conventional and “flash” respectively for the outdoor and indoor Spire simulator procedures.

To supplement the conventional outdoor temperature coefficients and account for any transient behavior present during initial exposure to light, a “novel” procedure was also used to calculate a coefficient. After the modules had I-Vs taken for the conventional Tcoefs they were left under natural light exposure for a few hours (2.5kWh to 3kWh). After this relatively short exposure period the modules were cooled using water until the modules stabilized at a temperature of approximately 30°C and I-V curves were taken again as the module heated up. The equipment and placement was not changed in any way between the conventional and novel Tcoef procedures. It should be noted that the modules did not receive any thermal shock from this processes as the water temperature at the initial cooling phase was near or above the temperature of the modules and gradually cooled over a time of 20-30min. The major benefit of this cooling method was that the modules remained under light exposure during the process. This temperature coefficient is labeled as the “novel” Tcoef and covers a temperature range from 30°C to 60°C.

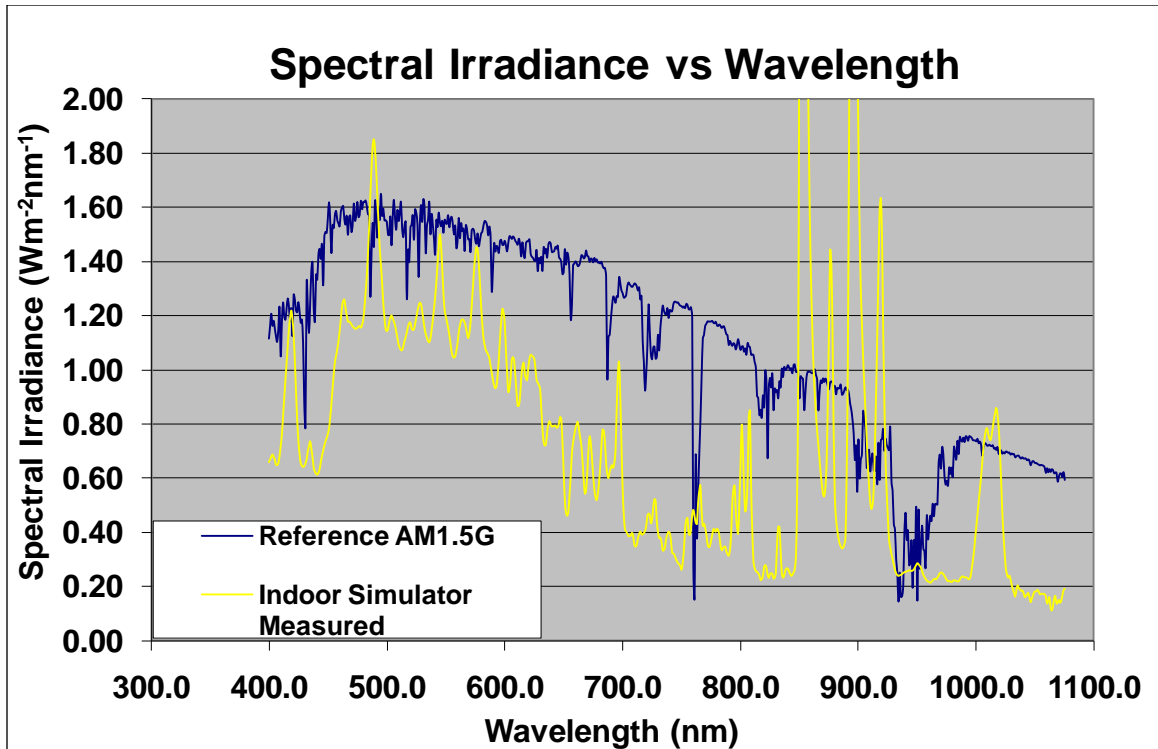


Figure 6: Measured spectral irradiance of Iwasaki Solar Simulator vs. ASTM reference spectrum.

3.5 Light Soaking:

The light soaking sequences for all modules was carried out in a class C large area Xenon arc lamp solar simulator. The Iwasaki Solar Simulation Chamber provided irradiance of approximately 800W/m². The temporal variance of the simulator was not specifically measured but evidence of its presence was found in the I-V curves, as can be seen in the wave pattern in the indoor solar simulator curve of Figure 7 and not in the natural light curve. The spectrum of the simulator was taken prior to this research and is given in Figure 6.

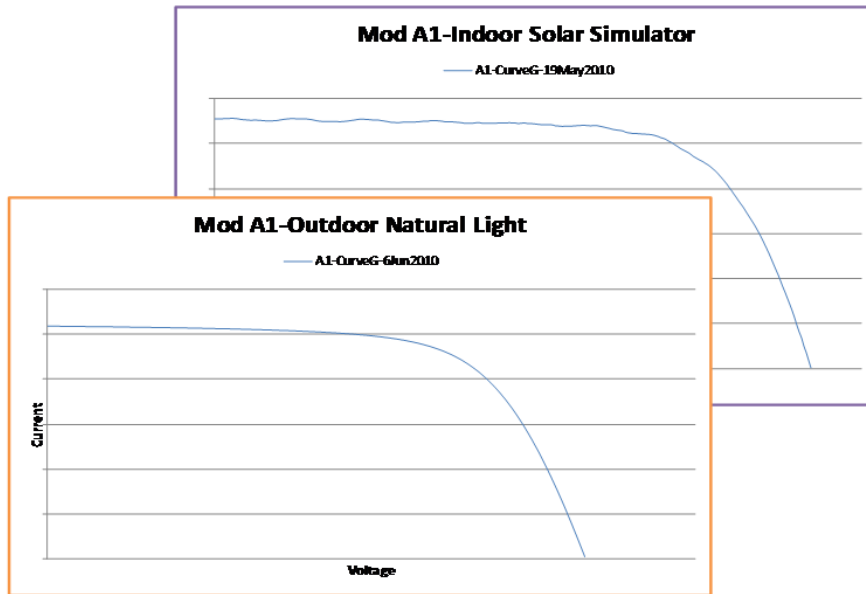


Figure 7: Comparison of I-V curves under natural (orange) and simulated (purple) light

During light soaking module A1 was held at P_{mp} loading and module A2 was held in open circuit conditions. The module loading for module set “A” was done by using a variable resistor set to the resistance calculated using the measured max power voltage, V_{mp} , and current, I_{mp} . However, the PERT1 has become available and will be used for loading on subsequent test runs using its MPPT capabilities.

Sequence duration was increased each successive light soak. In Figure 7, the approximate exposures are given in a timeline flow chart showing this increase in duration/exposure. The reason for this was to slowly identify an optimum exposure period that would capture the entire transient behavior while at the same time keeping exposure to a minimum.

As shown in the flow chart of Figure 9, exposures of nearly 200kWh were reached for both modules of set “A” by the third cycle, however a fourth cycle was executed on module A1. From the results of these cycles it was determined that exposures of 150kWh would be sufficient to capture meta-stable behavior and allow for IEC 61646 analyses for later module sets. This exposure period determination is expressed in the flow chart of Figure 10.

The switch to light exposure was preceded by a heating phase, in the dark, to near the projected module operating temperature. In this way thermal effects would be minimized during the first hour of light exposure. The heating phase took nearly 20 minutes to get the module to around 55°C, and transfer from the oven to the solar simulator to the first measurement took approximately 5 minutes.

Placement of reference cells was the same for all cycles for all modules and represented as best as possible the irradiance of the simulator. This was achieved using a stand that was placed in the simulator at a marked spot that gave irradiance readings close to the average over the total exposure area. Due to the temporal and especially spacial variance of the simulator, Isc and efficiency determinations are nonsensical to report. Measurements of voltage characteristics given in the next chapter are all normalized to initial value of the sequence L 1 I-V curve of each module.

3.6 Dark Storage:

Flash I-Vs were taken during dark storage sequence to provide a valid comparison between measurements taken during light soaking. As suggested in literature a dark I-V measurement would have significant enough differences from the light I-V to possibly skew the analysis of the module behavior [24].

Dark storage was done at a room temperature of 25°C and thus there is a large temperature gradient during the initial measurements taken during this sequence. Transfer to the flash simulator for measurement took no more than 5 minutes.

The Spire 4600 sun-simulator was calibrated to 1 sun of irradiance before every set of measurements. Reference cells were built into this device and unfortunately no irradiance comparison was able to be made using the reference cells of the light soaking sequence.

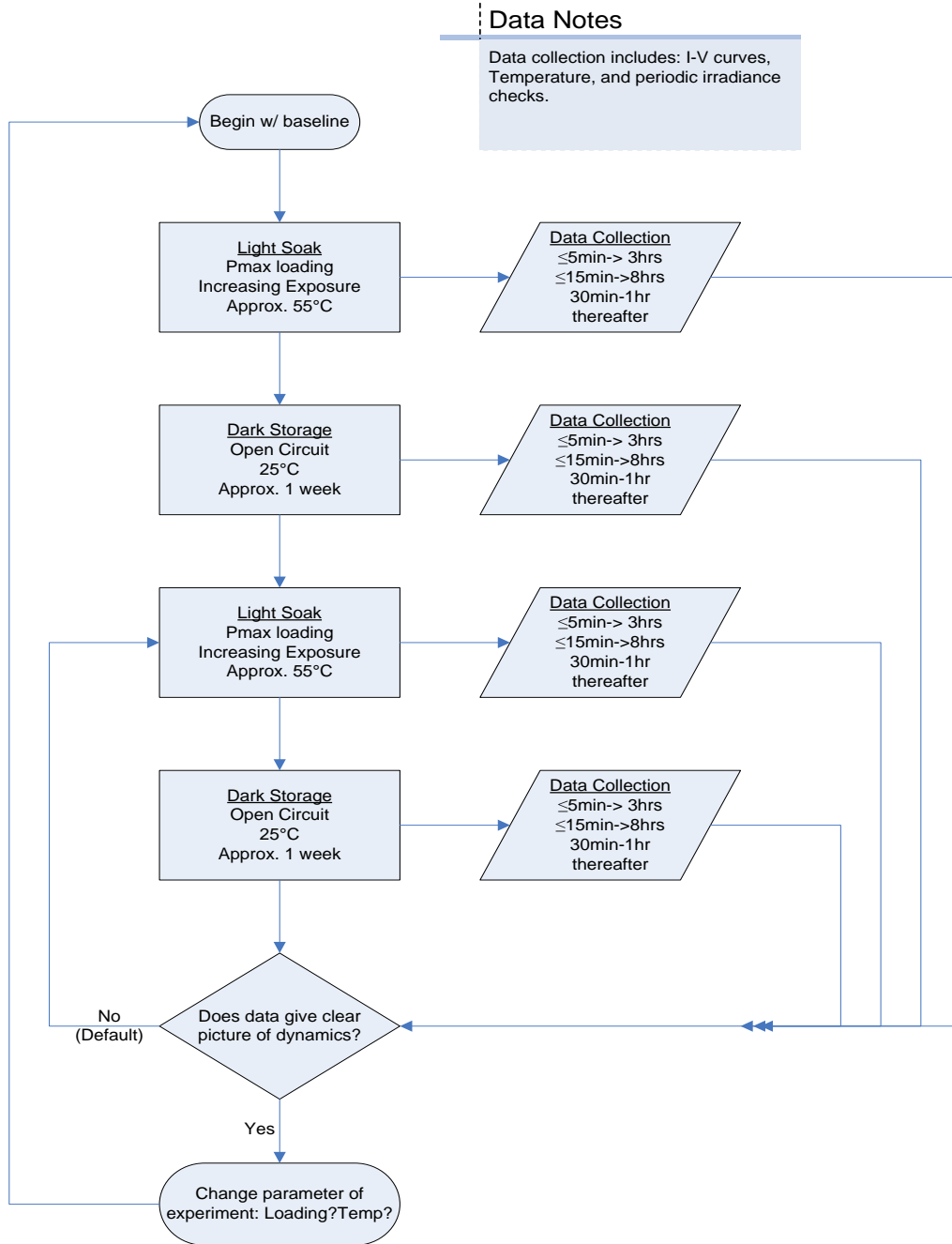


Figure 8: Experiment flow chart.

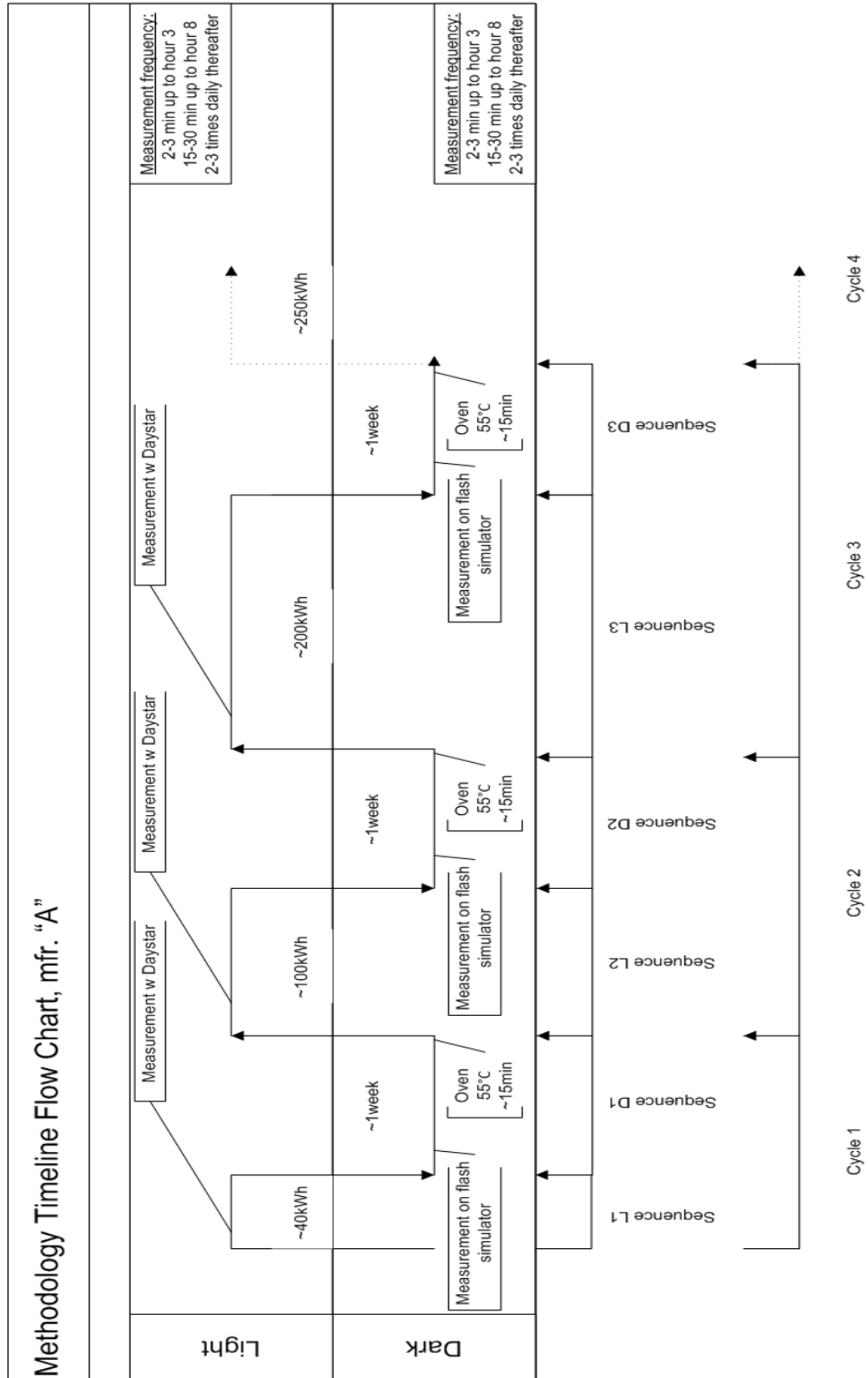


Figure 9: Time line flow chart of light cycling on module set "A" (note: only mod A1 went through cycle 4)

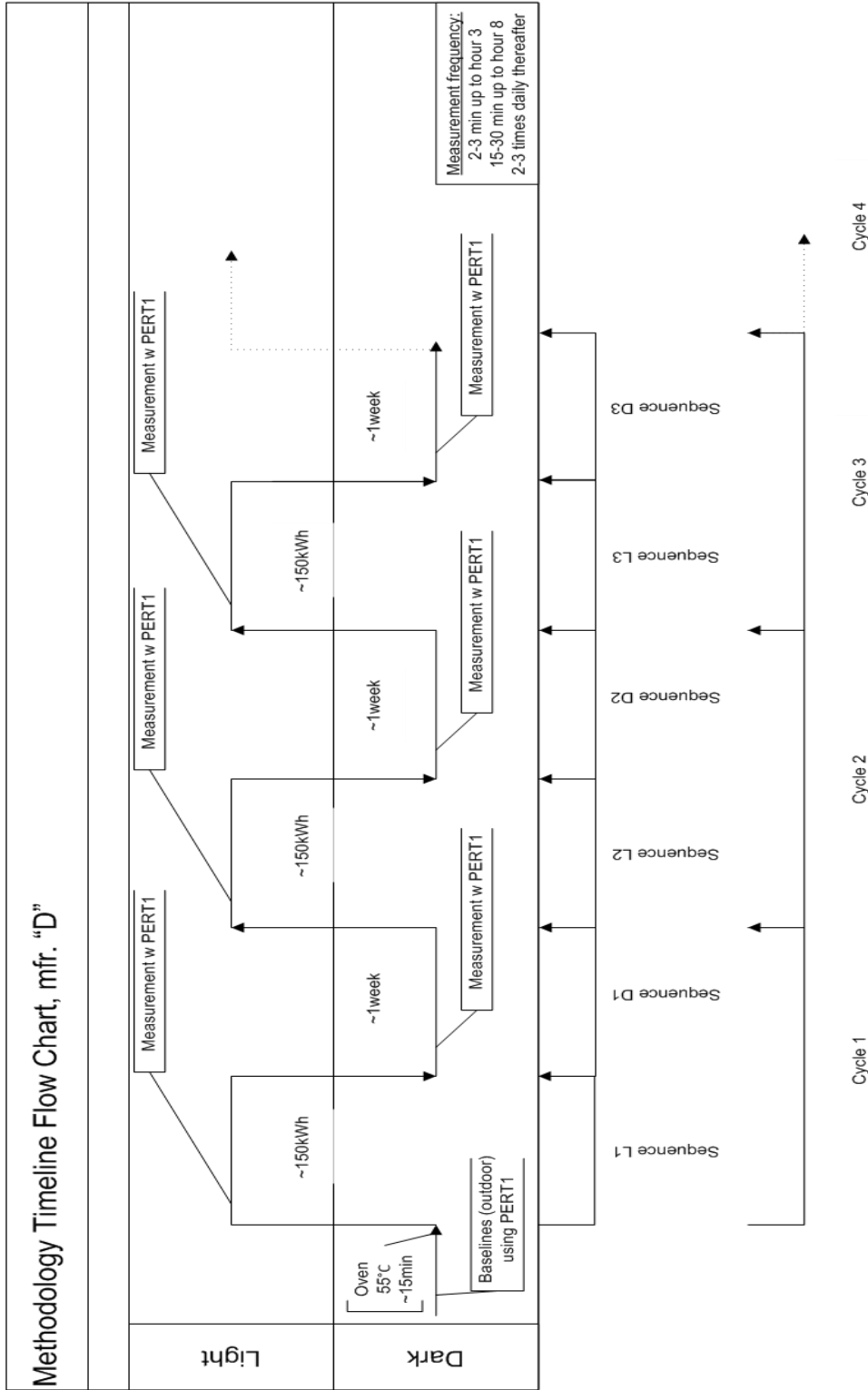


Figure 10: Time line flow chart proposed for module set "D"

3.7 Module set:

The sample pool consisted of 11 CdTe modules representing four commercial manufacturers. The modules have various exposure histories some of which are not completely known, however all modules are of a vintage of at least 2008. The known history of the module is given in the following table and broken up by manufacturer. The description of a module as having limited light exposure means that it is unlikely to have received more than 500kWh/m² of exposure.

Table 2: Sample pool and known module history

Description of Module Pool by Manufacturer, Quantity and Known History

Module mfr.	Quantity	Pre-existing exposure conditions
A	2	Limited light exposure, one year storage outdoors uncovered
B	2	No known light exposure, two year storage outdoors covered
C	1	Limited light exposure, two years storage indoors
D	4	Nascent

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview:

The focus of the experiment was to find a common Voc behavior for commercial CdTe modules. The results given in this section of the report are broken down into an analysis of the two phases of the procedure, light and dark, for each module set. In light of the transient behavior discovered in the cycling of the modules, a novel temperature coefficient method was developed and an analysis of this parameter is also addressed for each module set.

4.2 Stabilization study of module set "A":

This set consisted of two modules, of 2008 vintage, one of which, A1, was exposed under max load using a resistive load while the other, A2, was exposed to light under open circuit conditions. The load resistor for module A1 was calibrated using the following equation:

$$R_{load} = V_{mp}/I_{mp}$$

where, V_{mp} and I_{mp} were determined from the baseline measurements taken prior to cycling. The results of these baseline measurements are analyzed later, in the temperature coefficient section, taking advantage of the behavior seen during cycling. Both modules A1 and A2 show similar behavior despite loading during light and dark cycling. To begin, an overview of the Voc behavior for the entire experiment is given in Figure 11 and Figure 12.

Here the Voc of module A1 is normalized to STC conditions using the procedures outlined in the IEC standards. To offset spectral variation between the measurements of light and dark sequences, the reference point for the change in Voc is set to the initial measured point of L1 for light data points. The reference point for dark measurements was taken from the dark baseline measurements. The temperature coefficient used to generate this chart was obtained using conventional methods as the module heated up naturally.

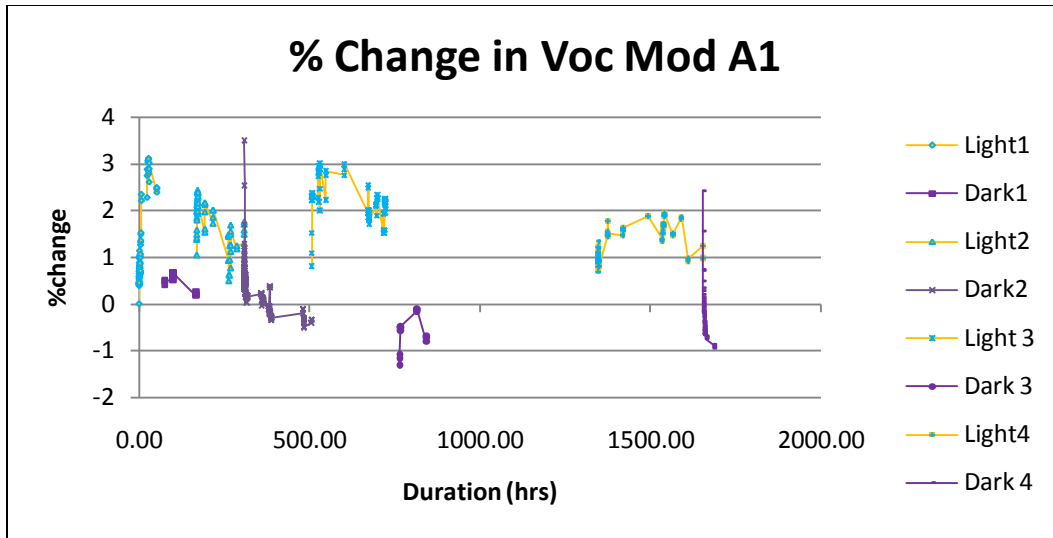


Figure 11: Change in STC normalized Voc as referenced to the initial measurement of sequence L1 and baseline Voc of flash measurements (mod A1 held at Pmp)

As can be seen in each light sequence, there is an initial increase in the normalized Voc followed by a fall after an increase of approximately 2-3%. Two of the dark sequences, D2 and D4, also show similar behavior with a sharp drop in normalized Voc shortly after the transition to the dark followed by a slower fall into a stabilized state. The gaps seen between L1 and D1, and L3 and D3 are unfortunately due to power outages that occurred at the lab over night. Thus the transition from light to dark could not be captured. A third power outage happened in the middle of L2 but power was restored quickly (within an hour) and the sequence was continued.

The Voc values here are again normalized to STC conditions using a temperature coefficient calculated according to the IEC standards. Module A2, exposed under open circuit conditions, also shows the strong transient behavior upon initial light exposure followed by a drop in normalized Voc after an approximate 2-3% gain. The sharp drop followed by a slower degradation is again seen during dark storage, similar to module A1. The relative smoothness of the light sequence curves here as compared to those of module A1 reflect the continuous open circuit state of module A2. The jagged behavior of A1 is attributed to the effects of offloading the module to open circuit prior to taking I-V curves. This will be seen in more detail in the breakdown of each sequence.

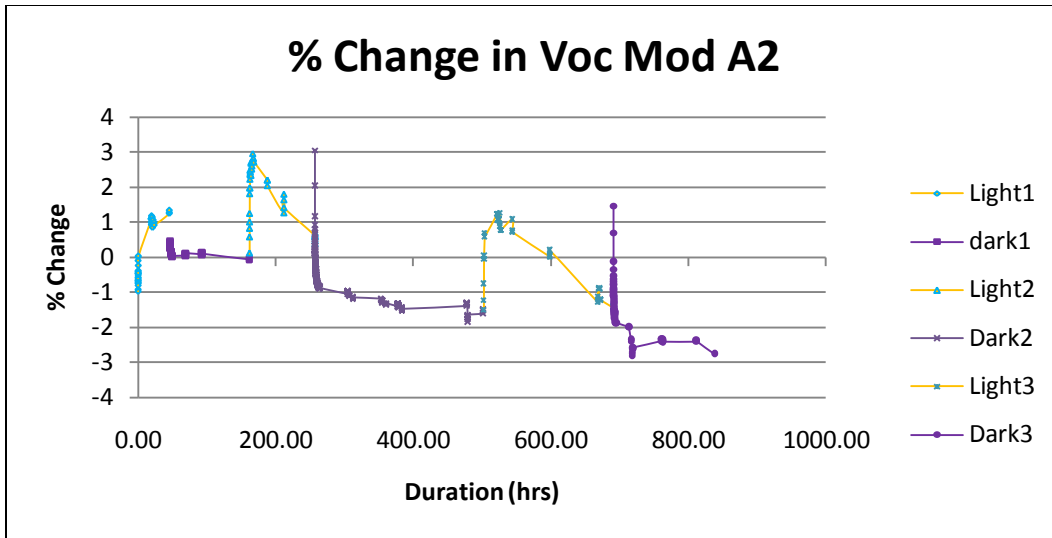


Figure 12: Change in STC normalized Voc as referenced to the initial measurement of sequence L1 and baseline Voc of flash measurements (mod A2 held at Voc)

4.2.1 Light Sequences

A chart of module A1 light sequence L2 gives a representative example of the Voc behavior during light exposure. As can be seen in Figure 13 the module temperature is fairly constant for the entire sequence duration and more specifically during the first day of exposure when the transient is most apparent. Over the course of this first day the temperature is within a 2°C range from 51.5°C to 53.5°C. This gives a clear picture of how the Voc climbs during initial light exposure. It should be noted that the change in measured Voc is referenced to the first data point of the sequence and in subsequent charts measured Voc will be referenced the same. In other light sequences there is a larger module temperature gradient during the transition to light and thus the transient is not as apparent in the measured Voc.

Figure 13 and Figure 14 juxtapose the STC corrected (normalized) and measured Voc along with the module temperature. Over the first day both normalized curves show similar behavior – a strong transient increase in Voc - and in subsequent days, a slow decay. It is interesting to observe that during the L2 sequence of module A1 the temperature profile remains relatively flat, yet a very dramatic transient is present in the measured data. This is very direct evidence of strictly light induced behavior during the transition from dark to light.

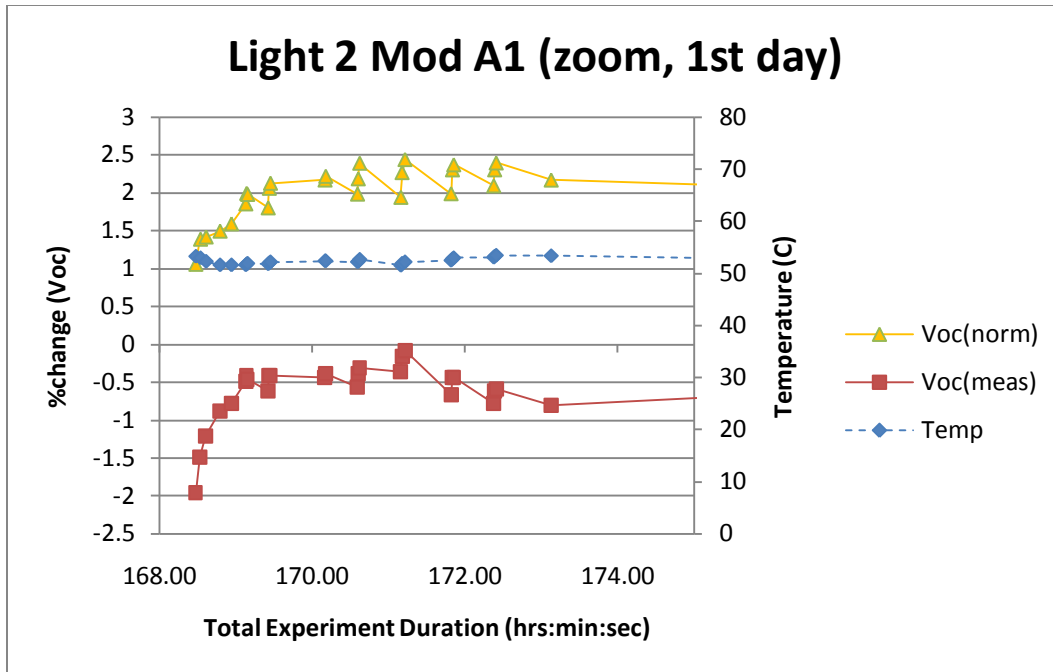


Figure 13: Change in normalized and measured Voc during relatively flat temperature period

The second light sequence of module A2 gives direct evidence the transient as well; however in this case there is an increasing temperature profile during the dark to light transition. The measured Voc here remains flat during the increase in temperature instead of falling proportional to the temperature rise as would be expected. It is suspected that the transient must be the compensating factor causing the Voc to remain flat.

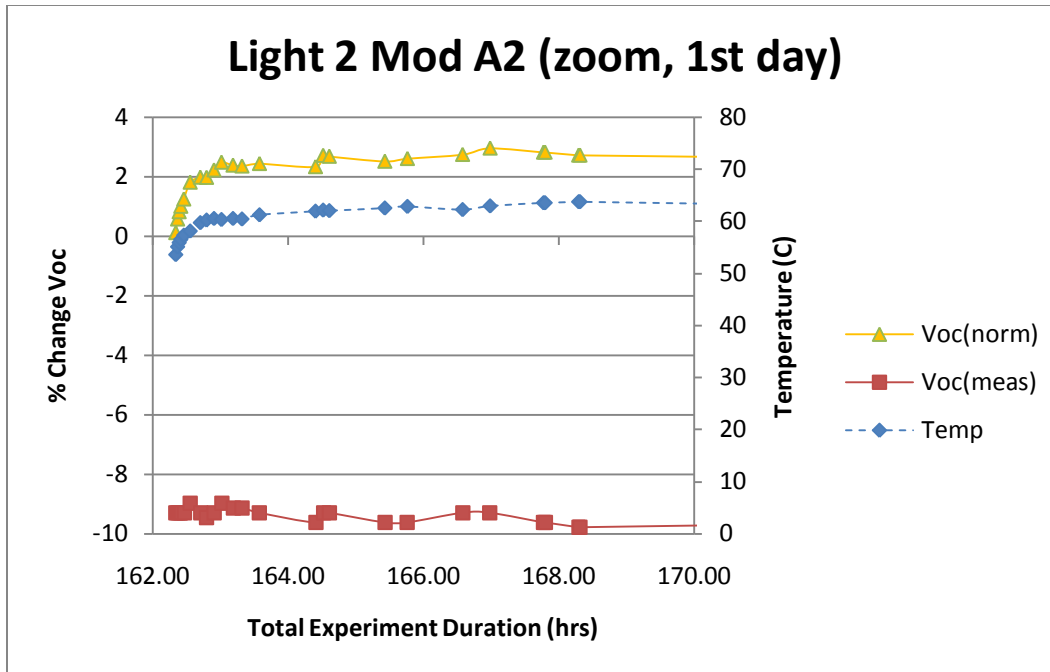


Figure 14: Rise in normalized Voc with flat measured Voc during module temperature rise

Some anomalous behavior relative to that given above was found in the L4 sequence of module A1. Here there is a short dip in both normalized and measured Voc along with a flat temperature profile during the first day of light exposure, as seen in Figure 15. Given the stable temperature a strong transient increase in Voc should be present. The behavior over the course of the entire light sequence does, however, have a similar shape to the other light sequences as seen in Figure 11: exhibiting a peak midway through the sequence and gradually falling towards the end.

Similarly disparate behavior was found in the analysis of the beginning of the L1 sequence of module A2. Here the temperature and measured Voc act as would be expected of any PV module (proportional decrease in Voc with a rise in temperature) with the resulting normalized Voc remaining flat. The fact that this module was not preheated prior to light exposure could explain why a transient was not apparent during the transition to light. However it should be noted that the initial transient for L1 of both modules and L4 of A1 showed slower transients suggesting that the time in dark storage has an effect on the ensuing transition to light, since each of the sequences followed dark periods of 20 or more days.

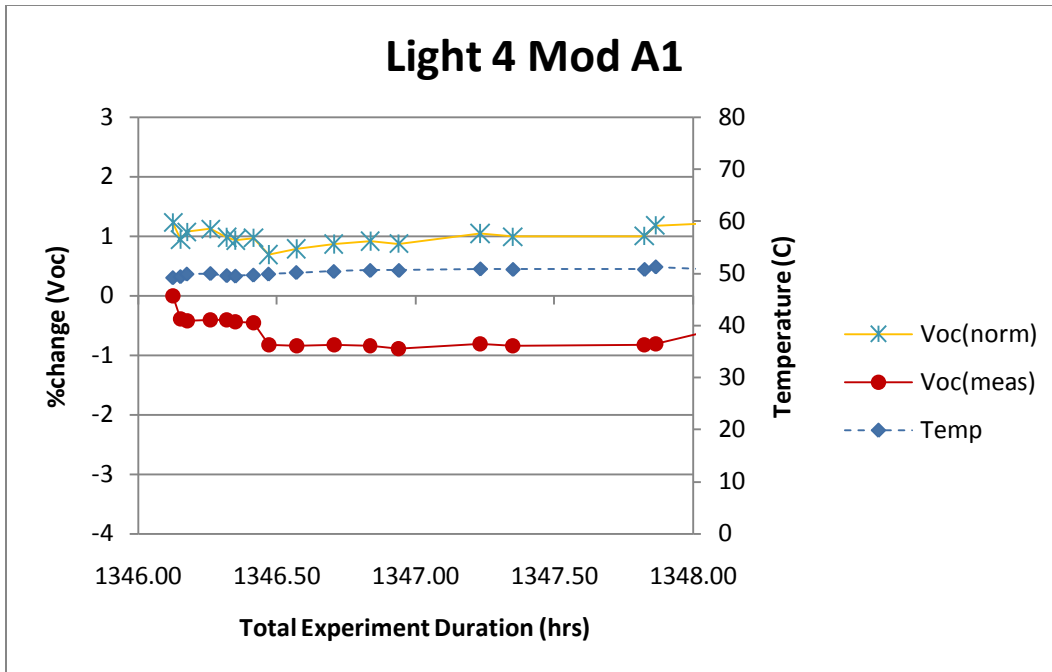


Figure 15: First hours of L4 for mod. A1 showing relatively flat behavior for normalized and measured Voc

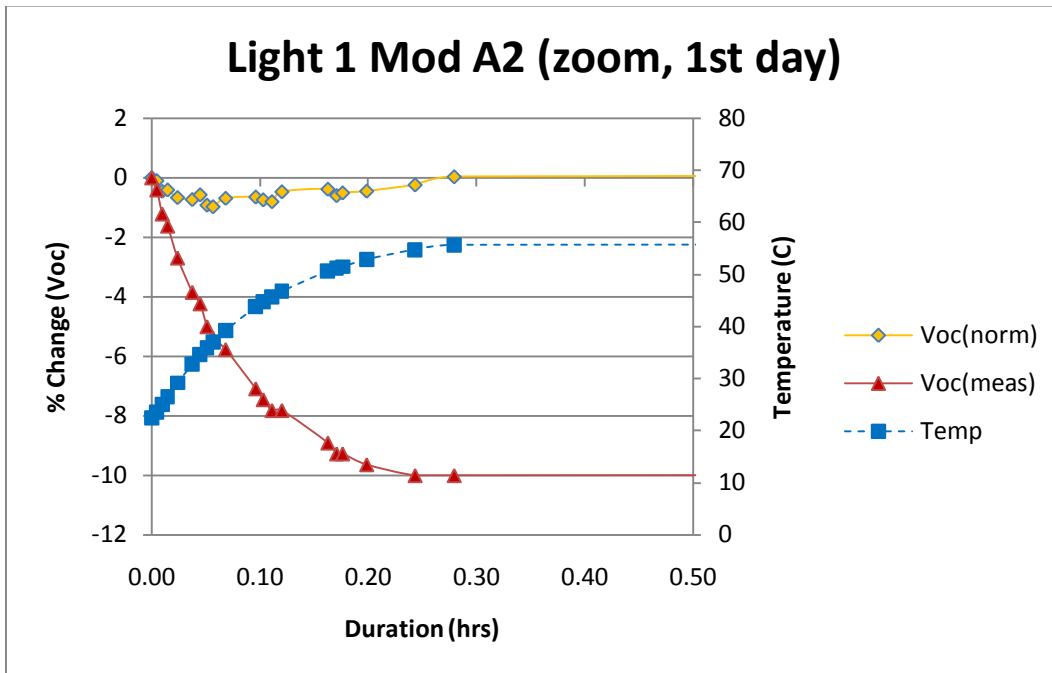


Figure 16: First hour of L1 for mod. A2 showing expected Voc variance with temperature and a flat normalized Voc

Though some of the light sequences had anomalous initial behaviors, over all the Voc behavior in light was consistent across all light exposures and modules. The transient in the Pmp loaded module A1 was in general slower than that of the open circuit module A2. Despite this, however, the transient represented a 2-3% change in Voc for most light sequences.

4.2.2 Dark Sequences

The module behavior during dark storage was also similar for both modules as shown in the charts below which are representative of all the dark sequences. Again it should be noted that for two dark sequences on module A1 the transition was not captured thus Figure 17 is representative of only two sequences, D2 and D4. In Figure 17, a sharp drop over the first few measurements followed by a gradual drop is seen when the data is analyzed using the conventional temperature coefficient. On the other hand, the measured Voc exhibits a strong inverse correlation to temperature as is typically expected. However this was not strictly seen in the light exposure sequence given above where measured Voc remained flat during a temperature change (see Figure 13).

Module A2 had very consistent and regular data for all of its dark sequences similar to that of A1. For this second module, only dark sequence 2 is given because of this consistency and similarity throughout the three cycles. The dark sequences of both modules are nearly identical in behavior as seen in Figure 17 and Figure 18.

After the temperature stabilized within a couple degrees of room temperature (after approximately 1 hour in dark storage) both modules showed a little to no degradation in Voc over the course of the week. An initial drop in the Voc of both modules, of approximately 3%, occurs during the first 35 minutes of being removed from light exposure.

The general result from light cycling module set A was a clear transient behavior that causes a change in V_{oc} of 2-3%. As well this transient dissipates very quickly when

the module is taken out of light, though there may be lingering effects of the transient if duration in dark storage affects the module response when reintroduced to light.

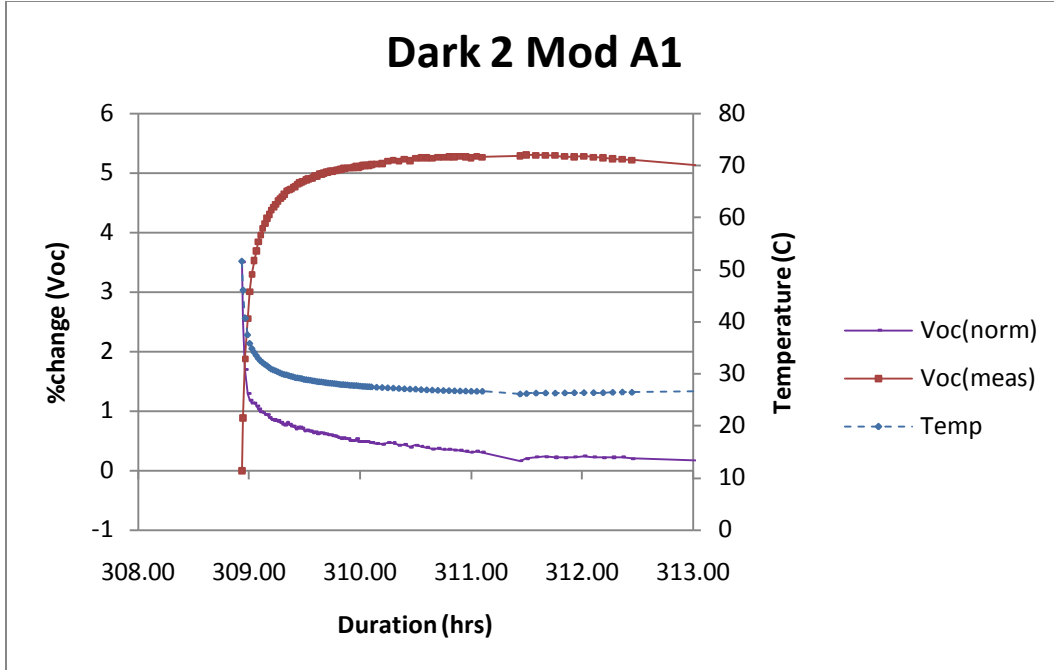


Figure 17: First hours of D2 sequence, measured and STC normalized Voc

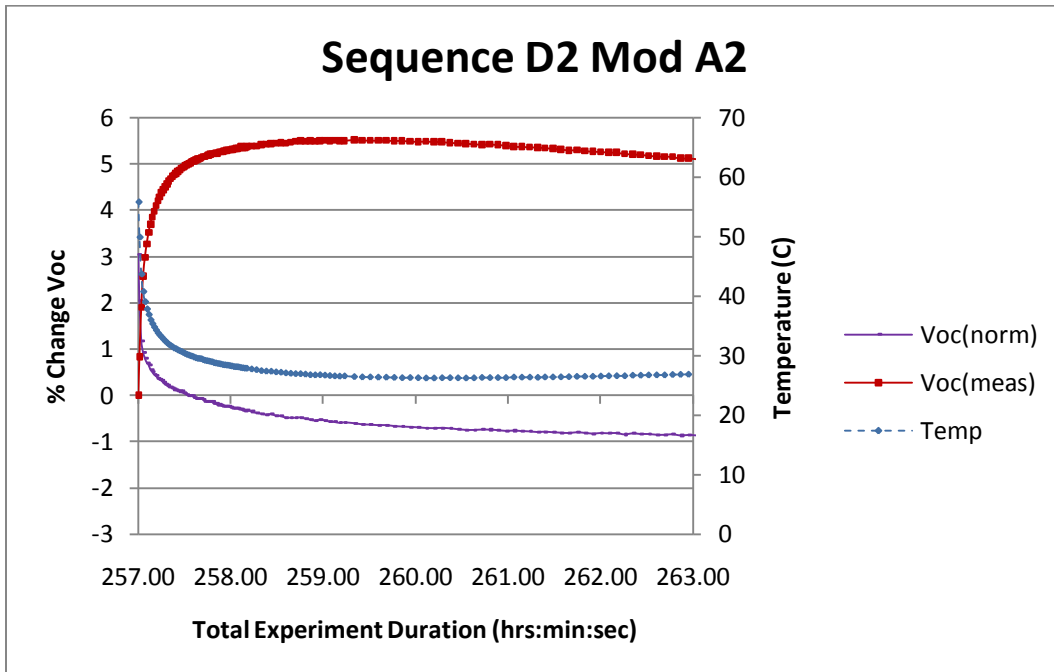


Figure 18: First hours of D2 sequence, measured and STC normalized Voc

4.2.3 IEC 61646 Analysis

This section looks at the interpretation of the all the previous data using the stabilization procedures of the international thin-film standard. The first analysis is of V_{oc} using the stabilization guidelines of the standard, though it is understood that these guidelines are applied to P_{mp} . And as such, P_{mp} will be addressed after the V_{oc} analysis.

According to the standard: "Stabilization occurs when measurements from two consecutive periods of at least 43 kWh/m², each integrated over periods when the temperature is between 40 °C and 60 °C, meet the following criteria: $(P_{max} - P_{min})/P_{average} < 2 \%$." [21]

In this first case P_{max} , P_{min} , and $P_{average}$ are replaced with the corresponding V_{oc} values. The analysis of V_{oc} also broke down the stabilization into exposure periods of at least 35kWh because continuous 43kWh periods were not conveniently found in the data set. As seen in the charts the stabilization of Voc for both modules occurs immediately for both exposure periods. There also seems to be little difference between the total exposure necessary for a comparable stabilization for either 35kWh or 43kWh periods. In other words, by the second exposure period both modules are within 1.5% stable for 35kWh periods or 43kWh.

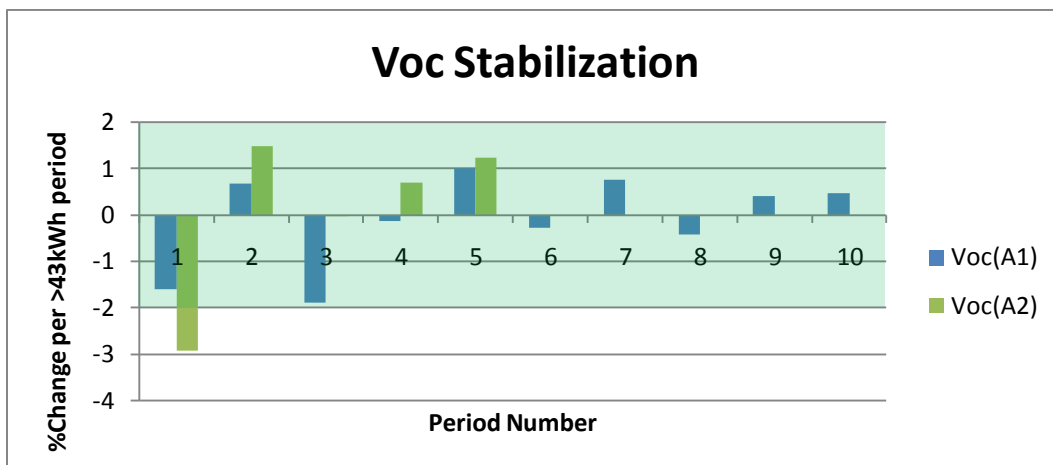


Figure 19: Voc stabilization according to IEC 61646 min. 43kWh exposure periods

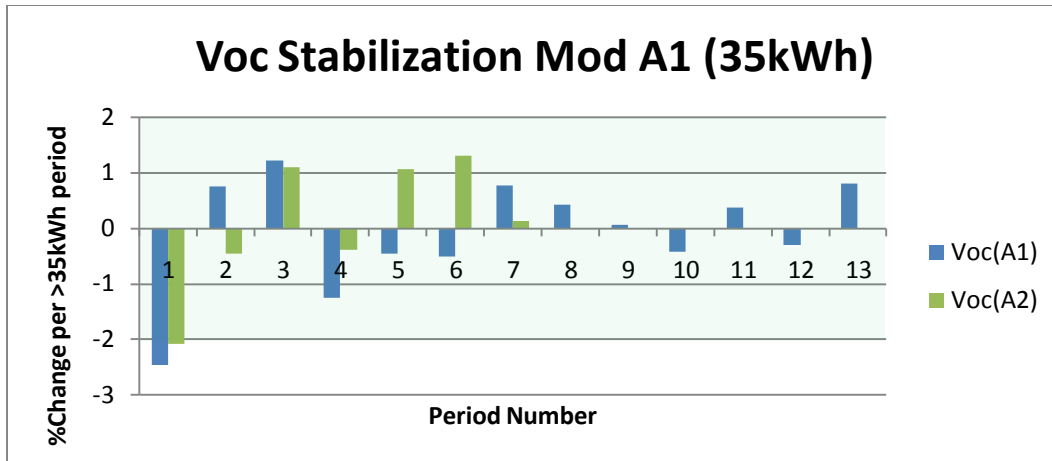


Figure 20: Voc Stabilization with min. 35kWh exposure periods

The larger percent change across the first exposure is believed to be a result of the strong transient occurring during initial light exposure. In other words, an initial measurement as the module transitions to light is subject to the transient occurring there. On the other hand, during extended light exposures the periods of 43kWh do not contain a transition from light to dark or visa versa. Subsequent changes in Voc over the other periods do not catch the transient behavior characteristic since the module does not undergo a transition. Indeed, considering the strong behavior at the transition into the dark, if a module is undergoing light soaking and its performance is not measured within 10 minutes after removal from a chamber there could be large swings in the measured Voc rating.

Now power is analyzed, as intended by IEC61646, and it should be noted that performance measurements were taken under an artificial light source with non-negligible spectral, temporal, and spacial variance from natural light. However, this source is compliant to IEC61646 for light soaking and measurements are not compared to measurements made with other light sources. As such the data should be considered representative of relative behavior and not absolute.

The following results show that both modules would meet stabilization criteria (defined as a change in Pmp of less than 2% between subsequent measurements for two consecutive light exposure periods) after the fifth exposure period specified under

standard IEC61646, Figure 21. However the extended testing of module A1 shows that after exposure period 8 it would be not meet the criteria, but might again be considered stabilized after exposure period 10. Similarly when data points were taken across shorter, 35kWh, exposure periods stabilization is satisfied, unsatisfied, and again possibly re-satisfied upon extended light soaking, Figure 22. Module A1 shows stabilization after period 6, fails the criteria after period 9, but recaptures it after period 12. Module A2 is behaves similarly with periods 1, 3, and 5 respectively.

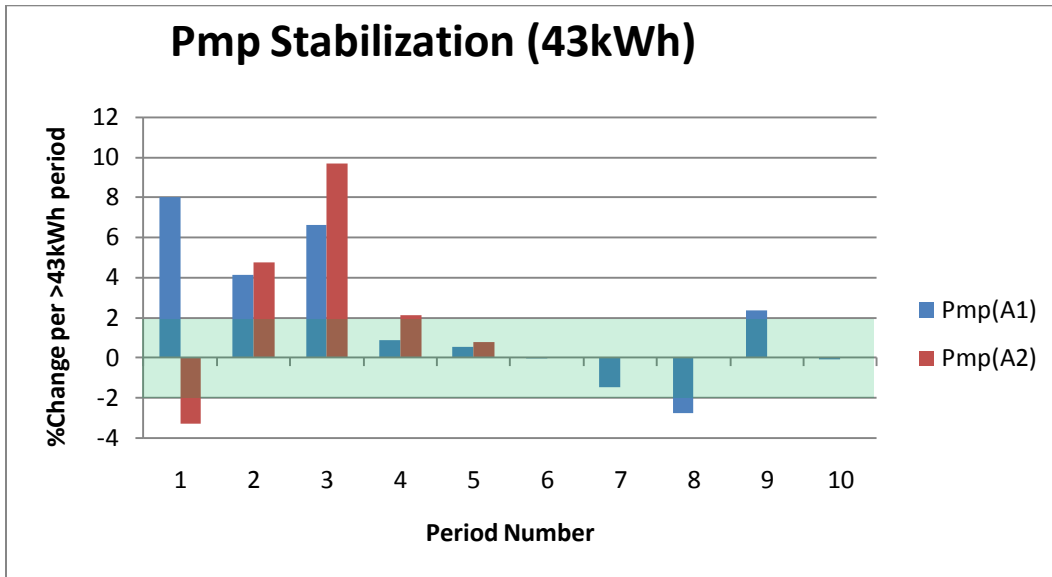


Figure 21: Pmp stabilization according to IEC61646 43kWh minimum exposure periods. (Range of exposures 43kWh - 70kWh)

Due to the nature of the experiment some of the 43kWh stabilization periods were an aggregate of light exposures taken from different light sequences. The percentage change given for period numbers 1, 3, and 7 (A1 only) use measurements taken in two different light sequences. Another analysis modifying the IEC61646 exposure period was done using 35kWh minimum periods which made it possible to compare measurements strictly within single light sequences, Figure 22. The stabilization criterion was met at 286kWh for module A1, and at 250kWh for module A2 whether 43kWh or 35kWh periods were used. This results leads to the conclusion that dark storage periods (of no more than one week) between measurements do not have an effect on module stabilization.

However given the fast transient observed in during both transitions (light to dark and dark to light) explicitly specifying the timing of measurements may smooth the fluctuating stabilization behavior. By slicing the data set even further to exposure periods of at least 15kWh the shorter term transient should have a more pronounced effect. The fluctuations are indeed more apparent using smaller exposures periods between measurements, Figure 23.

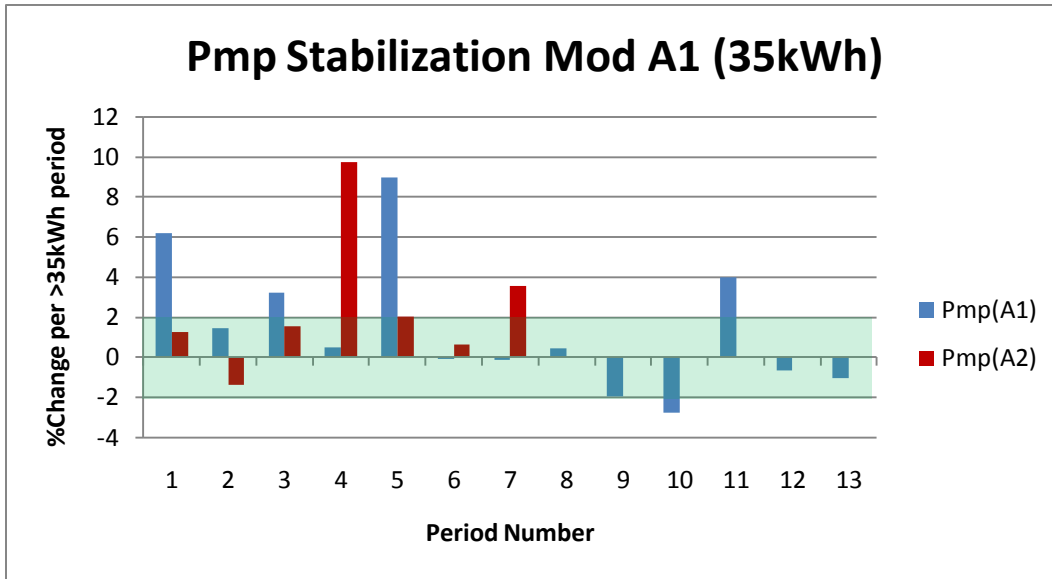


Figure 22: Pmp stabilization using 35kWh minimum exposure periods. (Range of exposures 35kWh – 62kWh)

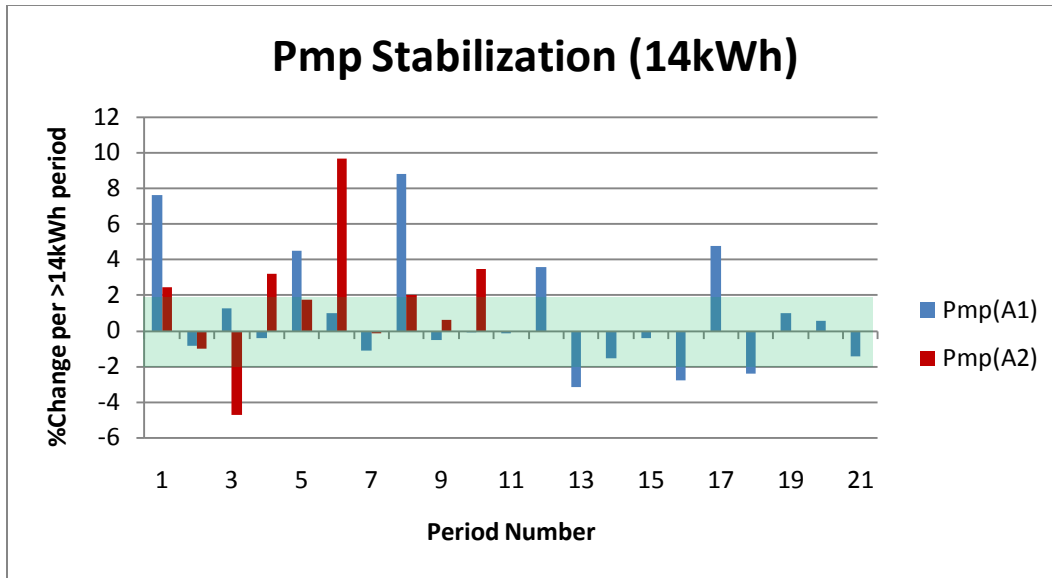


Figure 23: Pmp stabilization using 14kWh minimum exposure periods. (Range of exposures 14kWh - 61kWh)

Measurement timing coming out of light exposure appears of critical importance for power as it was for open circuit voltage. From dark storage measurements max power is seen to drop by up to 2% in the first 10 minutes after removal from light exposure. So, as with Voc rating, Pmp is sensitive to whether measurements are made immediately or after a short period in dark storage. Figure 24 shows the max power behavior of module A2 clearly illustrating the Pmp drop during the dark storage state.

Comparisons between light measurements are not particularly illuminating because of the spectral variances, but within each sequence there is apparent monotonic power degradation throughout the light exposure. In this respect the Pmp behavior is opposite of that seen in the Voc which increases initially and then falls towards the end of the light exposure.

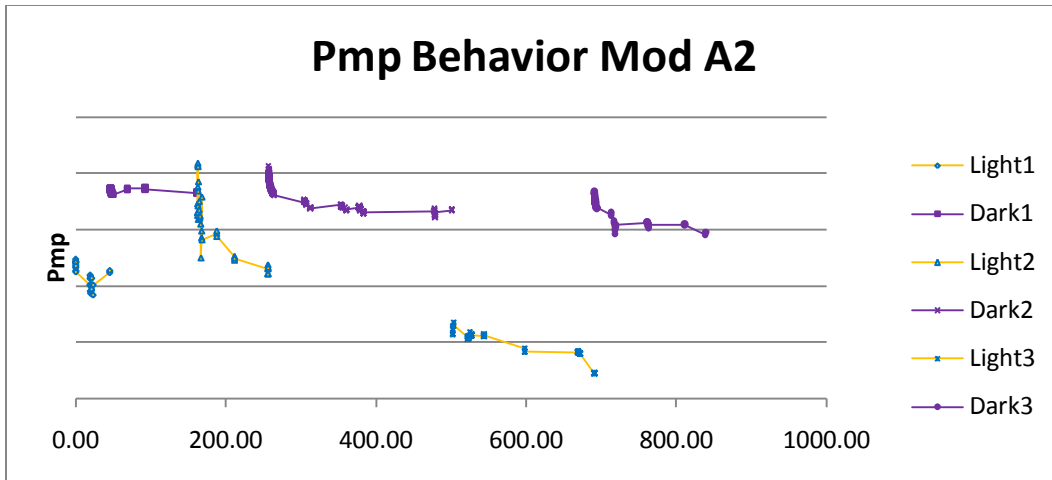


Figure 24: STC normalized Pmp behavior as referenced to the initial sequence measurements (the y-axis is blank due to proprietary concerns)

The module set A has given several insights to CdTe module behavior. Voc has a strong transient at the transitions from dark to light, and light to dark of around 2%. This is typically an increase in STC normalized Voc from dark to light, and a decrease from light to dark. Loading of the module under light exposure shows little effect on this transient, but the short load cycling necessary for measurement results in choppy behavior.

The analysis of the data according to IEC61646 yields intriguing results as well. Voc stabilization is unaffected by a change in exposure period and shows very quick stabilization using these methods, despite showing a strong short term transient in the Voc vs. Time charts. Power on the other hand shows fickle stabilization, but is not strongly affected by a change in exposure period magnitude.

4.3 Novel temperature coefficient method across four manufactures:

These results from above are the impetus for the following temperature coefficient (Tcoef) analysis. Considering the strong transient behavior it was hypothesized that temperature coefficients taken immediately after light exposure would differ from Tcoefs taken after significant light exposure. Thus a novel technique was used to make this comparison using natural light. To this point and where applicable, all the data presented has been analyzed using Tcoefs attained by conventional methods.

Also to be considered, the module temperature behavior may also differ depending on whether it was heating up or cooling down - as was the case during dark storage sequences. It should be mentioned that the dark storage measurements were also taken with different equipment than the light exposure measurements. Therefore, as a comparison a set of Tcoefs were taken using the flash simulator as the module dropped from a high to low temperature. The novel Tcoefs were taken on three of the four manufactures, where module sets "A" and "B" had Tcoefs taken using the Daystar single curve tracer and set "D" had all measurements taken on the PERT1 multi-curve tracer. For comparison module A2 also had PERT1 Tcoef measurements taken. All the Voc and Pmp temperature coefficients taken using the various methods are list in Table 3 and Table 4.

The comparison between the Tcoefs is given in the bar charts of Figure 25 through Figure 28. For every module across all three manufacturers the Voc temperature coefficient becomes less negative after 3-5 hours of continuous exposure (Figure 25 and Figure 26). A similar trend is seen in the Pmp bar charts, except that the Pmp for module A2 shows an increase in negativity when measured on the Daystar (Figure 27 and Figure 28). This may be related to the timing of the Tcoef measurements on module set "A". The novel Tcoef method was performed after the set "A" had been through the entire experiment, whereas all other modules had conventional and novel Tcoefs taken before any testing or extended exposure.

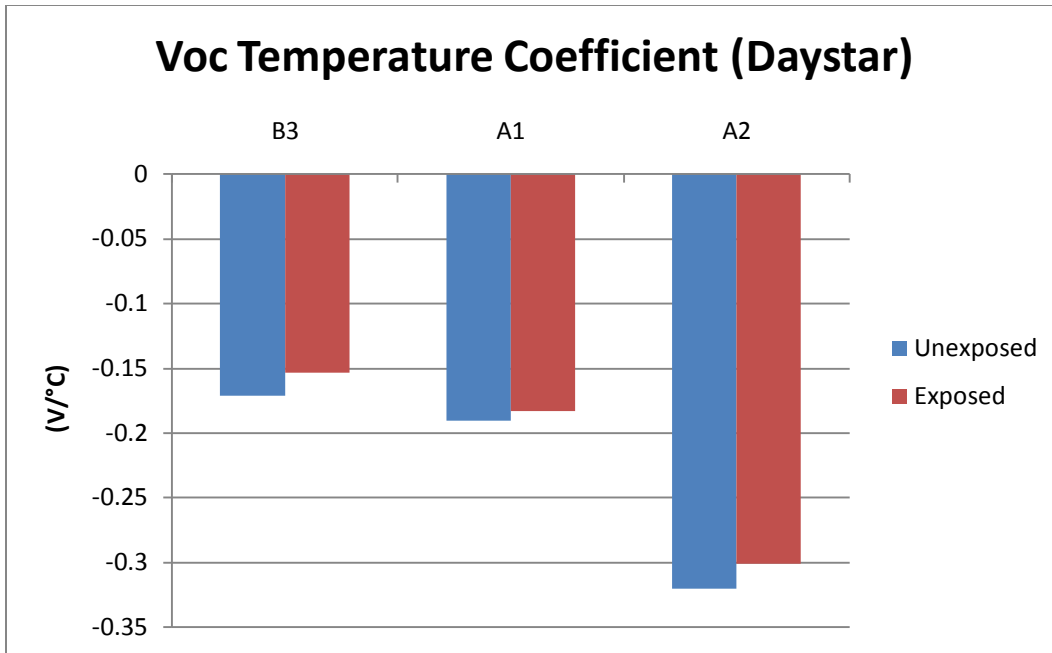


Figure 25: Conventional (unexposed) compared to novel (exposed) Voc Tcoefs for modules from set "A" and "B"

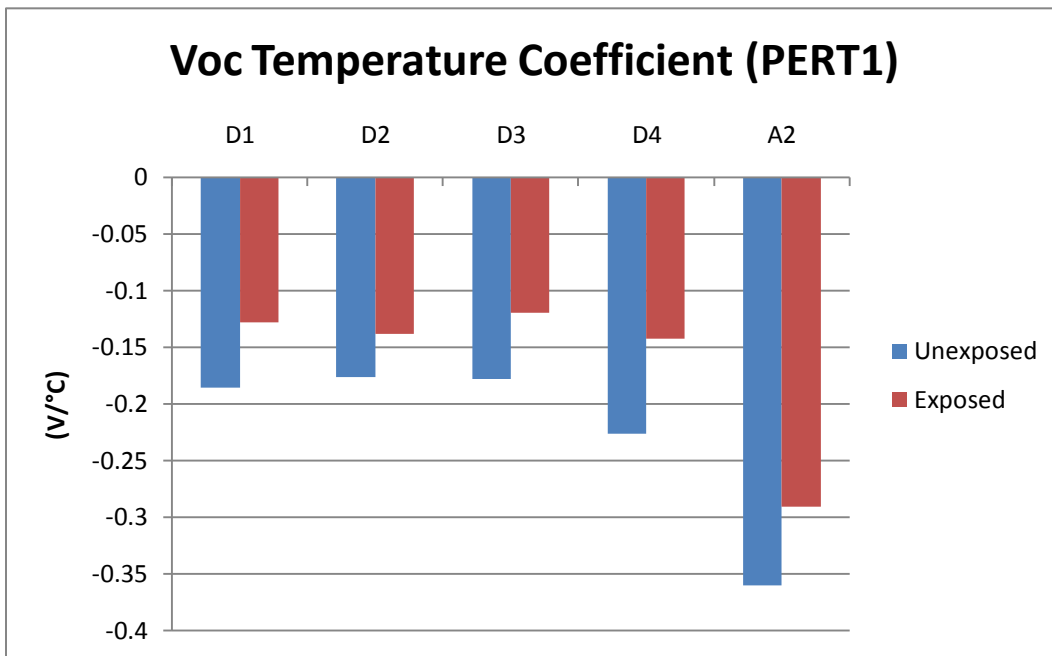


Figure 26: Conventional (unexposed) compared to novel (exposed) Voc Tcoefs for modules from sets "A" and "D"

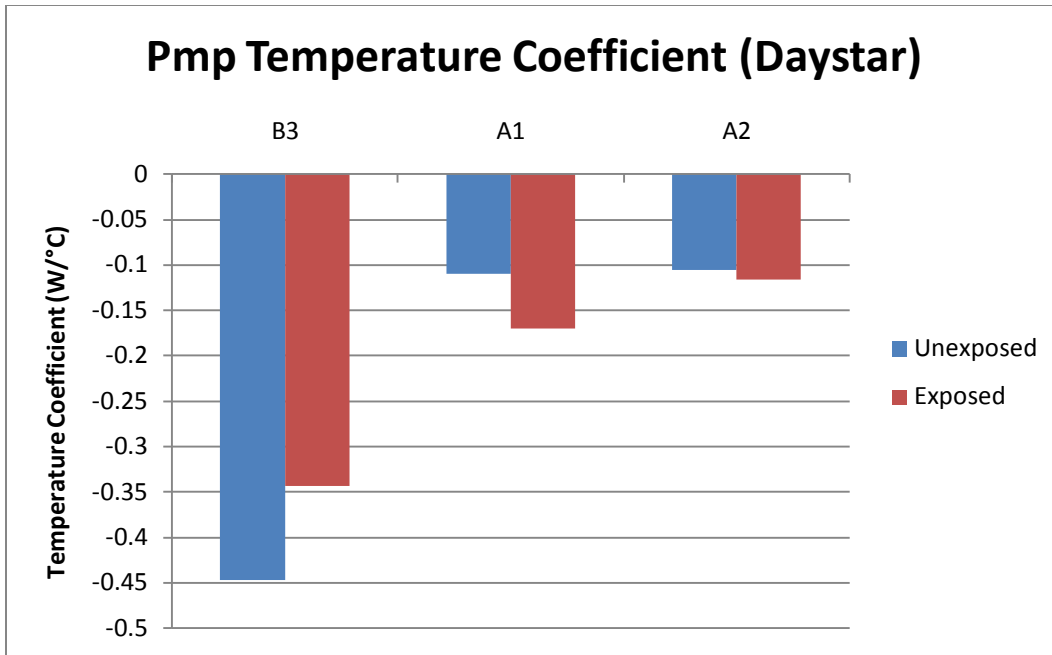


Figure 27: Conventional (unexposed) compared to novel (exposed) Pmp Tcoefs for modules from set "A" and "B"

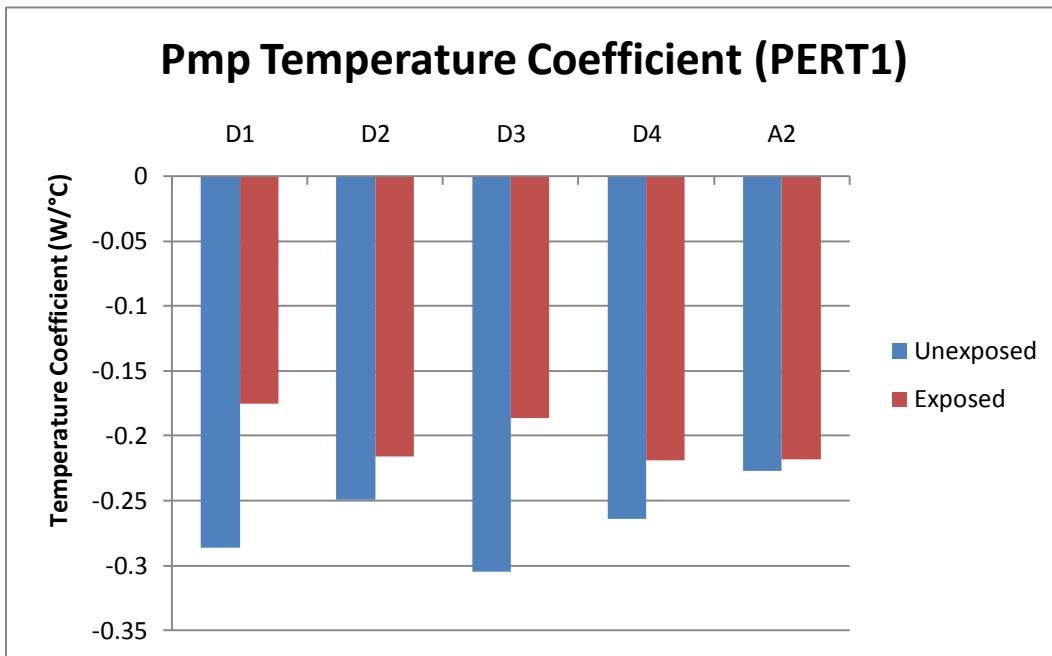


Figure 28: Conventional (unexposed) compared to novel (exposed) Pmp Tcoefs for modules from sets "A" and "D"

The following figures show, graphically, the change in slope of Voc and Pmp with temperature depending on method. In Figure 29, the high temperature to low temperature (HT->LT) measurements taken on the flash simulator clearly have a less negative slope than either other method measuring from low to high temperature. Similarly in Figure 30, the HT->LT slope has a more pronounced difference than any of the others measuring from low to high temperature.

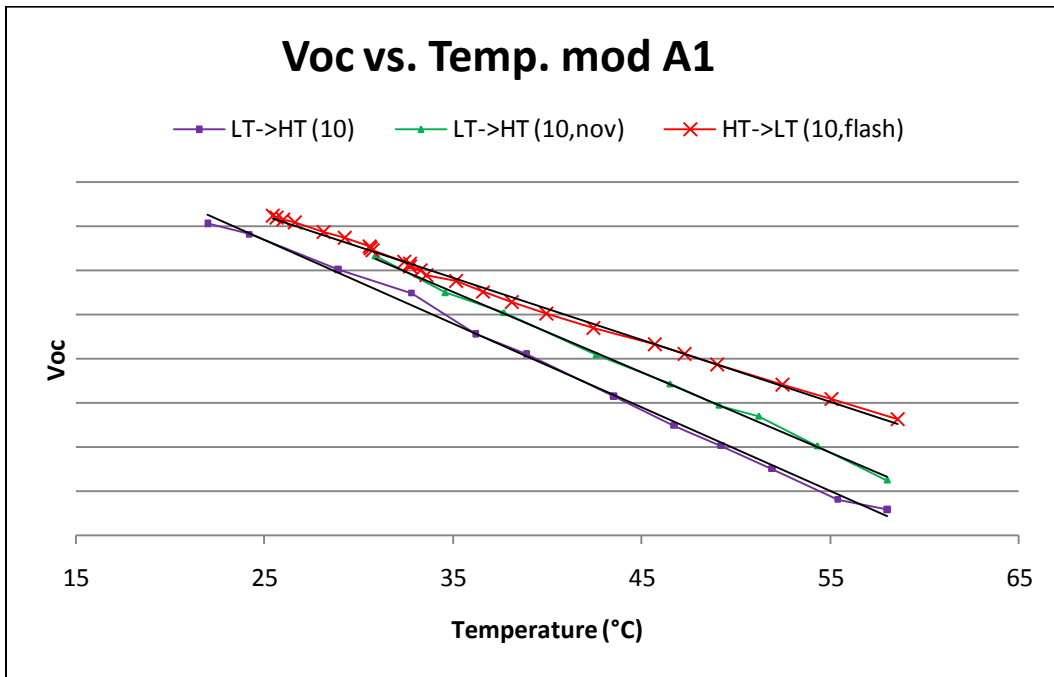


Figure 29: Comparison of behavior from low to high and high to low temperature

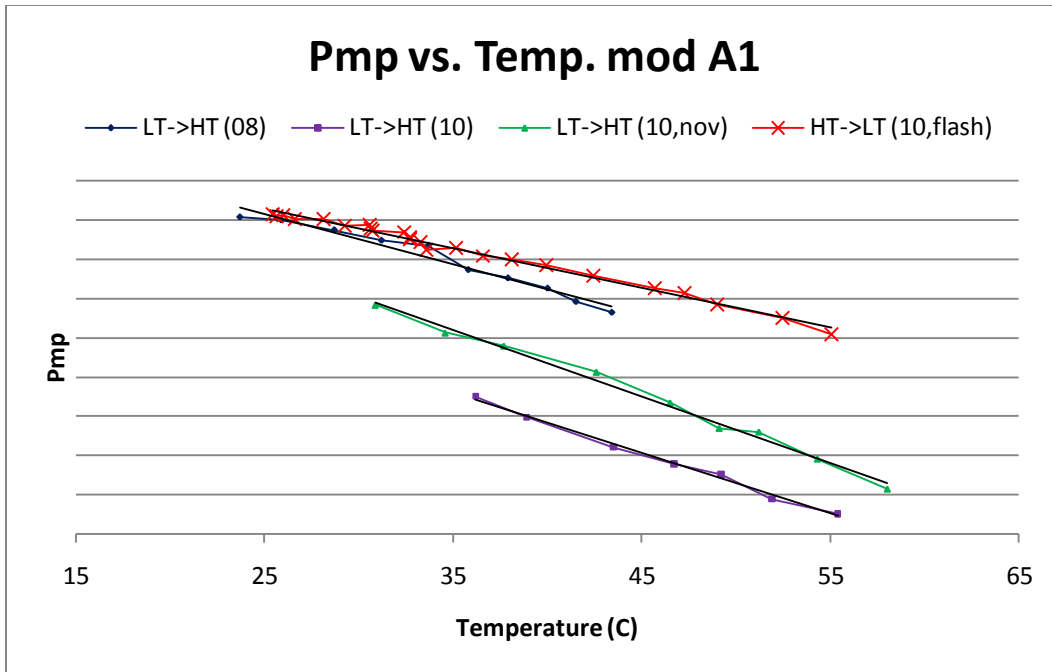


Figure 30: Comparison of behavior from low to high and high to low temperature

In Table 3 under the PERT1 section, three thermocouple locations were used as an internal comparison between the Tcoefs. In general the center and corner locations had similar yet varying temperature profiles but yielded consistent results. The back location had a more stable temperature profile throughout the measurements however the resulting is not so consistent with the other two locations. As such it remains to be determined which is the more suitable Tcoef rating for the modules.

Comparing the PERT1 to the Daystar measurements of module A2, the unexposed Tcoef is larger for all locations, though the exposed Tcoefs for the center and back locations are smaller. This could be a stabilization effect, as opposed to a transient one, since A2 was in dark storage for a significant period of time between Daystar and PERT1 measurements.

The following tables show all the Tcoefs values, described earlier, for all modules:

Table 3: V_{oc} temperature coefficients as measured by device and method.

		V_{oc} Temperature Coefficient (V/°C)							
PERT1									
TC loc.	Exposure	D1	D2	D3	D4	C1	B3	A1	A2
Center	Unexposed	-0.19	-0.18	-0.18	-0.23				-0.36
	Exposed	-0.13	-0.14	-0.12	-0.14				-0.29
Corner	Unexposed	-0.18	-0.17	-0.18	-0.17				-0.37
	Exposed	-0.14	-0.16	-0.13	-0.14				-0.35
Back	Unexposed	-0.26	-0.25	-0.22	-0.24				-0.35
	Exposed	-0.13	-0.16	-0.15	-0.17				-0.29
Daystar									
	Unexposed					-0.28	-0.17	-0.19	-0.32
	Exposed						-0.15	-0.18	-0.30
Flash									
	Unexposed					-0.22		-0.14	-0.23

Table 4: P_{mp} temperature coefficient as measured by device and method.

		P_{mp} Temperature Coefficient (V/°C)							
PERT1									
TC loc.	Exposure	D1	D2	D3	D4	C1	B3	A1	A2
Center	Unexposed	-0.29	-0.25	-0.31	-0.26				-0.23
	Exposed	-0.18	-0.22	-0.19	-0.22				-0.22
Corner	Unexposed	-0.28	-0.25	-0.31	-0.21				-0.25
	Exposed	-0.18	-0.26	-0.20	-0.23				-0.20
Back	Unexposed	-0.40	-0.36	-0.36	-0.29				-0.23
	Exposed	-0.17	-0.25	-0.23	-0.24				-0.19
Daystar									
	Unexposed					-0.11	-0.45	-0.11	-0.11
	Exposed						-0.34	-0.17	-0.12
Flash									
	Unexposed					-0.10		-0.10	-0.10

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions:

The conclusions and recommendations that can be drawn from this research are related to module stability and illumination effects to performance. Direct tracking and periodic analysis of module parameters shows both meta-stable and transient effects and leads to new methods of module characterization. Interesting results also surfaced when new methods were used in an attempt to filter out light induced transients in temperature coefficient measurements.

From the Voc vs. time graphs of the two modules that have undergone cycling, a regular and clear transient occurs with the onset and removal of illumination. This transient was seen to be about 2-3% of the originally measured value in light soaking and dark storage. The duration of this transient in the dark storage measurements were very regular and quick for all sequences occurring in under an hour. This sharp behavior during the first minutes and hour after removal from light lead to the conclusion that the timing should specified for module rating measurements performed after light soaking. Similarly in the light, a sharp transient during onset would influence module measurements coming out of a dark closet or box.

The stability of power measurements also showed similar sharp light and dark onset transients. Stabilization analysis of this small sample set lead to two interesting findings. First, from the comparison of stability data points that include periods of dark storage and those that do not, it appears that such periods within light soaking stabilization procedures do not affect the total time to stabilization of the module. All dark storage periods held the module at a temperature of 25°C and it would be of interest to pursue whether or not the a higher dark temperature would affect the stabilization of CdTe modules.

The second point from the power stabilization analysis is motivated by a fluctuating stabilization in the modules. From both modules it is observed that IEC

616146 stabilization criteria is satisfied, but upon further light soaking they fell out of accord. One of the modules received a much longer light soaking duration and in this case the module achieves a second stabilization during the extended light soak. This suggests that stabilization in CdTe may have some periodicity that can be used to define a more robust definition of stabilization in this technology.

Finally, the temperature coefficient of all four manufacturers modules were reexamined with respect to the transient and meta-stable effects observed during light cycling. It was found that a temperature hysteresis and the recent illumination history of the module affected the temperature coefficient of Voc and Pmp. Three modules across two manufacturers had their temperature coefficients measured as the module temperature increased and as it decreased. The comparison between the two measurements shows an apparent hysteresis between the two temperature paths. Thus suggesting that temperature direction should be specified in module rating and temperature coefficient measurement procedures.

Illumination effects were examined across seven modules from three manufacturers. Here after only a short exposure period there was a non-negligible change in the measured temperature coefficients. In all cases the temperature coefficient taken after light exposure was more favorable (i.e. less negative or flatter). Since these Tcoefs were taken as module temperature increased from low to high temperature, they were compared (when applicable) to the Tcoefs measured as module temperature decreased. Since a slope difference was apparent, it may again be recommended that more detailed temperature coefficient procedures be developed in standards applied to CdTe.

5.2 Recommendations:

It is recommended that the entire sample pool undergo the light cycling of module set "A". An improvement to the cycling to be considered would be to use a consistent light source for all sequences this allowing greater comparison between light and dark sequences. Furthermore this may allow a definitive decision on temperature

coefficient measurements to be made (i.e. which Tcoef is more relevant to module characterization). Finally, an experiment exploring the effect of dark storage temperature on stabilization time is suggested in light of the findings here. Such an experiment could subject four of the same modules to dark storage periods of specified temperature and duration then follow this with light stabilization procedures of the current standards.

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