R&D to Ensure a Scientific Basis for Qualification Tests and Standards

Final Report: FY19–FY22

Ingrid Repins and Steve Johnston, Principal Investigators

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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Final Technical Report (FTR)

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1 Executive Summary

Project return on investment in a photovoltaic (PV) system depends increasingly on maintaining high energy yields, and the system lifetime is a major factor in levelized cost of electricity (LCOE). Thus, the rate of PV deployment and the success of these assets depends upon reliable long-term power generation. This program advances PV module reliability of commercial products through identification of reliability needs, characterization that provides scientific understanding of targeted degradation mechanisms, and translation of those data into practical and predictive test protocols and standards. This report describes program scope, results, milestones, and accomplishments over the three-year period of performance.

A major area of success under this program is the development of standards, which reduce investor risk, ensure reliable products to consumers, and avoid market spoiling. Specifically,

- Seventeen international standards were published over the course of the program, with 18 more currently in progress.
- NREL led a team of 71 technical experts from 13 countries to update IEC 61215, a widely-used module design qualification standard. NREL had a large technical input to potential induced degradation (PID) testing, use of representative samples, testing and labeling of bifacial modules, and dynamic load testing.
- NREL's previous work on PID-shunting (PID-s) in Si (IEC 62804-1) has been extended to include PID-delamination (PID-d) (IEC 62804-1-1), while a predictive thin film PID test (IEC 62804-2) will publish shortly. Experiments to define test conditions for PID-polarization (PID-p) have begun.
- NREL led a number of studies and standards to ensure rigorous and repeatable polymer testing as these materials are expected to change due to cost cost reductions. A backsheet cracking test that reproduces recent field failures was developed and incorporated into to IEC TS 62788-2. NREL led international studies to develop consensus on encapsulant test procedures related to IEC 62788-1-4, IEC 62788-1-7, and IEC TS 62788-7-2.
- NREL has taken Light and Elevated Temperature Induced Degradation (LeTID) through the stages of field observation, characterization, and international collaborative testing, to a standards document in progress (IEC TS 63342).

Progress was also made in the recognition of reliability needs and understanding the degradation, as must precede standardization. In particular,

- Case studies of four different sites identified root cause of degradation. These root causes included LeTID, solder bond failure, corrosion of fingers with a different ink composition, and movement of H in the solar cell.
- Measurement of cracked cell fragment movement, and documenting that there can be electrical contact between fragments even when the grid finger is broken.
- Solder bond fatigue in new low-temperature solders was found to have different characteristics than traditional SnSb solders. Notably, the 200 thermal cycles used in module design qualification is a less rigorous test for the low temperature solders.
- An artificial soiling test apparatus for full-size modules was developed and shows some correlation to fielded results.
- PV stakeholders were engaged via highly-attended annual reliability workshops and NREL's key roles in international PVQAT collaborative activities.

Table of Contents

2 Background:

Project return on investment in a photovoltaic (PV) system depends increasingly on maintaining high energy yields,[1] and the system lifetime is a major factor in levelized cost of electricity (LCOE).[2] Thus, the rate of PV deployment and the success of these assets depends upon reliable long-term power generation. While most PV systems perform as expected,[3] a small fraction of systems (<10%) of systems underperform. It is important to product designs likely to underperform before these products hit the market. Such identification – via standardized testing - reduces investor risk, ensures reliable products to consumers, and avoids market spoiling.

This program advances PV module reliability and useful life of commercial products through identification of reliability needs, characterization that provides scientific understanding of targeted degradation mechanisms, and translation of those data into practical and predictive test protocols and standards.

3 Project Objectives

The general path of research under this program is shown schematically by the red arrow in Figure 1. The first step is the identification of needs, which NREL performs via site inspections, test to failure (for products with short fielded history), and interaction with system owners and other stakeholders. The next step is understanding how the degradation progresses. This step involves extensive characterization and accelerated testing, so that all the important factors in the degradation are identified, a physical model can be developed, and thus an acceleration factor to relate test and fielded behaviors can be derived. 30% of the resources in this program have been dedicated to characterization, to ensure robust interpretation of physical mechanisms. The final step is to transfer findings to commercial products via test protocols, the most mature of which may be included in international standards. The entire process is performed in an environment of stakeholder involvement (upper right in Figure 1), which includes a yearly PV Reliability Workshop (PVRW), continued leadership in the International PV Quality Assurance Task Force[1] (PVQAT), participation in standards organizations such as the International Electrotechnical Commission (IEC) and the U.S. Technical Advisory Committee (USTAG), and dissemination of results via publications and presentations. While Figure 1 shows each step being performed in succession (as for a single degradation mechanism), several degradation mechanisms are studied under this program. Thus, each type of activity exists concurrently in our research.

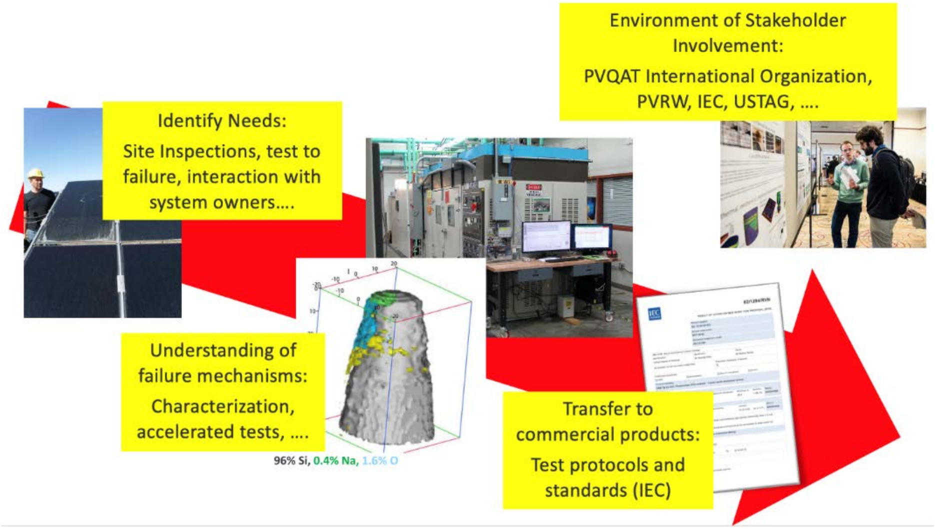

Figure 1: Schematic representation of the flow of research under this program.

The overarching objective of this program is to improve photovoltaic (PV) module reliability via development of standards. This object is organized into tasks as follows:

Task # 1: Direct Work on PVQAT and Standards. NREL has reduced risk and costs to PV customers by crafting quality and reliability standards, and by engaging an international group of stakeholders in the Photovoltaics Quality Assurance Task Force (PVQAT).

Task # 2: Cell-Related Module Degradation Modes in Commercial Modules. This task has examined module performance degradation that originates from within the solar cell. We have

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[1] See www.pvqat.org

examined cell cracking, light-induced degradation, and potential-induced degradation, incorporation both traditional module design and new higher-efficiency module designs into our studies.

Task # 3: Interconnect-Related Degradation Modes. Work under this task has studied thermomechanical fatigue in multi-wire interconnects found in current products. Science-based recommendations for accelerated tests that may be suitable for standardization were developed.

Task #4: Package-Related Degradation Modes. Work under this task has studied module degradation due to UV weathering, backing cracking, coating abrasion, and delamination. Science-based tests were developed, and several were incorporated into standards.

The milestones that have allowed progress toward the project objectives to be measured are listed and described briefly in Table 1. All milestones were satisfied on schedule.

Table 1: Summary of milestones with brief description.

Milestone Number, Type, And Due Date	Milestone Description and Justification
1.2.1 **Quarterly** **12/31/2018**	Quantification of signatures of LeTID via a graph showing module output power as a function of LeTID-inducing stressor exposure time, extending for at least 1000 hours, for at least 2 different commercial products. Quantifying LeTID is important for predicting system energy generation and making informed decisions when procuring modules.
1.1.1 **Quarterly** **3/31/2019**	Stakeholder engagement: NREL will host the PV Module Reliability Workshop, with more than 100 attendees.
1.4.3 **Quarterly** **6/30/19**	Publication summarizing the first-year results for the field abrasion study for PV coating materials. Soiling limits PV power production, being the most significant location- and climate-governed factor after insolation and temperature. PV coating technologies presently lack the methods that might be used to develop, select, and ensure confidence in their durability.
1.2.4 **Annual** **9/30/19**	At least two published reports that document field failures in at least 4 PV systems, with at least one serious failure having the potential to reduce annual energy production by 5%. Assess the need for one or more standard tests that could be used to detect in advance whether a system is prone to the serious failure. Field data are a critical component to identifying where standardized testing has been effective and where new standards or tests are needed.
2.2.1 **Quarterly** **12/31/19**	Publish paper illustrating micro-characterization of the degradation mechanism(s) of a high-efficiency cell technology. To further reduce LCOE, the PV industry needs accelerated tests with a view into longer module lifetimes even in the face of decreasing costs. The understanding gained by microcharacterization helps develop the understanding for more meaningful tests and their limits of applicability.

Milestone Number, Type, And Due Date	Milestone Description and Justification
2.1.2 **Quarterly** **3/31/20**	Stakeholder engagement: NREL will host the PV Module Reliability Workshop, with more than 100 attendees.
2.3.3 **Quarterly** **6/30/20**	Quantify interfacial bonding and fracture for multi-wire interconnects on Si cells: Demonstrate repeatability and sensitivity to accelerated exposures. Measurement of these properties is necessary to develop meaningful accelerated tests for multi-wire interconnects.
2.3.4 **Annual** **9/30/20**	Demonstrate suitability of at least three new accelerated tests for incorporation into standards. Success is judged by either of the following conditions: a) The test separates known good and known bad samples (from fielded data) for at least four product types; or b) Derived acceleration factors allow extrapolation of laboratory experiments to fielded modules with small enough uncertainty that useful conclusions can be drawn. Development of proven, science-based tests leads to more effective international standards, longer product lifetime, and lower LCOE.
3.4.1 **Quarterly** **12/31/20**	Published paper that demonstrates a method of reproducing and evaluating backsheet cracking using a small laboratory coupon. Backsheet cracking is observed in fielded modules, but, prior to this program, ways to predict cracking were not available. The lack of a measurement dependent only on the material properties prevented development of a backsheet component standard that could increase module reliability.
3.1.2 **Quarterly** **3/31/21**	Stakeholder engagement: NREL will host the PV Module Reliability Workshop, with more than 100 attendees.
3.2.3 **Quarterly** **6/30/21**	Cost and/or value evaluation: Relate accelerated test results to degradation rate and LCOE for at least two different accelerated tests on two different products. This analysis will illustrate how lower LCOE can result from manufacturers designing to pass certain accelerated tests, or screening products that fail those tests.
3.1.4 **Annual** **9/30/21**	Incorporate results from this program into at least two standards. International standards provide a consistent and widely-adopted way for industry stakeholders to verify module reliability and quality.

4 Project Results and Discussion

Results in this reporting period are described below, listed in order of task and sub-task from the statement of work.

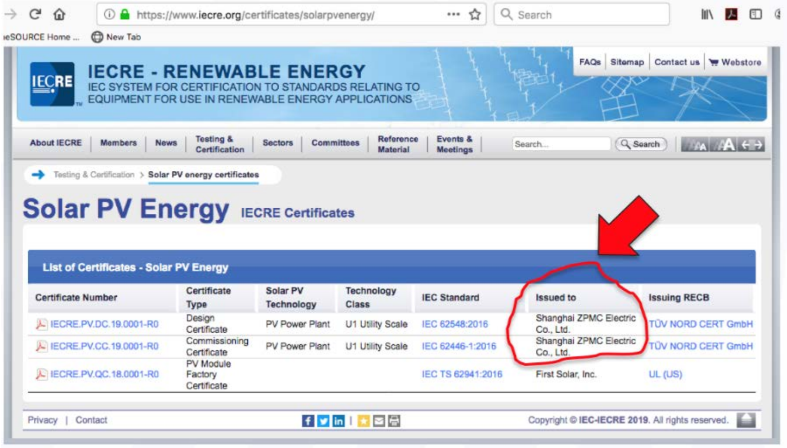
4.1 Task 1: Direct Work on PVQAT and Standards Development

Implementation of R&D results into international and national consensus standards provides direct community benefit. If the standards are quickly implemented and uniformly adopted, they reduce risk, and, thereby cost, to the PV customer and investor. NREL acts as an impartial third party in several standards processes, where other participants may have a vested interest in the results. NREL's activities include both direct involvement in the standards processes, stakeholder engagement via PVQAT, PVRW, and other interactions.

In the project period, NREL has participated in the development of 35 standards documents. These documents are listed in section 8.9 of this report, "Standards (By Standard Number)." Direct participation in the standards process has included

- leading international project teams,
- participating as a team member on some projects,
- representing U.S. interests by providing comments on all proposed IEC PV documents via the U.S. National committee,
- advising on the adoption of such standards by Nationally Recognized Test Laboratories by participating in UL technical panels
- leading the U.S. technical advisory committee (via subcontractor Powermark Corporation), and
- ensuring a functional international standards process by sponsoring the IEC secretary, through subcontract to Sunset Technology.

An encouraging development during this reporting period is issuing of the first certifications for utility-scale systems under the IECRE system. NREL researchers, and many experts world-wide, have written and updated standards in recent years to enable certifications for all stages of PV system life. This expansion of standardization to systems, rather than just components (such as modules), forms the IECRE system. While the need for PV system quality is clear, it has been unclear in the short time since the IECRE system was created whether such certifications would become common contractual requirements. Figure 2 shows the list of IECRE certificates issued, now including the first design and commissioning certificates for a utility-scale system. These certificates may be a first development in a trend of improvements in system quality.



Solar PV Energy IECRE Certificates

List of Certificates - Solar PV Energy

Certificate Number	Certificate Type	Solar PV Technology	Technology Class	IEC Standard	Issued to	Issuing RECB
IECRE.PV.DC.19.0001-R0	Design Certificate	PV Power Plant	U1 Utility Scale	IEC 62548:2016	Shanghai ZPMC Electric Co., Ltd.	TÜV NORD CERT GmbH
IECRE.PV.CC.19.0001-R0	Commissioning Certificate	PV Power Plant	U1 Utility Scale	IEC 62446-1:2016	Shanghai ZPMC Electric Co., Ltd.	TÜV NORD CERT GmbH
IECRE.PV.QC.18.0001-R0	PV Module Factory Certificate			IEC TS 62941:2016	First Solar, Inc.	UL (US)

Figure 2: IECRE website documenting design and commissioning certification for utility-scale system in China.

An important prerequisite to a standards document is international agreement regarding the need for a standard and identification of likely accelerated tests. NREL is involved in several stakeholder engagement activities, including PVQAT and PVRW, that precede standards development.

The international PVQAT organization leads global efforts to create and assemble the data needed to conceptualize quality and reliability standards. NREL participates in all aspects of PVQAT. NREL holds several seats on the PVQAT steering committee, and participates in all technical task groups. NREL leads task group 3 on humidity, temperature, and voltage; task group 5 on UV, temperature and humidity; task group 8 on thin film; task group 10 on connectors and J-boxes; task group 11 on power electronics; task group 12 on soiling; and task group 15 on Repair, Reuse, and Recertification. NREL hosts and updates the PVQAT website (https://www.pvqat.org).

This period has also seen the formation of new subject matter task groups, demonstrating continued growth and vitality in the PVQAT organization. A task group 14 "PVQAT India" is lead by Narendra Shiradkar at IIT Bombay. It focuses on PV reliability topics of high priority in India, and meets at times convenient in India, but is open to all who would like to participate. A new task group 15 "Reuse/Repair/Recycle" was also established. Task group 8, "Thin film," has seen a renewal of activity recently as consideration of perovskites has been incorporated into the group's scope.

Another significant development in PVQAT during this reporting period is a resurgence of activity in task group 10 (junction box and connectors). Task group 10 had been largely inactive for a period of months. However, the group has recently taken on a study of failed connectors, with NREL leadership. Connectors are frequently cited as an unresolved reliability problem for PV modules. Because they are easily replaced, failure is not usually catastrophic, the problems are simply fixed as they occur, allowing the problems to be easily hidden from public scrutiny. However, such replacements are time-consuming and decrease project return on investment. Failure frequently stems from intermating connectors different manufacturers (despite installation instructions to the contrary and invalidation of the certificaiton) and from manufacturing repeatability issues. Many manufacturers make connectors that will physically connect but which are not certified to be used together. This practice is misleading and an unnecessary source of system failures. PVQAT TG10 is studying failed fielded connectors (as shown in Figure 3 and using spares from the same installation to determine if the failures could have been detected by an accelerated test. Existing connector tests (such as UL 9703 Current Overload, UL 9703 thermal cycling 200, UL 486a-486b Current Cycling) have been applied to the samples but have not yet reproduced the failures. Harsher tests may be needed. Additionally, a group from NEMA has started a subgroup called the Solar Photovoltaic Council which has taken on a project to write a standard for intermateability of connectors. Through the PVQAT organization, NREL has been instrumental in connecting interested parties to this effort.

Figure 3: Photo of some failed connectors under study by PVQAT TG10.

One of the ways in which NREL supports stakeholder engagement is through hosting the annual Photovoltaics Reliability Workshop ("PVRW"). Workshops were held in February of 2019, 2020, and 2021, each with more than 200 attendees. Session topics are changed from year to year to address timely issues. The workshop series continues the tradition of engaged attendees: Participation requires sharing of a paper—either an oral or poster presentation—by each company at some time during the week. Traditionally, the PVRW is held in-person to facilitate interactions (Figure 4, left) and adjunct meetings. However, due to CoVID restrictions, the 2021 event was held using an interactive on-line platform (Figure 4, right). In attendee feedback, while there was consensus that the in-person event is preferred, several attendees said it was the best, most interactive, virtual event that they had ever attended.

Figure 4: Interacting at a PVRW poster session in person (left, 2019) and on-line (right, 2021).

4.2 Task 2: Cell-Related Module Degradation Modes in Commercial Modules

This task examines module performance degradation that originates from within the solar cell. The task includes both observation of fielded modules and examination of specific degradation mechanism where important questions need to be answered. Some work involves researching specific degradation modes that are suspected to be important and prevalent. These modes include cell cracking (subtask 2.1), light-induced degradation (subtask 2.2), fielded cell degradation (subtask 2.3), and potential induced degradation (subtask 2.4). In these examinations, we emphasize the impacts of new higher-efficiency module designs and of new system designs.

4.2.1 Subtask 2.1: Cell Cracking

PV module packaging materials mechanically protect crystalline silicon solar cells. However, cells can crack during manufacturing, transportation, installation, and service.[4] Cracks can initially be bridged by the cells' metallization or may not separate active area from a current pathway to bussing allowing current to continue to be collected from broken portions of cells. The initially small effect on performance can become severe when these cracked contacts are further damaged by thermal and mechanical cycling.[5] In thermal cycling, the mismatches in coefficient of thermal expansion (CTE) of module packaging materials leads to displacement and mechanical strains during the thermal cycle.[6] Understanding and quantifying the relative movement of cell fragments, as well as the nature of the electrical contact between neighboring cell pieces, is essential to predicting the progression of performance loss. Such quantification also enables developing accelerated tests that can predict the progression of performance loss in a field-relevant way. We are also periodically observing modules outdoors, so that we can compare our loss predictions with data from fielded modules.

We first describe the outdoor data. Seven modules exposed to a severe hailstorm on May 8, 2017 in Golden, Colorado are being tracked. Current-voltage (IV) measurements and electroluminescence (EL) images were taken on each measurement just after storm, two years later, and four years later. While EL images of modules with hail damage (Figure 5, center and right) show a progressive darkening of hail-cracked areas over four years, current voltage data show no change within measurement uncertainty (Figure 6) so far. For series S/N 17xx, hail-damaged modules exhibit <4% power loss due to cell cracking, even when up to half of the cells in a module have cracks. The lack of performance change over the years, despite cell cracks, underscores the need to quantify the relationship between physical stressors and electrical degradation for cracked cells. Simply viewing the EL image an replacing the module based on severe cracking may cause unnecessary expense. Such expense occurs both in terms of replacement costs (system downtime, labor, etc.) and in terms of increased insurance premiums.[7] Our observations regarding hail damage have been reported in several publications and presentations. (See accomplishments #75, 83, and 85.)

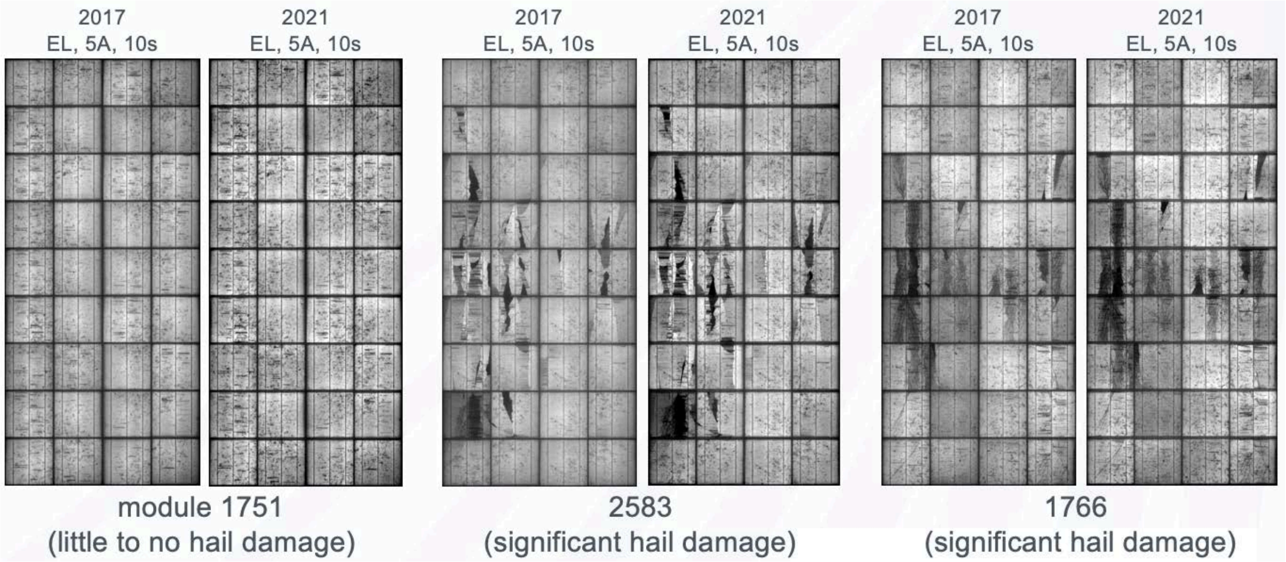


Figure 5: For three modules a comparison of EL images just after hail storm (2017) and after 4 more years of field exposure (2021).

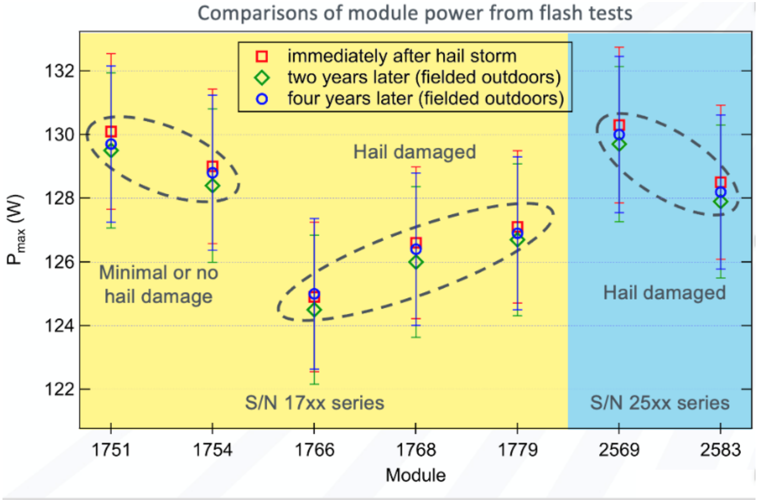


Figure 6: For 7 modules, a comparison of indoor flash tests just after the hailstorm (2017), two years later (2019), and four years later (2021).

To enable predictions of power loss as a function of exposure after cracking, we embarked upon a fundamental study of the cracks. Our goal is to understand how cell fragments move, how the movement degrades the electrical contact between fragments, and thus ultimately how the module performance evolves as a function of fielded exposure after cracking.

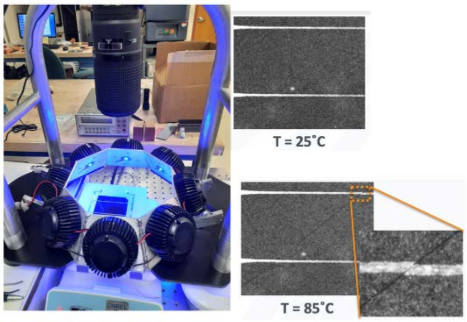


Figure 7: Experimental apparatus (left), and digital image of crack at 25 ^{o}C (upper right) or 85 ^{o}C (lower right).

We have developed digital imaging for measuring crack movement during thermal cycling. The experimental apparatus is shown in the left half of Figure 7. The apparatus features a digital camera centered above the test sample and high-intensity lighting to obtain high quality images. The test sample can be set on a hot plate for thermal cycling. An example of images obtained using this apparatus are shown in the right half of Figure 7 . At 25ºC, the crack in the sample is barely visible, yet at 85ºC the cell fragments have moved, making the crack visible to the naked eye and demonstrating temperature-dependent misalignment of the gridlines. We developed digital imaging processing to quantitatively track the movement of points on the cell surface. A surprising conclusion from our microscopic characterization is that the cracks in the solar cell can immediately propagate through the metal grid, but the grid can maintain electrical contact once the load is removed. This conclusion is illustrated by the data in Figure 8. For this module, an EL imaging was utilized locate a crack. We then extracted a sample of cracked cell from the surrounding packaging materials. We used scanning electron microscopy (SEM) to verify that the interior of the sample was free from cracks introduced by the extraction process. We then collected images of front metallization bridging cracks. We used a xenon plasma focused ion beam (FIB) to remove material and collected cross-sectional views. Resulting images are shown in Figure 8. The images show a line of silver metallization (top) bridging the crack and a cross-sectional view of the same line (bottom). While there is little or no visible contact, this line continued making electrical contact after the crack was formed.

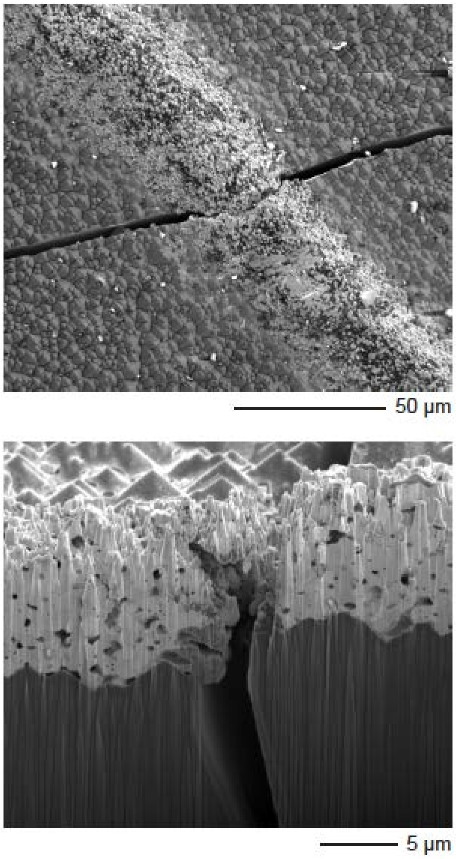


Figure 8: SEM images from a cracked solar cell, viewing a grid line crossing the cell crack in plan view (top image) and cross-section (bottom image).

We have also developed techniques for diagnosing cracks and their history in deployed modules. While numerous publications have shown that it is possible to use electroluminescence (EL) to locate cracks in a module, system owners have stressed to us that it is important to have more information about the origin of the crack. For example, if cracked modules are detected during site commissioning, did the cracks occur during transportation from the manufacturer, during installation, or during yesterday's wind storm? Thus we developed capabilities for ultra-violet fluorescence (UVF) imaging and data analysis. UVF is advantageous because it can be used to quickly scan arrays for cell crack damage and also can help date the time of damage. While EL scanning of a module currently takes about 5 minutes for 250 micron resolution, a UVF image of a module can take just a second using digital single lens reflex (DSLR) camera. Furthermore, as oxygen diffuses through the crack and into the encapsulant on top of the cell, the UV response of the encapsulant around near crack changes. This evolution allows the width of UV features to be qualitatively correlated with the time since the crack was formed. Figure 9 and Figure 10 illustrate how UVF helps determine when a crack was created. Figure 9 is an EL image of a cracked cell in a module. An older crack is circled in blue, and a newer crack – added just before characterization – is bracketed in orange. Figure 10 shows how the UVF image of the same cell evolves over the course of 10 days. The dark area around the new crack becomes wider as time passes. The dark area around the old crack is much wider and reached its equilibrium width before the Figure 10 data series started. Looking forward, it is expected that the trend toward new multi-wire configurations, which allow decreased metallization on the cell surface, may decrease crack tolerance and make diagnosis of these issues even more urgent. At the same time, customers are demanding increased hail resistance, as evidenced by the new technical specification IEC TS 63397 currently under development, “Guidelines for qualifying PV modules for increased hail resistance.”

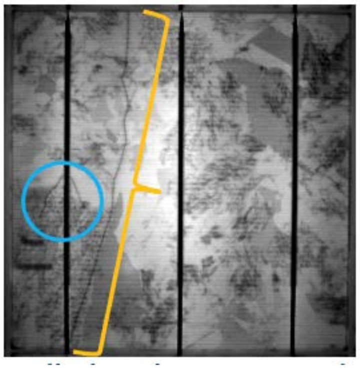


Figure 9: EL image of a Si solar cell showing a pre-existing crack (circled in blue), and a newly-added crack (bracketed in orange).

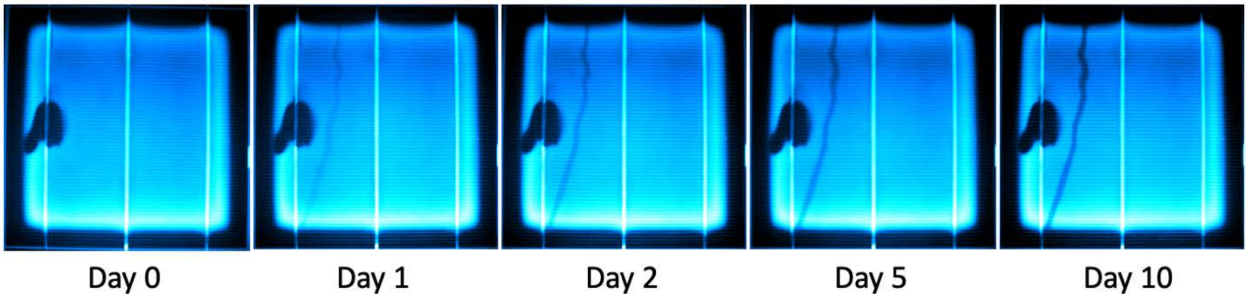


Figure 10: Time-evolution of UVF images of the cell pictured in Figure 9.

4.2.2 Subtask 2.2: Light-Induced Degradation

Treating (BO LID),[8,9,10] and light and elevated temperature induced degradation (LeTID)[11,12,13,14,15,16,17] has become more urgent with the increasing prevalence of higher efficiency cells, because both BO LID and LeTID cause a degradation in the high minority lifetime that is critical to high efficiencies. Our main goals are to specify correct accelerated test procedures for design qualification, and to correlate test results with fielded behavior.

Due to the urgency of publishing a standard test for LeTID, NREL organized an international interlaboratory LeTID study. The purpose of the interlaboratory test was to exercise global testing capabilities, evaluate the effectiveness of the protocol in identifying LeTID, and to estimate cross-lab reproducibility. Module manufacturers and testing labs participated on a volunteer basis. Six different manufacturers supplied 10 different module types, for a total of 64 different modules, which were distributed to 14 different testing labs. The six participating manufacturers represented five different countries, and testing labs represented ten different countries. It was found that the reproducibility of LeTID testing is likely within ±1% of maximum power (P_{mp}), and that the test correctly identified degradation in modules intentionally engineered to exhibit LeTID. The results of the interlaboratory study are in publication (accomplishment #15).

A kinetic model for LeTID was created based on Boltzmann statistics. rate equations, and published data. The details of the model were presented (see accomplishment #123) and are the subject of an upcoming publication. Examples of kinetic model predictions compared against experimental data are shown for accelerated tests (Figure 11) and fielded module data (Figure 12). The ability to predict LeTID as a function of climate led to the use of such profiles to quantify the impact of LeTID on LCOE. (See accomplishment #175.)

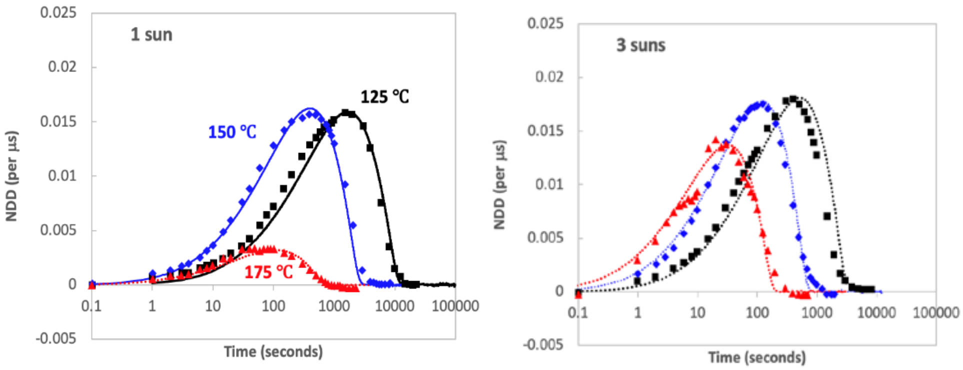


Figure 11: Normalized defect density (NDD) as measured in reference[18] (discrete data points) compared with predictions from this work (lines).

The kinetic model was also applied to estimate how BO LID or LeTID might unintentionally impact module design qualification results (e.g. the question raised earlier about regeneration during thermal cycling). This application was described in a paper (see accomplishment #27), which was awarded "Best Paper for PV Systems" in 2021 by the journal Solar Energy. It was found that while LeTID was unlikely to cause false test results, BO destabilization could occur and cause good modules to fail the damp heat test. An alternate stabilization to prevent these false results was recommended and immediately incorporated into IEC 61215. This alternate stabilization removed a major stumbling block for high-efficiency PERC modules. Industrial experience documenting the failure of good PERC modules was gathered and posted in a public data repository.[19]

A sophisticated interpretation of fielded module performance separates degradation into multiple mechanisms that may proceed at different rates. Such an interpretation is necessary to develop better predictions of long-term system performance. A difficulty in incorporating LeTID into such predictions is that it is presently only identified by the rate of degradation as a function of stress, and thus may be confused with other degradation mechanisms. To solve this problem, characterization was performed to attempt to identify fundamental characteristics of LeTID that could be used as a "fingerprint" in its detection. Characteristics of LeTID as observed by deep level transient spectroscopy (accomplishment #'s 53, 86, 87) and scanning Kelvin probe force microscopy (accomplishment #145) and documented.

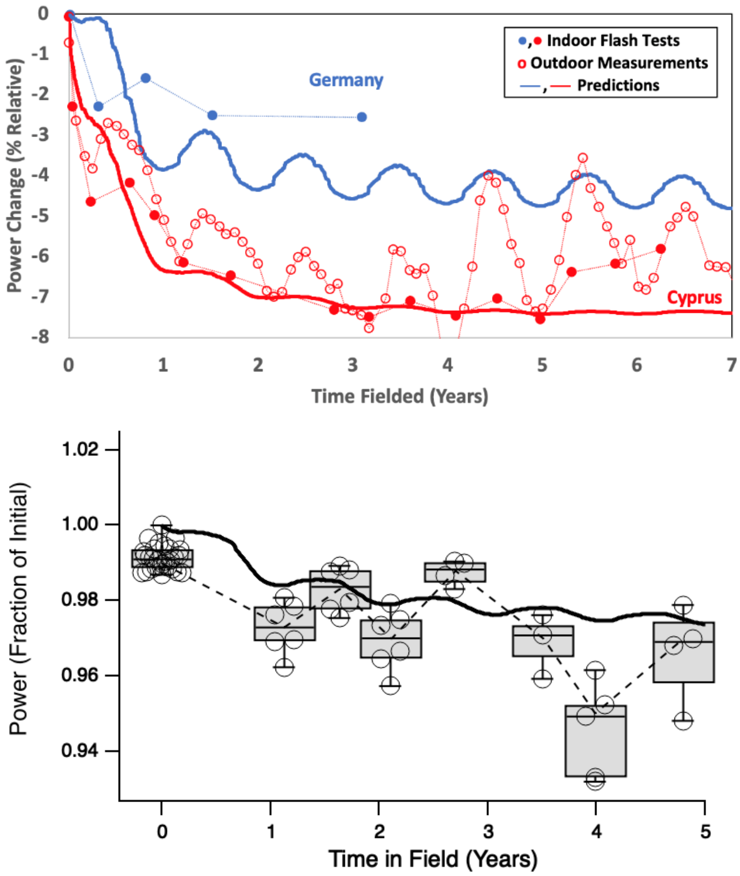


Figure 12: Comparison of predictions (thick lines) with experimental data points from modules fielded outdoors in Germany and Cyprus [1,1] (top) and from modules fielded at NREL (bottom).

An interesting discovery that may be general to PERC cells was made while looking for signatures of LeTID. PERC cells were stressed under one sun illumination at various temperatures. Two types of degradation were observed on the PERC cells. We observed a fast degradation that was roughly consistent with BO-LID, both in terms of reaction rate and performance recovery. We also observed a slower degradation that did not recover ("irreversible"). Secondary ion mass spectrometry (SIMS) on a few extracted cell cut-outs suggests that the irreversible degradation is associated with H movement in the cell. Spectral response degradation was largest at short wavelengths. Both effects are consistent with degradation of the front passivation. Utilizing the derived activation energy, power degradation predictions for fielded modules are around 0.3% per year for warm climates. Experimental observations of fielded modules, even those that are ostensibly free of obvious or identifiable degradation processes, commonly show long-term yearly power output decreases of around 0.5%.[20] It is hypothesized that this work has detected a surface passivation degradation that is at least partially responsible for baseline degradation. This work is documented in accomplishment #37.

4.2.3 Subtask 2.3: Fielded Cell Degradation

Under subtask 2.3 we have been applying an in-depth approach to case studies degradation, particularly in underperforming systems. The goal is to utilize time-series analysis, site inspections, and microscopy to gain a detailed understanding of degradation modes that affect energy yield. These case studies provide data on the most important types of degradation in modern modules, and suggest which mechanisms are ripe for accelerated test development. Below we discuss analysis of commercial modules from five different sites.

At the first site, the system operator investigated lower performance and found that ~7% of modules were operating at 2/3 of their nameplate power. As these modules contained 3 parallel strings, an effect that could remove an entire string from operation – such as a faulty ribbon or a bypass diode failed closed – was suspected. Further investigation at NREL showed that the problem was faulty solder bonds, as shown in Figure 13. The appearance of this failure was initially mysterious, as the thermal cycling test in module design qualification (IEC 61215) has been designed to screen for solder bond failure in qualified modules. However, after consulting the product literature and speaking with a manufacturer representative, it became clear that these modules were not qualified to IEC 61215. This incident underscores the importance of applicable standards, and requiring the appropriate qualifications in code or the procurement process.

Figure 13: Faulty solder bonds as seen by discoloration (left) or heating in IR image (right).

A second utility-scale site consisted of mono-PERC modules. After two years, the system owner observed a bimodal distribution in field IV power, with large fraction of the modules operating at less than 95% of their nameplate power. Given that the underperforming modules exhibited slow degradation (years), voltage drop, and cell-to-cell variation, which are all characteristics of LeTID, a LeTID accelerated test was performed on one of the degraded modules. The module regenerated. The time scale and uniformity changes were also consistent with LeTID. The work (see accomplishment #4) is the first published account of LeTID in a utility-scale system.

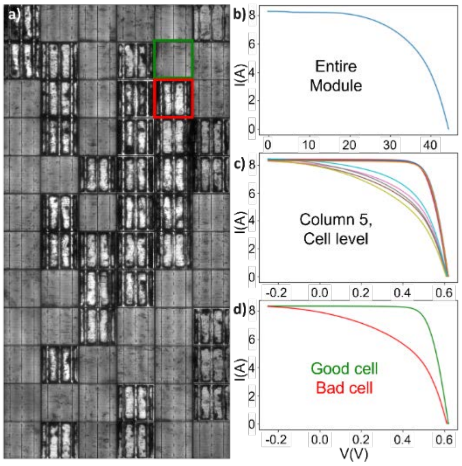


Figure 14: a) EL imaging of a degraded module, b) IV scan of the same module, c) IV scans of all cells in column 5, d) IV scans of a unaffected and affected cell, outlined in green and red respectively in the module.

A third utility scale system exhibited a long tail of underperforming modules in the power distribution. At NREL, it was shown that some of the cells in the underperforming modules EL images exhibited a dark halo around the grid fingers, as in Figure 14a. This same EL pattern was observed at two other sites in two other commercial products, showing that it is not an isolated occurrence. Samples were cored from good and bad cells in affected modules, and the corrosion was correlated with the grid finger ink composition, as shown in Figure 15. Results were presented (accomplishments # 73, and 74) and published (accomplishment 46). Presently, an accelerated test to screen for this effect is under development.

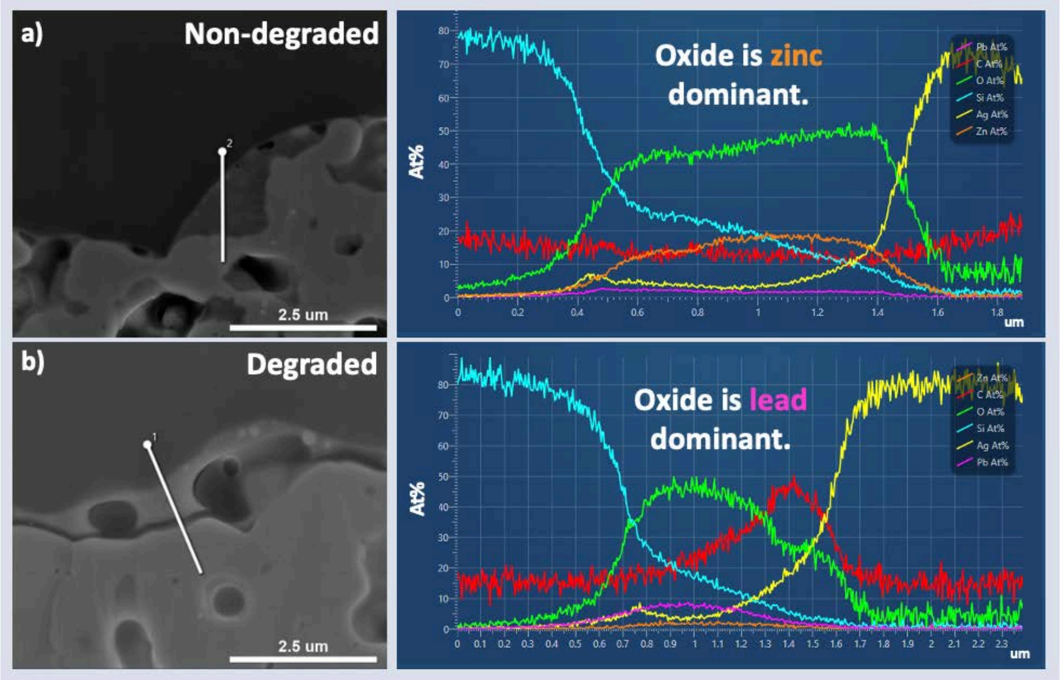


Figure 15: Figure 4. SEM imaging showing associated EDS elemental line scans at the finger-Si interface for a) a good cell and b) a bad cell. EDS indicates that the oxide is zinc dominant in the good cell, but lead dominate in the degraded cell.

A fourth utility-scale site was partially built with n-type mono-Si modules, and outdoor IV indicates that these are performing at less than 90% of their nameplate power after 5 years. EL measurements taken at NREL reveal multiple atypical patterns not documented in the literature. We are currently working to determine the root cause of degradation in these modules.

In a fifth PV system, degradation of high-efficiency HIT modules that were fielded at NREL for 10 years was studied. Figure 16 shows how current voltage (IV) curves have evolved over the years for these deployed modules. To measure the IV curves of Figure 16, the modules were removed from the outdoor test area, measured indoors on a flash tester at standard conditions, then replaced outdoors. These modules exhibit a 0.7% per year performance loss which is dominated by voltage change, though some increase in series resistance (1.15 to 1.75 Ωcm^2) is also observed. It was found that the degradation of the HIT modules correlated with movement of H within the solar cell, as shown in Figure 17. Accomplishments #31, 49, 55, 62, 82, 92, and 93 are publications and presentations on this subject. Later, it was determined that H movement is associated with degradation of PERC cells as well (accomplishments #54, 55, 88).

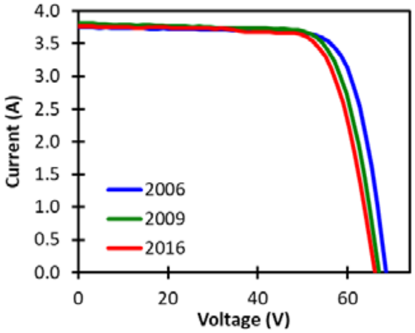


Figure 16: Evolution of HIT module IV curves over the course of 10 years.

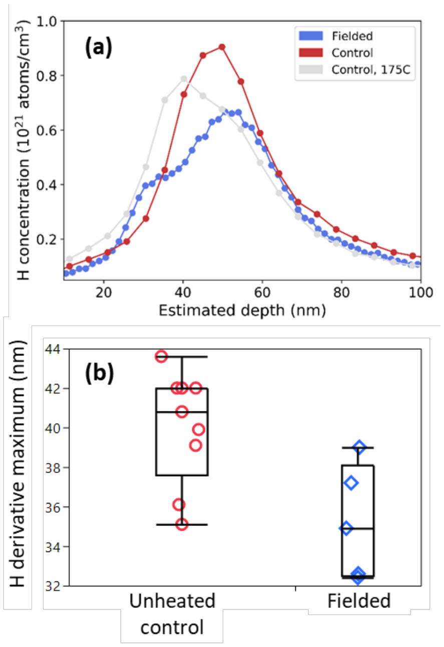


Figure 17: Hydrogen concentration from dynamic secondary ion mass spectroscopy traces for a fielded, control and a control sample that was heated to 175ºC (a). The maximum of hydrogen concentration derivative for control and fielded samples (b).

4.2.4 Subtask 2.4: Potential Induced Degradation

Potential Induced Degradation (PID) was first observed in 2012, and since that time NREL has played an active role in understanding this degradation mode and how to perform meaningful accelerated tests for it. Specifically, NREL led a project team to develop standardized test methods for PID, which were published in 2015 as IEC TS 62804-1. Work on PID under this program looks to develop appropriate tests and interpretation for new cell types (e.g. bifacial), for new system types (e.g. floating), and for situations where climate may play a strong role in the occurrence of PID (e.g. wet climates with low sunlight where PID-polarization may be more severe than PID-shunting).

Three test levels in IEC TS 62804-1 (60°C, 65°C, and 85°C with 85% relative humidity "RH") were examined in relation to some of the world's most stressful conditions for inducing PID. Experimental data were gathered from:

- a land-based PV system near Tengeh reservoir in Singapore,
- a floating PV system on Tengeh reservoir (as in Figure 18)
- an inland rooftop system in Singapore,
- a system in Cocoa, Florida (near water), and
- an inland system in Golden, Colorado.

In these systems, current transfer between the module circuit and exterior were taken as an indicator of the relative PID stress in each environment. Current transfer was observed to be largest in the Singapore floating systems. Current transfer in the floating Singapore systems was about twice as large as that occurring in Florida, and about 10x larger than that occurring in Colorado. Based on coulomb transfer analysis, testing modules at the harshest conditions in 62804-1 (85°C, 85% RH, 96 h, system voltage) is anticipated to be suitable to screen modules for mitigation of PID-s in crystalline silicon modules for floating PV applications at reservoirs and lakes in tropical equatorial climates. Work on PID in floating PV was documented in accomplishments #57, 77, and 106.

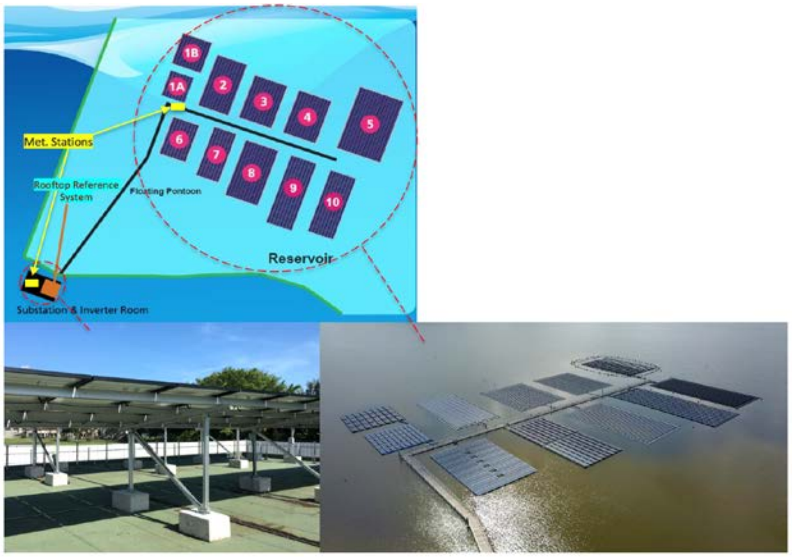


Figure 18: The Tengeh Reservoir FPV site, consisting of the land-based substation rooftop reference system (SG-RR, bottom left), and the multiple FPV systems (SG-FPV, bottom right), of which four are analyzed.

In PID-related standards activity, IEC 62804-1-1 on PID delamination testing was published. IEC 62804-2 on thin film PV has advanced to the draft technical specification phase.

Finally, we build upon earlier PID-shunting (PID-s) work, to develop a PID-polarization (PID-p)[21] test that is applicable to bifacial modules. A first step is creating an experimental setup that will make PID-p tests as representative as possible of fielded conditions in terms of voltage bias, front surface conduction, and the presence of light. Toward this end, TOPCON modules[22] were tested outdoors in the apparatus shown on the left side of Figure 19. In this setup, the module surface is covered with a conductive gel, to mimic outdoor conditions such as condensed dew or high relative humidity. -1000V (a reasonable system voltage) is applied between the cell circuit and the package. The module is maintained at 60 °C ± 10 °C for 3 hours. Preliminary results are shown on the right side of Figure 19. A 1 % power loss seen using this method. The dependence of the PID-p magnitude on the rear packaging will be investigated in future work.

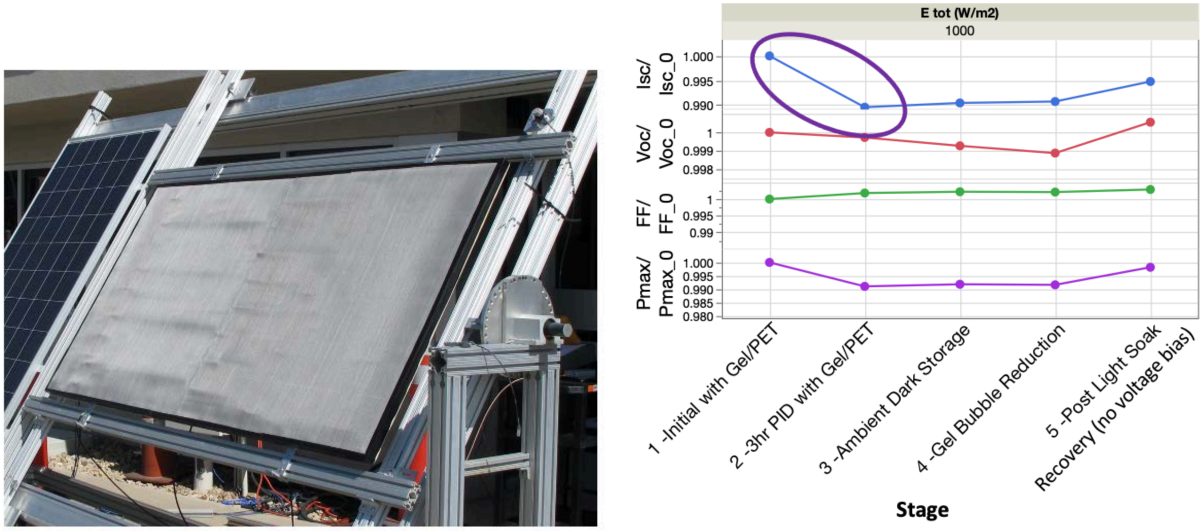


Figure 19: Test apparatus for PID-p (left) and initial results (right).

4.3 Task 3: Interconnect-Related Degradation Modes

Solder bond failures due to thermomechanical fatigue were common in early PV modules and thermal cycling was added to qualification tests to decrease these occurrences. Recent work at NREL demonstrated the equivalence of accelerated test conditions to field exposure for traditional solder bonds.[23] Due to the incorporation of appropriate thermal cycling accelerated tests into module design qualification, the solder bond failure in modern modules is rare.

Recently, novel interconnect technologies leveraging low melting temperature solders, such as multiwire interconnects, are being deployed in photovoltaic (PV) modules. The goal of these new technologies is improved reliability through interconnect redundancy and lower thermal loads during lamination. However, the equivalency of standardized accelerated testing to field conditions has not yet been established for these emerging technologies. In this subtask, the thermomechanical fatigue resistance of low temperature solder alloys is investigated and compared to that of conventional SnPb to assess the acceleration behavior of these alloys.

Low temperature solders were studied by making solder joint test structures, exposing these to thermal cycles, and measuring the resultant crack growth in the solder joint. Figure 20 demonstrates the progression of crack growth as monitored by confocal scanning acoustic microscopy (C-SAM). In Figure 20a the initial voids are evident as bright white shapes, with the light area around the edges indicating very early phases of a crack. Figure 20b shows the same joint 2900 thermal cycles later, where the edges of the joint have cracked appreciably. Figure 20c shows a representative cross-sectional SEM image, confirming significant cracking through the solder interface.

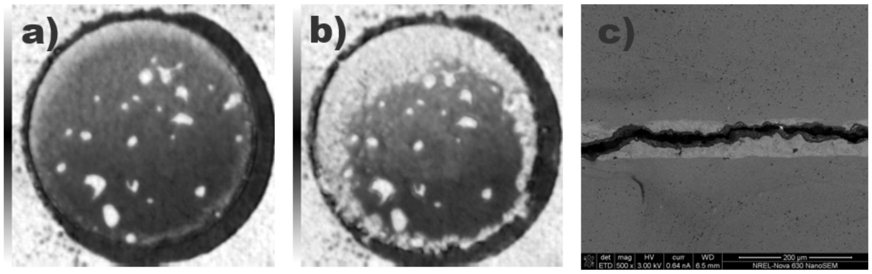


Figure 20: C-SAM image of a SnBi solder joint after a) 1000 thermal cycles (TC) and b) 3900TC; c) SEM cross-section of a separate joint demonstrating cohesive cracking through the solder layer.

Compilations of the number of thermal cycles likely to produce failure under various conditions are shown in Figure 21 and Figure 22. Data indicates that the thermomechanical fatigue resistance of the Sn-Bi alloys will be quite poor at field conditions. Under the milder thermal cycling condition (TC-3 in Figure 21), which is the most similar condition in this study to outdoor exposure, the Sn-Bi alloys have an order of magnitude lower lifetime than the conventional SnPb solder. Results also indicate that acceleration factors for Sn-Bi alloys would be less than one. This conclusion can be derived from Figure 22, where a decrease in thermal cycling intensity results in a decrease in lifetime. Thus, comparable performance for multiwire modules using Sn-Bi alloys and conventional modules under a TC200 exposure cannot be interpreted as comparable performance under field conditions. This situation demonstrates the importance of obtaining acceleration factors for new materials and architectures to design meaningful tests.

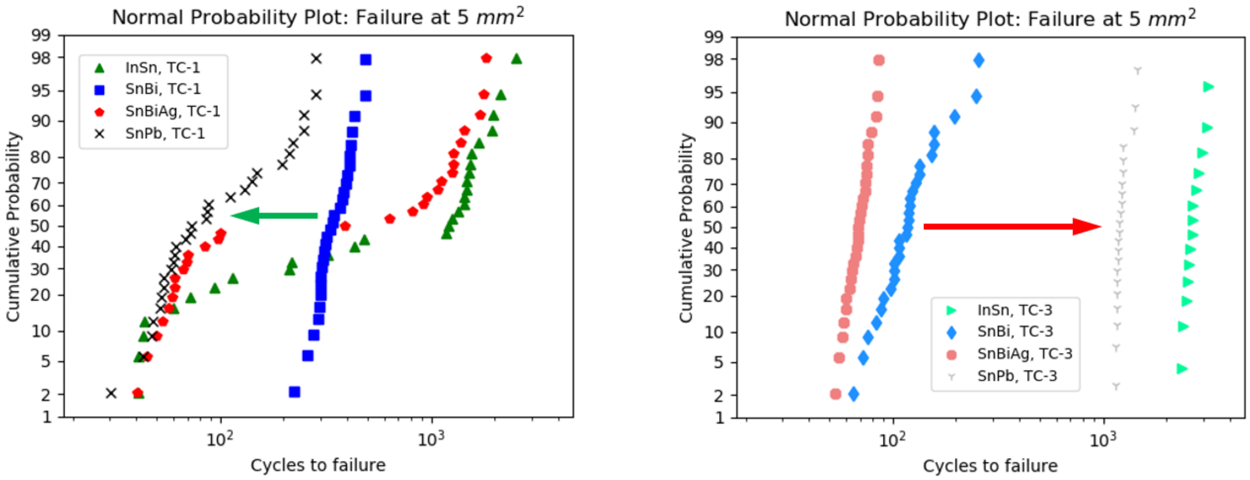


Figure 21: Comparison of the four solder alloys under a high intensity thermal cycle (TC-1, left) and a low intensity thermal cycle (TC-3, right). The Sn-Bi alloys appear to outperform SnPb under TC-1 but have much lower lifetimes than SnPb under TC-3.

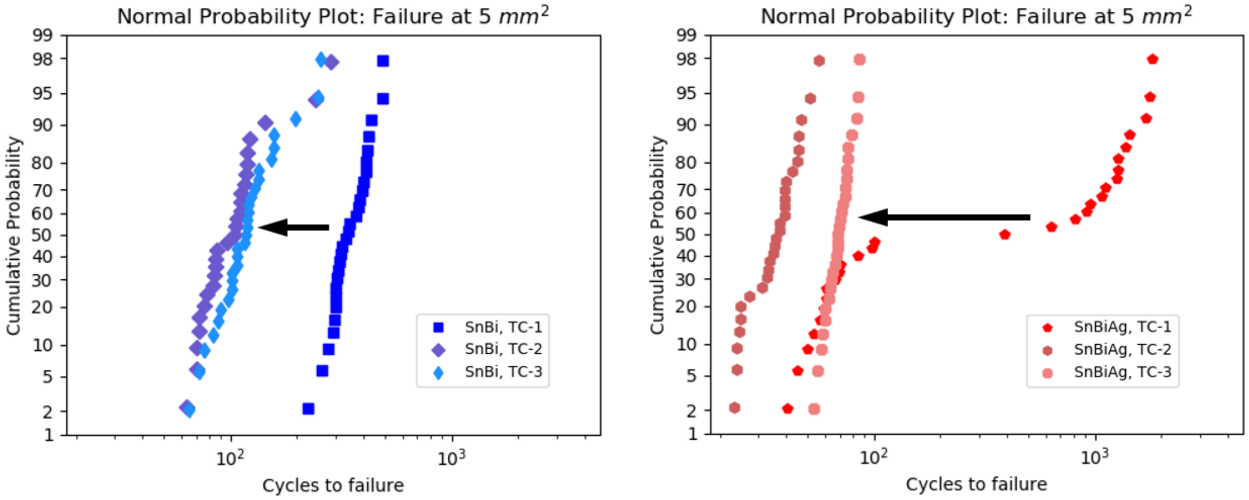


Figure 22: Probability distributions for SnBi (left) and SnBiAg (right) for all three thermal cycling profiles. Decreasing thermal cycle intensity decreases lifetime.

4.4 Task 4: Package-Related Degradation Modes

Degradation modes related to the module package continue to make up a large fraction of reported module failures. Such failures include those related to discoloration of transparent materials, backsheet cracking, and package delamination. These failures have been documented in the literature and observed by NREL personnel on external site visits. Package-related degradation modes require continued additions or modifications to existing standards as expected module lifetimes are pushed to 30 years and beyond, customer demands on quality control become more stringent, and new materials are incorporated into existing products for decreased cost and/or increased functionality. More recently, coatings on the front glass (anti-reflective, anti-soiling, etc.) have been explored in the industry to increase energy yield. However, prolonged increased energy yield requires that the coatings remain intact in outdoor conditions for much of the module lifetime. NREL has worked in developing the standards, and the scientific basis for standards in the areas of transparent materials, backsheet cracking, coating abrasion, and delamination.

4.4.1 Subtask 4.1: UV Weathering

NREL led several studies in conjunction with PVQAT task group 5 to support the development of robust standards related to UV weathering of polymers. Such studies are necessary as standards must provide rigorous and reproducible test results even in the face of cost-cutting additive substitution, a proliferation of suppliers, introduction of new materials, and availability of new test equipment (e.g. high-intensity LED lamps).

A first study was performed to survey the factors most affecting encapsulant adhesion, including the ultraviolet (UV) source (ie, Xe or fluorescent lamp[s]), the optical filters for the lamp, the chamber temperature, and the relative humidity. Natural weathering was also performed at several outdoor locations, including the following: Golden, Colorado; Miami, Florida; Phoenix, Arizona; QiongHai, China; Riyadh, Saudi Arabia; and Turpan, China. Specimens were constructed using a laminated glass/poly (ethylene-co-vinyl acetate)/glass geometry. The compressive shear test (CST) was used to quantify the mechanical strength of attachment. CST equipment is picture in Figure 23. The fractography of select specimens (including cross-sectional optical microscopy) was used to verify the failure mode (delamination or decohesion). Additional analysis of the local solar spectrum as well as the specimen temperature was performed to interpret the results of natural weathering. The goals of this study were to identify the most significant stressors, clarify where strong coupling may occur between stressors, and validate accelerated test results relative to natural weathering.

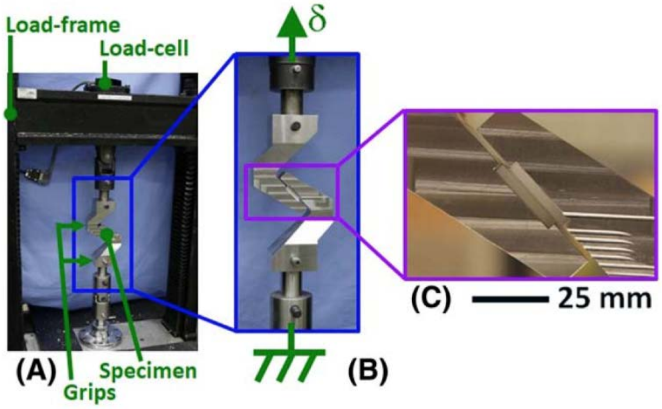


Figure 23: (A) The equipment for the compressive shear test. Specimens are sheared apart when the movable top grip is displace as indicated in (B). Detail of the relative displacement of the grips, glass superstrate, and glass substrate is shown in (C).

Several important conclusions resulted from the PVQAT TG5 delamination study. First, it was found that the effect of water humidity levels was often more significant than the effect of UV radiation. Second, the importance of hygrometric (combined temperature and humidity) degradation was identified from natural weathering. No other factors (including UV intensity, UV dose, maximum temperature, and temperature range) may be readily correlated to the most affected experiments in the hot-humid locations of Miami and QiongHai. Damage from UV photodegradation is confirmed.

A second study was performed in conjunction with PVQAT TG5 to examine degradation in encapsulant transmittance with an artificial weathering study. The study was performed to benchmark polymeric packaging materials relative to IEC 62788-1-4 and IEC 62788-1-7, provide feedback towards improvement of the methods, and give insight regarding optical degradation. Contemporary materials were examined, including: poly(ethylene-co-vinyl acetate) (EVA), thermoplastic polyolefin (TPO), polyolefin elastomer (POE), and polyvinyl butyral (PVB) encapsulants; a poly(ethene-co-tetrafluoroethene)/poly(ethylene terephthalate) Key results from the transmission study include the following:

- The activation energy for UV degradation of the contemporary materials in this study was found to range in the order of 15 kJ·mol^{-1} to 80 kJ·mol^{-1}, with an average of 48 kJ·mol^{-1}.
- The degradation mode of discoloration was observed for some encapsulants in this study, but to a lesser extent relative to the known bad EVA-A formulation. The evolution of crystalline content is significant for some of the PO encapsulants in this study based on measured change in haze, i.e. optical scattering.

- The pass/fail criteria of 5% reduction in transmittance was found to be a meaningful threshold for encapsulants prone to early degradation, provided the coupon size is large enough.
- A UV cut-off criteria (change in wavelength greater than 20 nm) may also help distinguish inappropriate materials.

4.4.2 Subtask 4.2: Backsheet Cracking

In recent years there have been some significant failures of photovoltaic backsheets resulting from inadequacies of design that are not detected in current versions of the qualification standards. In some cases, the backsheet behavior has resulted in catastrophic failure in less than 5 years of deployment. An example of cracking observed in a fielded module is shown in Figure 24.

Figure 24: An example of a polyamide backsheet cracking between cells. This module was fielded for 5 y.

In this subtask, we have developed a test sample construction and accelerated exposure sequence necessary to duplicate the cracking field failure of backsheets using a small and manageable coupon. The sample uses a piece of solder wire to put some controlled topology and stress into the backsheet. Through exposure to different environmental stressors it was found that the application of thermal cycling stresses, after thermal and/or ultraviolet radiation exposure, is of primary importance to duplicate field failures.

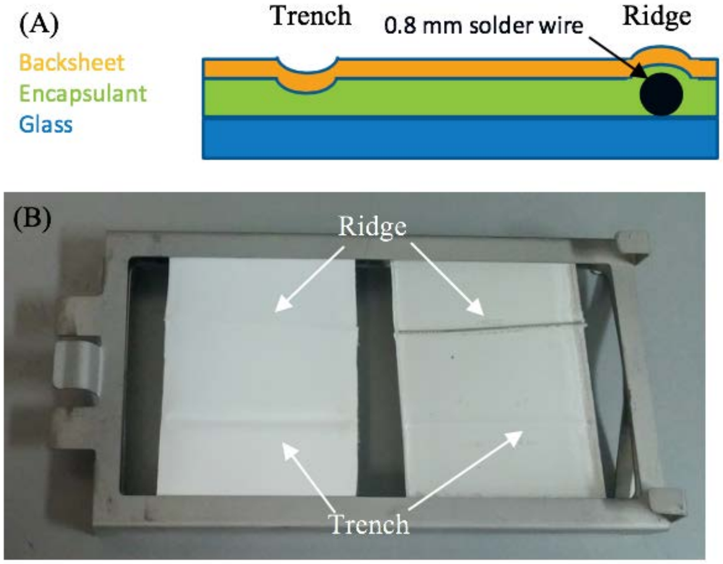


Figure 25: Test coupon for backsheet cracking, shown A) as a side view schematic and B) in a photo.

The novel test coupons were constructed by laminating Solite glass, EVA, and a backsheet. A 0.8 mm thick solder wire, representing a worst-case solder bump was included between the EVA and the glass, and on top of the backsheet. These two wires cause localized mechanical stress in the sample, forming a ridge and a trench, as shown in Figure 25A. Without this localized mechanical stress, the test does not reproduce known field failures. Different types of backsheet were tested in the configuration of Figure 25, including:

- one composed of three layers of polyamide (which has been known to experience catastrophic field failures),
- backsheets composed of polyvinylidiene fluoride (PVDF)/PET/”E” (where “E” is a low-vinyl-acetate EVA based seed layer), which has exhibited minor problems in the field, and
- backsheets composed of PET/PET/”E” (PPE) where the first PET layer is pigmented and the second is transparent, which has not been observed to crack in the field.
- A known good construction of Tedlar/PET/Tedlar.

When the coupons are exposed to UV, heat, humidity, and thermal cycling, the cracking failure mode seen in fielded modules is reproduced when expected, and not seen on the known good construction.

The test has been added to IEC TS 62788-2 “Measurement procedures for materials used in photovoltaic modules: Frontsheets and backsheets”. The backsheet cracking test will also be also referenced by IEC 63209-2 “Extended-stress testing of photovoltaic modules: Component materials and packaging,” which is likely to be published next year. The eventual goal is that module qualification tests will reference IEC 62788-2-1 which will include this test. This will increasing module reliability with minimal testing cost. This work satisfies quarterly milestone 3.2.1 regarding demonstrating a method of measuring backsheet cracking that is independent of sample geometry. Results have been presented and published (e.g. accomplishments #56, 99, 101, 103, and 105).

4.4.3 Subtask 4.3: Coating Abrasion and Soiling

Natural soiling and the subsequent requisite cleaning of photovoltaic (PV) modules result in abrasion damage to the cover glass. The durability of the front glass has important economic consequences, including determining the use of antireflective and/or anti-soiling coatings as well as the method and frequency of operating maintenance (cleaning).

The abrasion of coatings and glass was explored via a field study, where coupons have been deployed in the soiling-prone locations of Dubai (United Arab Emirates), Kuwait City (Kuwait), Mesa (Arizona), Mumbai (India), and Sacramento (California). In these locations, side-by-side coupons are subjected to different types of cleaning, and one set of coupons from each location will be returned to NREL each year, for five years. The characteristics of material integrity, surface energy, optical transmittance, surface roughness, and scratch size were examined to provide feedback regarding the cleaning equipment, cleaning methods, coatings, and abrasion standard development.

The optical transmittance of the returned coupons was reduced by more than would be predicted from the particle coverage (soiling) alone, indicating abrasion damage to the antireflective surface coating. The scratch width in the damage to the module surface is comparable to size of particulates contaminating the module surface. Thus, it is believed that the contamination, rather than the brushes, acts as an abrasive during cleaning operations. An example of data leading to this conclusion is shown in Figure 26. The left image shows an atomic force microscopy (image) of the surface of a coupon fielded for one year in Dubai, and cleaned by the dry brush technique. The right side of Figure 26 shows a line scan extract from the AFM image, along the green line (points 1 to 2) in the image. The average scratch width is 7.3 µm, and the average scratch depth is 100 nm. The NREL-verified size of contaminant particles on the surface of this coupon ranged from 1.5 to 12.1 µm.

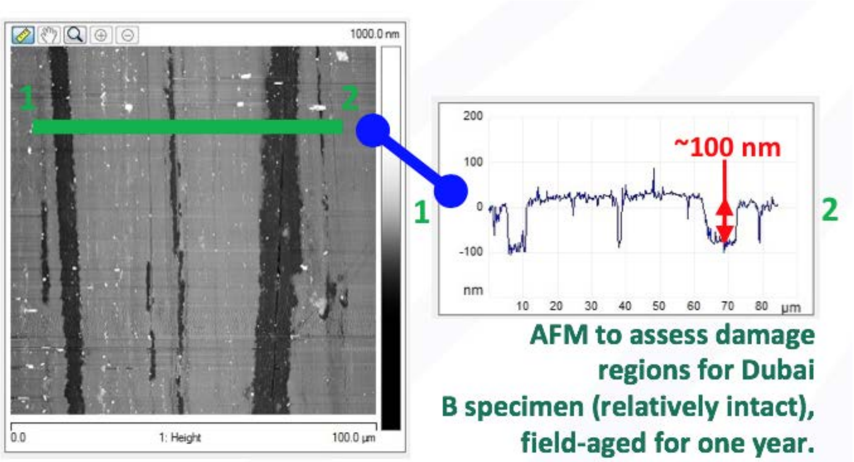


Figure 26: AFM image (left) and line scan (right) showing size of scratches in fielded coupon.

Approximately 300 stakeholders have requested to be included in the development of an abrasion standard tailored to PV, via participation in project team meetings, or the distribution of the project team documents and minutes. Most work in this reporting period has involved artificial linear brush abrasion, with added slurry and dry dust. It was found that this testing creates damage similar to that observed in fielded coupons. (See accomplishment #22.) NREL has led the development of IEC 62788-7-3 ED1, “Measurement procedures for materials used in photovoltaic modules - Part 7-3: Environmental exposures - Accelerated abrasion tests of PV module external surfaces,” which is currently projected to be published in May 2022. NREL also leads activities in PVQAT task group 12, on soiling.

Subcontractor Arizona State University (ASU) is developing techniques for artificial soiling. Such techniques may be suitable for incorporation into a standard that quantifies the tendencies of various types of PV glasses or coatings to soil. ASU modified their artificial soiling apparatus to interface with full-size commercial modules, as shown in Figure 27. ASU measured several module types that include some products that have been observed to soil relatively heavily in the field, and other products where normal soiling has been observed. The soiling test did predict a heavier soiling rate for the known bad modules; however, the predicted difference between the known good and know bad modules was more subtle than that observed in the field. Subsequently, it was discovered that the known bad modules undergo some visual change in appearance related to coating aging. It is hypothesized that the coating aging may increase the tendency of the module to soil. In future work, ASU will aim to reproduce the coating aging via heat and humidity. Then they will repeat the artificial soiling test on the known good and know bad modules, and see if the magnitude of the difference observed in the field is reproduced in the artificial test.

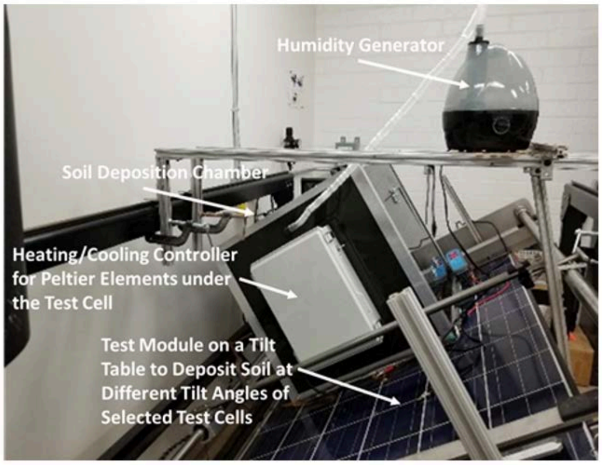


Figure 27: Soil deposition chamber for full-size commercial modules at ASU.

4.4.4 Subtask 4.4: Delamination

Encapsulant delamination in photovoltaic (PV) modules has been identified as the second most prevalent failure mode seen in the field, according to two recent surveys.[24,25] Thus, in this subtask we aim to develop physical models for encapsulant adhesion degradation that can inform accelerated tests and standards.

Previous work had identified that a subcritical debonding model based on the viscoelastic relaxation of EVA describes experimental adhesion measurements well.[26] Therefore, a portion of this task has focused on characterizing viscoelastic relaxation for the predominate PV module encapsulants EVA and polyolefin (POE). Viscoelastic characterization is measured via dynamic mechanical analysis (DMA), which applies a time varying strain to the bulk material and measures its time varying stress response. The measurement data allow production of a master curve that describes the materials storage modulus (stiffness) across decades of strain rate.

According to the theory developed by Williams, Landel, and Ferry[27], shift factors can be derived that allow that then master curve to be shifted to any temperature. Together, the master curve and shift factors can describe the materials instantaneous stiffness at any strain rate and temperature. This procedure has been performed on specially fabricated double lap shear samples produced with the encapsulants of interest, as shown in Figure 28.

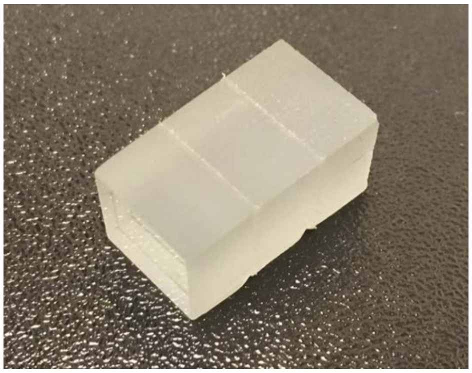


Figure 28: Double lap shear sample consisting of three layers of glass that sandwich two layers of encapsulant.

The Dauskardt Group at Stanford University has continued to refine a predictive model of EVA adhesion degradation, capable of incorporating specific climate data and specific material rate coefficients. The model predicts the progression of the dominant EVA delamination mechanisms[28]: deacetylation, scission, and hydrolytic depolymerization. The rates of these processes are parameterized with four rate coefficients. The critical adhesion energy (G_c) was measured as a function of accelerated stress exposure periodically over 17,600 hours to define the coefficients. The measurements utilize a 12.5˚ width-tapered beam test performed at room temperature with a 1.6 mm titanium beam. Stress to the mini-modules is applied at 85˚C, and either 10% or 23% RH. G_c is observed to decrease with time in stress, but there is not a clear dependency on RH. For the first time, delamination failure at both cell and glass interfaces without UV exposure has been observed, as shown in Figure 29. Evidence of hydrolytic depolymerization and deacetylation in conditions without UV has not been achieved before since it requires very long exposures. Because it allows evaluating rates with UV-dependency removed, it is a substantial step forward in refining coefficients and UV-dependency within the model.

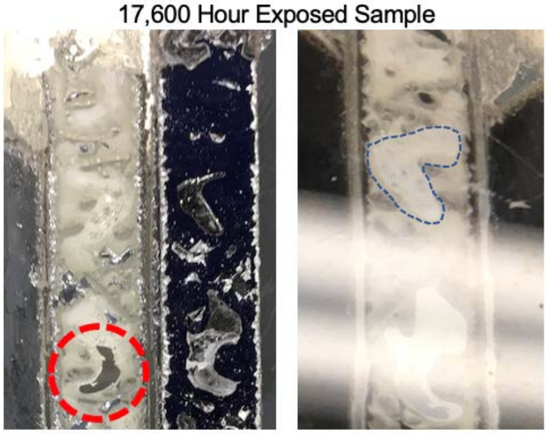


Figure 29: Sample exposed to heat and humidity for 17,600 hours showing delamination at cell interface (left) and glass interface (right).

5 Significant Accomplishments and Conclusions

This program advances PV module reliability and useful life of commercial products through 1) identification of reliability needs, 2) characterization that provides scientific understanding of targeted degradation mechanisms, and 3) translation of those data into practical and predictive test protocols and standards. Our significant achievements are those that provide well-defined landmarks in achieving those three steps.

Standards that make PV more reliability are the ultimate achievement of the program. Some significant achievements that have matured to the point of being incorporated into standards are listed below:

- 17 international standards were published over the course of the program, with 18 more currently in progress.
- Polymers in modules are likely to change in coming years for cost reduction. NREL participated in a number of studies and standards to ensure rigorous, repeatable, and science-based polymer testing. A backsheet cracking test that reproduces recent field failures was developed and incorporated into to IEC TS 62788-2, and is referenced by IEC 63209-2. Large international studies were led by NREL to develop consensus on encapsulant test procedures, stress levels, and performance thresholds related to IEC 62788-1-4, IEC 62788-1-7, and IEC TS 62788-7-2.
- NREL led a team of 71 technical experts from 13 countries to update IEC 61215, a widely-used module design qualification standards. The updated document addresses recent industry advances, including technical contributions from NREL scientists. In particular, NREL had a large technical input to PID testing (e.g. accomplishment #2), use of representative samples (e.g. accomplishment #19), testing and labeling of bifacial modules, and dynamic load testing.
- NREL unified 11 extended stress protocols offered by private test labs into one consensus test (IEC 62903-1), saving manufacturers time and money while provided the most meaningful choice of test conditions, with carefully documented limitations on what conclusions can be drawn. In work on IEC 62903-2 (in progress) NREL and other team members aim to extend long-term testing to coupons, allowing inexpensive pre-qualification of module materials. A table has been inserted into IEC 61215 which allows insertion of required component or materials certifications. The IEC 63902 requirements can be added there once the industry has gained more experience with those methods.
- NREL has taken Light and Elevated Temperature Degradation through the stages of field observation, characterization, and international collaborative testing, to having a standards document underway LeTID (IEC TS 63342). (See accomplishments #4, 15, and 27). A kinetic model can predict how LeTID evolves during accelerated testing and outdoor exposure.
- NREL's older work on PID-s in crystalline Si (IEC 62804-1) has been extended to include PID-d (IEC 62804-1-1), while a predictive thin film PID test (IEC 62804-2) will be published shortly. Experiments to define relevant test conditions for PID-polarization have begun.
- Faster degradation at higher temperatures is commonly observed. NREL has participated in IEC TS 63126 to describe how modules for use in high temperature environments should be tested based on climate statistics and temperature models. (See accomplishment #16.)

- Prior to 2018, there was little consistency among test labs regarding how much a product can change before retesting for module qualification is required. NREL participated in the development of the first "re-test guidelines" (IEC 62915) and is currently updating the document to be more specific.

A number of NREL's significant achievements relate to the steps in the reliability process that precede standardization, i.e. recognizing needs and understanding the degradation. Specifically

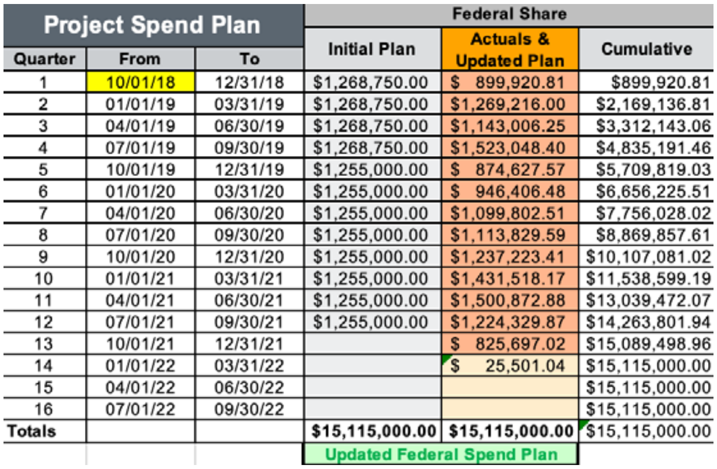
- Case studies of four different sites identified root cause of degradation. These root causes included LeTID, solder bond failure, corrosion of fingers of a different ink composition, and movement of H in the solar cell.
- Measurement of cracked cell fragment movement, and documenting that there can be electrical contact between fragments even when the grid finger is broken.
- Stakeholder engagement via highly-attended annual reliability workshops and filling key roles in international PVQAT activities.
- Solder bond fatigue in low-temperature solders, as used in new multi-wire modules, was found to have, different characteristics than traditional SnSb solders. Notable, the 200 thermal cycles used in module design qualification is a less rigorous test for the low temperature solders.
- An artificial soiling test apparatus for full-size modules was developed and shows some correlation to fielded results.

Several challenges were encountered under this award.

- In general, the pace with which degradation mechanisms can be understood and relevant tests developed is slow compared to the rate at which new products and technologies are currently introduced, particularly if the test under development requires prediction for decades of fielded performance.
- Our current methodology is good for design qualification, but we don't have a formalism to understand manufacturing consistency. When there is a consistency problem, unfailed fielded samples that are available for analysis might be good. Furthermore, modules are big expensive replicates. Sampling even a relatively large number of new modules might not reveal the problem, much less allow test development.
- In specific subject matter, our work on cracks has required us to revise our thinking. A lot of system owners are replacing modules if they see cracks in the luminescence images, so the issue of how power loss will evolve is very important. We were surprised to find that the grid line seems to break long before electrical contact between pieces is lost. Thus, we cannot use a conventional metal fatigue model. In future attempts, we will see if a wear model can describe the behavior.
- PID-p can produce large (~25%) power decreases in accelerated tests. Yet, little is known about the acceleration factors, and there is no standardized test. There are many several variables that need to be understood: climate, bifaciality, package design (e.g. transparent polymer backsheets vs. glass), cell type (e.g. PERC, TOPCON), etc.
- When trying to reproduce fielded soiling in an artificial test, we did not initially consider that aging of the coating on the module might be an important variable. We need to reproduce that aging first, and then try the soiling test.

6 Budget and Schedule

Cumulative spending through project end is $15,115,000, which is equal to the initial plan. Figure 30 shows this information in an excerpt from the RPPR-2 form, including actual expenditures and the initial spend plan, by quarter. The initial period of performance for the program was 12 quarters. A one-quarter no-cost extension was issued to allow the use of unspent fund to complete several publications, presentations, and reports based on the program work. A small amount of expenditures are shown during the 90-day close-out period (quarter 14) following the conclusion of technical work.



Project Spend Plan			Federal Share		
Quarter	From	To	Initial Plan	Actuals & Updated Plan	Cumulative
1	10/01/18	12/31/18	$1,268,750.00	$ 899,920.81	$899,920.81
2	01/01/19	03/31/19	$1,268,750.00	$1,269,216.00	$2,169,136.81
3	04/01/19	06/30/19	$1,268,750.00	$1,143,006.25	$3,312,143.06
4	07/01/19	09/30/19	$1,268,750.00	$1,523,048.40	$4,835,191.46
5	10/01/19	12/31/19	$1,255,000.00	$ 874,627.57	$5,709,819.03
6	01/01/20	03/31/20	$1,255,000.00	$ 946,406.48	$6,656,225.51
7	04/01/20	06/30/20	$1,255,000.00	$1,099,802.51	$7,756,028.02
8	07/01/20	09/30/20	$1,255,000.00	$1,113,829.59	$8,869,857.61
9	10/01/20	12/31/20	$1,255,000.00	$1,237,223.41	$10,107,081.02
10	01/01/21	03/31/21	$1,255,000.00	$1,431,518.17	$11,538,599.19
11	04/01/21	06/30/21	$1,255,000.00	$1,500,872.88	$13,039,472.07
12	07/01/21	09/30/21	$1,255,000.00	$1,224,329.87	$14,263,801.94
13	10/01/21	12/31/21		$ 825,697.02	$15,089,498.96
14	01/01/22	03/31/22		$ 25,501.04	$15,115,000.00
15	04/01/22	06/30/22			$15,115,000.00
16	07/01/22	09/30/22			$15,115,000.00
Totals			**$15,115,000.00**	**$15,115,000.00**	$15,115,000.00
			Updated Federal Spend Plan		

Figure 30: An excerpt from the RPPR-2 form, showing actual expenditures and the initial spend plan.

7 Path Forward

Our results from this program suggest a path for future research to continue improving PV module reliability.

To identify reliability needs, we will continue our very successful module case studies, which have been a cornerstone of NREL's reliability program for years. We will continue our recent emphasis on problems with the largest impact on energy generation, where the root cause is often elusive. We will continue to coordinate with system owner partners to identify underperforming systems, and we will leverage the PV Fleets dataset to identify systems in the tail of high degradation. We will continue to brings a suite of advanced characterization techniques to bear on root cause identification and understanding how degradation will progress in accelerated test or fielded conditions.

In a new effort, we will also prioritize the importance of various degradation mechanisms based on how much energy loss each causes, and in what fraction of products it is expected to occur. NREL will begin this Pareto analysis by quantifying effects on energy yield, cost, and prevalence for some degradation mechanisms studied. NREL's Strategic Energy Analysis Center will help evaluate financial implications of specific degradation profiles. NREL will also incorporate input from the case studies of underperforming systems, priorities identified by DuraMat Industry Advisory Board surveys, and literature data. Depending on availability from other efforts, inputs may also include conclusions from O&M records, fleet power analysis, large-scale aerial data, and EL surveys.

We will continue to study and develop predictive tests for several prominent degradation modes in commercial modules, though some of these mechanism may be different that for the preceding work. Our choices of which degradation mechanisms to address are based on several factors. We choose degradation mechanisms that pose the biggest potential risk in relatively new but promising commercial products (e.g. n-Si), are not adequately quantified by existing tests, are frequently-observed but are not understood in terms of effect on energy yield (e.g. cell cracking), or are not yet quantified in a way that can push energy generation predictions toward 50 years. Some examples of mechanisms, we will study and relate accelerated test and fielded behavior are PID-p, cell cracking, polymer stability via coupon tests, connector mateability, soiling, and coating abrasion.

We will continue to work with the international community on standards, both in the actual document creation, in collaborative PVQAT efforts that precede standard creation, and in stakeholder engagement activities such as the yearly PVRW.

8 Accomplishments: Inventions, Patents, Publications, and Other Results

Products of this program are listed below, alphabetically by first author. Products are divided into sections by type, including peer-reviewed journal articles, book chapters, conference publications, conference presentations, students supported, webinars, and standards.

8.1 Peer-Reviewed Journal Articles

1. Asadpour, R.; Sulas-Kern, D.B.; Johnston, S.; Meydbray, J.; Alam, M.A. "Dark Lock-in Thermography Identifies Solder Bond Failure as the Root Cause of Series Resistance Increase in Fielded Solar Modules" IEEE Journal of Photovoltaics 10, 5, 1409-1416, 2020.
2. N. Bosco and T. J. Silverman, "Solder Bond Fatigue is Insensitive to Module Size," IEEE Journal of Photovoltaics, Accepted March 2021.
3. N. Bosco, M. Springer, "Viscoelastic Material Characterization and Modeling of Photovoltaic Module Packaging Materials for Direct Finite Element Method Input", Submitted to Solar Energy Materials and Solar Cells, March 2020. (Supported by multiple programs.)
4. Michael G. Deceglie, Timothy J Silverman, Steve W. Johnston, Jim Rand, Mason Reed, Robert Flottemesch, Ingrid L. Repins, "Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System," IEEE JPV, 10(4), 2020, pp. 1084-1092.
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11. C.-S. Jiang, H.R. Moutinho, B. To, C. Xiao, C. Perkins, M. Muller, M.M. Al-Jassim, “Strong attraction and adhesion forces of dust particles by system voltages of photovoltaic modules”, IEEE J. Photovoltaics 9, 1121 (2019); DOI: 10.1109/JPHOTOV.2019.2907174
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13. D. Jordan, T. Barnes, N. Haegel, I. Repins, “Build solar-energy systems to last — save billions,” Nature, December 9, 2021.
14. Scott E. Julien, Jae Hyun Kim, Yadong Lyu, David C. Miller, Xiaohong Gu, Kai-Tak Wan, “Cohesive and Adhesive Degradation in PET-based Photovoltaic Backsheets Subjected to Ultraviolet Accelerated Weathering”, Solar Energy, 224, 2021, 637-649. https://doi.org/10.1016/j.solener.2021.04.065.
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37. Chuanxiao Xiao, Steve Johnston, Chun-Sheng Jiang, Vincenzo LaSalvia, Dana B Sulas-Kern, Michael D Kempe, David L Young, Dirk C Jordan, Mowafak M Al-Jassim, Ingrid Repins, Long-Term Degradation of Passivated Emitter and Rear Contact Silicon Solar Cell under Light and Heat, Sol. RRL 2100727. https://doi.org/10.1002/solr.202100727

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5. William B. Hobbs, Steve Johnston, Braden Gilleland, “Ultraviolet Fluorescence Bleaching Rates for New Cell Cracks,” Proceedings of 47th IEEE-PVSC, June 15th-August 21st, 2020 , Virtual meeting.
6. C.-S. Jiang, D.B. Sulas-Kern, H.R. Moutinho, D.C. Jordan, C. Xiao, S. Johnston, and M.M. Al-Jassim, “Local Resistance Measurement for Degradation of c-Si Heterojunction with Intrinsic Thin Layer (HIT) Solar Modules”, Proceedings of 47th IEEE-PVSC, June 15th-August 21st, 2020, Virtual meeting.
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9. Steve Johnston, Dana B. Sulas, George F. Kroeger, “Laser Cutting and Micromachining for Localized and Targeted Solar Cell Characterization,” Proceedings of the IEEE PVSC 46, 2019.

10. S. Johnston *et al*., "LeTID-affected Cells from a Utility-scale Photovoltaic System Characterized by Deep Level Transient Spectroscopy," *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, 2021, pp. 2276-2278, doi: 10.1109/PVSC43889.2021.9518401.

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16. H. Moutinho, B. To, D. Sula-Kern, C.-S. Jiang, M. Al-Jassim and S. Johnston, "Advances in Coring Procedures of Silicon Photovoltaic Modules." Proceedings of the the 47th IEEE Photov. Spec. Conf. (Virtual Meeting, Jun 15 – Aug 21, 2020).

17. S.C. Pop, J. Kapur, P. Hacke, M. Kempe, R.N. Schulze, X. Wang, "Double Layer Encapsulation Film for PV Modules Operating at High Voltage," *Proceedings of the 36th European Photovoltaic Solar Energy Conference and Exhibition*, pp 941 – 945, 2019, DOI: 10.4229/EUPVSEC20192019-4CO.4.4.

18. Cassidy Sainsbury, Ronald A. Sinton, Dirk Jordan, "On the Ambiguity of Using Isc for Analyzing Suns-Voc Data on Modules," Proceedings of 47th IEEE-PVSC, June 15th-August 21st, 2020, Virtual meeting.

19. Simon M.F. Zhang, Dana B. Sulas-Kern, Robert Lee Chin, Michael Pollard, Arman Mahboubi Soufiani, Dirk C. Jordan, Helio R. Moutinho, Perez-Wurfl, Ziv Hameiri"Investigation of SHJ Module Degradation: A Post-Mortem Approach," Proceedings of 47th IEEE-PVSC, June 15th-August 21st, 2020, Virtual meeting.

20. TJ Silverman, M Bliss, A Abbas, T Betts, M Walls, I Repins. "Movement of cracked silicon solar cells during module temperature changes," Proceedings of the IEEE PVSC 46, 2019.

21. L. J. Simpson, R. Huntamer, C. Weston, P. Ndione, B. McDanold, S. Toth, C. S. Jiang, M. Muller, H. Moutinho, D. C. Miller, L. Micheli, G. Perrin, and A. Martinez-Morales, "Increased PV Soiling from High Module Voltages," Proceedings of the IEEE PVSC, 47, 2020.

22. Laura Spinella, Nick Bosco, “Application of Electronics Packaging Fundamentals to Photovoltaic Interconnects and Packaging” *InterPACK 2019*, V001T07A003, 2019, doi:https://doi.org/10.1115/IPACK2019-6520 .
23. Laura Spinella, Kent Terwilliger, Patrick Walker, Greg Perrin, Chun-Sheng Jiang, Nick Bosco, “Reliability Implications of Multiwire Modules Under Dynamic Mechanical Loading,” Proceedings of the IEEE PVSC, 48, 2021.
24. Sulas-Kern, D.B.; Johnston, S.; Owen-Bellini, M.; Terwilliger, K.; Meydray, J.; Spinella, L.; Sinha, A.; Schelhas, L.; Jordan, D.C. “UV-Fluorescence Imaging of Silicon PV Modules After Outdoor Aging and Accelerated Stress Testing,”
25. T. Tanahashi, M. Woodhouse, K. Sakurai, P. Hacke, “Economic Analysis, Qualification and Testing, Reliability, Durability, c-Si PV module,” *Proceedings of the 36th European Photovoltaic Solar Energy Conference and Exhibition*, pp 1091 – 10943, 2019, DOI 10.4229/EUPVSEC20192019-4AV.1.46

8.4 Conference Presentations

1. K. Amou, Z. Hammond, V. Javalkar, G. TamizhMani "Inexpensive Indoor Spot-cell and Spot-light Methods for Angle of Incidence Measurements of PV Modules," IEEE PVSC 47, virtual, June 15-Aug 21, 2020.
2. Nick Bosco, Martin Springer, Jiqi Liu, Sameera Nalin Venkat, Roger H French, Timothy J Silverman, “Representative modules for accelerated thermal cycling and static load testing,” PV Reliability Workshop, poster presentation, 2021
3. Michael G Deceglie, Timothy J Silverman, Steve W Johnston, James A Rand, Mason J Reed, Robert Flottemesch, Ingrid L Repins, “Light and elevated temperature-induced degradation (LeTID) in a utility-scale photovoltaic system,”, PV Reliability Workshop, poster presentation, 2021.
4. Michael G. Deceglie, Timothy J Silverman, Steve Johnston, Ingrid Repins, Jim Rand, Mason Reed, “Degradation Case Studies: From the Field to the Lab,” Oral Presentation, PVRW 2020. PV
5. Ashley Gaulding, Michael G Deceglie, Timothy J Silverman, Steve W Johnston, Dana Sulas-Kern, Helio Moutinho, Ingrid L Repins, “Differences in printed contacts leads to susceptibility of silicon cells to series resistance degradation,” PV Reliability Workshop, poster presentation, 2021.
6. E. Ashley Gaulding, John S. Mangum, Steve W. Johnston, Chun-Shen Jiang , Helio Moutinho , Mason J. Reed , James A. Rand, Robert Flottemesch, Ingrid L. Repins, Timothy J Silverman, Michael G. Deceglie, "Differences in c-Si solar cell metallization and susceptibility to series resistance degradation”, IEEE PVSC, poster presentation, 2021.
7. P. Hacke, K. Terwilliger, A. Walker, V. Guthrie, “Analysis of Hail Damage in PV Modules with Respect to Mounting Angle and Direction,” Poster Presentation, PVRW 2020.

8. P. Hacke, "Collaborative updates: PVQAT TG 3 (Humidity, temperature and voltage [modules]), and TG 11 (PV systems - power electronics)" Invited oral presentation at the 2019 PVRW, Lakewood, Colorado, February 26, 2019
9. P. Hacke, H. Liu, V. Krishna, JL Leung, T. Reindl, W. Luo, Factors and Risks for PID in Floating PV System, Asia Clean Energy Summit, Singapore, October 31 - November 2, 2018.
10. Z. Hammond, T. Curtis, L. Simpson, G. TamizhMani, "Design advancement of an indoor soil deposition chamber: a road to standardization" PV Reliability Workshop, Feb. 2019.
11. S. Harvey, S. Johnston, C.P. Muzzillo, L. Mansfield, P. Hacke, M. Al-Jassim, "Utilizing TOF-SIMS to investigate module degradation mechanisms" poster presentation at the 2019 PVRW, Lakewood, Colorado, February 26, 2019.
12. William B.Hobbs, Steve Johnston, Braden Gilleland, “Ultraviolet Fluorescence Bleaching Rates for New Cell Cracks,” Presented at the 47th IEEE Photov. Spec. Conf. (Virtual Meeting, Jun 15 – Aug 21, 2020), Oral presentation.
13. Ryo Huntamer, Electric Field Induced Soiling, 2018 International PV Soiling Workshop, Golden, CO, October 31-November 2.
14. C.-S. Jiang, D.B. Sulas-Kern, H.R. Moutinho, D.C. Jordan, C. Xiao, S. Johnston, and M.M. Al-Jassim, “Local Resistance Measurement for Degradation of c-Si Heterojunction with Intrinsic Thin Layer (HIT) Solar Modules”, 47th IEEE-PVSC, June 15th-August 21st, 2020, Virtual meeting, Oral presentation.
15. Steve Johnston, Dana B. Sulas-Kern, and Dirk Jordan, “Module Imaging for Hail Damage Assessment and Two-Year Follow Up,” poster presentation, Photovoltaic Reliability Workshop ・ Lakewood, CO ・ Feb. 25-27, 2020
16. Steve Johnston, Dana B. Sulas-Kern, “Outdoor Module Electroluminescence Imaging Without Disconnecting Cables,” poster presentation, Photovoltaic Reliability Workshop ・ Lakewood, CO ・ Feb. 25-27, 2020
17. S. Johnston, D.B. Sulas, D. Jordan, “Silicon Module Imaging for Detection of Cracked Cells and Assessment of Hail Damage,” poster presentation, 29th NREL Silicon Workshop, Winter Park, CO, Aug. 4-7, 2019.
18. Steve Johnston, Chuanxiao Xiao, Michael G. Deceglie, Ashley Gaulding, Chun-Sheng Jiang, Harvey Guthrey, Dana B. Kern, George F. Kroeger, Mowafak Al-Jassim, Ingrid L. Repins, "Letid-affected Cells From A Utility-scale Photovoltaic System Characterized By Deep Level Transient Spectroscopy”, IEEE PVSC, poster presentation, 2021.
19. Steve Johnston, Chuanxiao Xiao, Chun-Sheng Jiang, E Ashley Gaulding, Michael G Deceglie, Harvey Guthrey, Dana Kern, Mowafak Al-Jassim, Ingrid L Repins, “LeTID cells from a utility-scale photovoltaic system characterized by deep level transient spectroscopy”, PV Reliability Workshop, poster presentation, 2021.
20. Dirk Jordan, Mike Deceglie, Kevin Anderson, Kirsten Perry, Matt Muller, Robert White, Chris Deline, Mike Kempe, Ingrid Repins, Long term performances of PV plants, SUPSI PV Days, 11/29/2021

21. Dirk C. Jordan, Chris Deline, Michael Deceglie, Ingrid Repins, Joshua Stein , "Current Topics in Si PV Degradation," Oral presentation, 29th NREL Silicon Workshop, Winter Park, CO, Aug. 4-7, 2019.
22. D. Jordan, "Degradation rate case studies," Invited oral presentation at the 2019 PVRW, Lakewood, Colorado, February 26, 2019
23. D. Jordan, Solar PV Mythbusting - How reliable are Photovoltaics really?, Colorado Renewable Energy Society, Golden, Colorado, Jan. 2019.
24. Dirk Jordan, D. Kern, S. Johnston, H. Moutinho, CS. Jiang, M. Young, A. Norman, C. Deline, R. Bhoopathy, Z. Hameiri, A. Sinha, L. Schelhas, D. Colvin, K. Davis, Silicon Heterojunction Field Performance, invited plenary oral presentation, 3rd International Workshop on Silicon Heterojunction Solar Cells, 2020.
25. D.C. Jordan, D.B. Sulas-Kern, S. Johnston, H.R. Moutinho, C. Xiao, C.S. Jiang, M. Young, A.G. Norman, C. Deline, I. Repins, R. Bhoopathy, O. Kunz, Z. Hameiri, C. Sainsbury, High-efficiency Module degradation - from Atoms to Systems, oral presentation, EU PVSEC, 2020.
26. Dirk Jordan, Mike Kempe, Ingrid Repins, John Bleem, Jeff Menard, Paul Davis, "Life after 30 years—a PV system in Colorado," PV Reliability Workshop, poster presentation, 2021.
27. Joseph Karas, Ingrid Repins, Max B Koentopp, Friederike Kersten, Jean-Nicolas Jaubert, Daqi Zhang, Fangdan Jiang, Christos Monokroussos, Lukas Jakisch, Mauro Pravettoni, Stefan Wendlandt, Mauro Caccivio, Giovanni Bellenda, AK Tripathi, et al., "Summary of findings from the International Round Robin Study on Light and Elevated Temperature Induced Degradation (LeTID)" PV Reliability Workshop, poster presentation, 2021.
28. Todd Karin, David Miller, Dirk Jordan, Ashley Maes, Bruce King, Anubhav Jain, Anti-reflection coatings for photovoltaic module glass: how long do they last in the field?, Duramat workshop, virtual, September 21-23, 2020.
29. G. Kelly, "IECRE site inspection demonstration" poster presentation at the 2019 PVRW, Lakewood, Colorado, February 26, 2019.
30. M. Kempe, "Accelerated Stress Testing of Flexible Polymeric Frontsheet Films," Invited Oral Presentation, Sayuri PV Reliability Workshop, Tokyo, Japan, November 11-12, 2019.
31. Mike Kempe, "Solder Bump Coupon Testing of Backsheets for Simplified Comprehensive Evaluation," Invited oral presentation, NIST/UL Workshop on Photovoltaic Materials Durability, Gaithersburg, MD, December 12 and 13, 2019.
32. Michael Kempe, Derek Holsapple, and David Miller "Using Meteorological Data to Evaluate Worldwide PV degradation Rates", Poster Presentation, PVRW 2020.
33. M. Kempe, "Evaluating the durability of transparent backsheets for bifacial modules" Invited oral presentation at the 2019 PVRW, Lakewood, Colorado, February 26, 2019
34. Michael Kempe, "Understanding the Variability in Extrapolation from Lab to Field Conditions," NIST/UL Duability Workshop 12/7/20

35. M. Kempe, "Degradation of Polymeric components in PV Modules" PV Module Forum 2019, Cologne, Germany, February 2019, Invited oral presentation.
36. S. Kurtz, "Update on IEC 63209: Why a Scientific Basis is Both Essential and Impossible," poster presentation at the 2019 PVRW, Lakewood Colorado, February, 2019.
37. Michael Kempe, Nancy Phillips, Josh Morse, Xan McPherson, Derek Holsapple, “Sequential Multi-Factor Stress Testing for Backsheet Durability Evaluation”. PV Reliability Workshop, poster presentation, 2021.
38. H. Liu, W. Luo, A. Kumar, T. Reindl, P. Hacke, “Evaluation of Risk for Potential-Induced Degradation in Floating PV Systems,” 5BO.7.4, Oral presentation, 36th EU PVSEC, Marseille, France, 09 - 13 September 2019.
39. A.N. McPherson, J.F. Karas, D.L. Young, I.L. Repins, “Excess Carrier Concentration in Silicon Devices and Wafers: How Bulk Properties are Expected to Accelerate Light and Elevated Temperature Degradation,” Materials Research Society Meeting, 12/8/21
40. David Miller “Artificial Linear Brush Abrasion of Coatings for Photovoltaic Module First Surfaces,” oral presentation, 2019 International PV Soiling Workshop, Marrakech, Morroco; October 28-30, 2019.
41. David Miller, “Round-robin Verification of Specimen Temperature during Accelerated Testing for the PVQAT TG5 Studies,” Invited Oral Presentation, NIST/UL Workshop on Photovoltaic Materials Durability, Gaithersburg, MD, December 12 and 13, 2019.
42. David Miller, Material-Level Test Standards: Encapsulation & Abrasion, IEEE WG2 Meeting, Busan Korea, October 15, 2018.
43. David Miller, Soiling Related Abrasion and the Development of a PV Abrasion Standard, International PV Soiling Workshop, Golden, CO, October 31-November 2.
44. David Miller, "Updates on PVQAT TG 5 (UV weathering) and TG 12 (soiling)" Invited oral presentation at the 2019 PVRW, Lakewood, Colorado, February 26, 2019
45. H. Moutinho, B. To, D. Sula-Kern, C.-S. Jiang, M. Al-Jassim and S. Johnston, “Advances in Coring Procedures of Silicon Photovoltaic Modules.” Presented at the 47th IEEE Photov. Spec. Conf. (Virtual Meeting, Jun 15 – Aug 21, 2020), Oral presentation.
46. Craig Perkins, Surface Chemistry of PV Module Glass, International PV Soiling Workshop, Golden, CO, October 31-November 2 .
47. S.C. Pop, J. Kapur, P. Hacke, M. Kempe, R.N. Schulze, X. Wang, “Double Layer Encapsulation Film for PV Modules Operating at High Voltage,” 4C0.4.4, Oral presentation, 36th EU PVSEC, Marseille, France, 09 - 13 September, 2019.
48. Ingrid Repins, Kent Terwilliger, Chris Deline, “Accelerated Testing for Light and Elevated Temperature Degradation (LeTID),” poster presentation, PVRW, Feb. 2020.
49. I.L. Repins, D. Jordan, M. Woodhouse, M. Theristis, J.S. Stein, H. Seigneur, D. Colvin, J.F. Karas, A.N. McPherson, C. Deline, “Understanding Light and Elevated Temperature Induced Degradation in Fielded Array,” Materials Research Society Meeting, 12/8/21

50. Ingrid Repins, “Component Qualification and Beyond: How Standards Help Us Improve PV System Reliability,” SETO Colloquium Series, October 19, 2021
51. I.L. Repins, 61215 New Edition Committee Draft, IEC Working group 2, Web presentation to Busan, Korea, October 15, 2018
52. I.L. Repins, "Qualification of PV Modules - Status of the IEC 61215 New Edition," PV Module Forum 2019, Cologne, Germany, February 2019, Invited oral presentation.
53. Ingrid Repins, Steve Johnston, "Component Qualification and Beyond: How Standards Help Us Improve PV System Reliability," UL/ ANSI/USTDA Workshop on Clean Energy: Advancing Growth of PV Development in India, Invited oral presentation, September 29, 2020.
54. I.L Repins, “An Update on the New Edition of IEC 61215 for Module Design Qualification”, PV Reliability Workshop, poster presentation, 2021.
55. I.L. Repins, D. Jordan, M. Woodhouse, J.F. Karas, A.N. McPherson, C. Deline , M. Theristis, J.S. Stein, H. Seigneur, D. Colvin, “Understanding Light and Elevated Temperature Induced Degradation (LeTID) in Fielded Arrays,” MRS Fall Meeting, 2021, Session EN04.10, December 7, 2021.
56. Cassidy Sainsbury, Ronald A. Sinton, Dirk Jordan, “On the Ambiguity of Using Isc for Analyzing Suns-Voc Data on Modules,” Presented at the 47th IEEE Photov. Spec. Conf. (Virtual Meeting, Jun 15 – Aug 21, 2020), Oral presentation.
57. TJ Silverman, "Reliability, physics of failure, and thermal performance in PV modules," Invited seminar at Bangor University, Bangor, Wales, March 2019.
58. Simon M.F. Zhang, Dana B. Sulas-Kern, Robert Lee Chin, Michael Pollard, Arman Mahboubi Soufiani, Dirk C. Jordan, Helio R. Moutinho, Perez-Wurfl, Ziv Hameiri“Investigation of SHJ Module Degradation: A Post-Mortem Approach,” Presented at the 47th IEEE Photov. Spec. Conf. (Virtual Meeting, Jun 15 – Aug 21, 2020), Oral presentation.
59. L. J. Simpson, J. M. Newkirk, C. Lanaghan, A. Einhorn, R. Huntamer, A. Bergeson-Keller, L. T. Schelhas, C. Engtrakul, D. Holsapple, J. Morse, B. To, P. F. Ndione, H. R. Moutinho, A. Alnuaimi, J. J. John, B. To, “IEC 62788-7-3 Standard: PV abrasion development “IEC 62788-7-3 Standard: PV Abrasion; Development Update” Poster presentation, PVRW 2020.
60. L. Simpson, “Cleaning Best Practice,” International PV Soiling Workshop, Golden, CO, October 31-November 2.
61. L. Simpson et. al., "Development of a Rotating Brush Abrasion Method," PV Reliability Workshop, Feb. 2019.
62. Lin Simpson, “Artificial Rotating Brush Abrasion Test of Coating for Photovoltaic Modules,” oral presentation, 2019 International PV Soiling Workshop, Marrakech, Morroco, October 28-30, 2019.
63. L. Spinella, “Characterization of low temperature solder reliability for PV applications,” Invited Oral Presentation, Sayuri PV Reliability Workshop, Tokyo, Japan, November 11-12, 2019.

64. L. Spinella, N. Bosco, “Application of Electronics Packaging Fundamentals to Photovoltaic Interconnects and Packaging,” oral presentation, ASME International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems (2019 InterPACK), Anaheim, CA, October 7-9, 2019.
65. Laura Spinella, Kent Terwilliger, Patrick Walker, Greg Perrin, Chun-Sheng Jiang, Nick Bosco, “Reliability Implications of Multiwire Modules Under Dynamic Mechanical Loading,” IEEE PVSC, poster presentation, 2021.
66. L. Spinella, N. Bosco, “Reliability of low temperature solder for multiwire interconnects” PV Reliability Workshop, oral presentation, 2021
67. D.B. Sulas-Kern, S. Johnston, J. Meydbray “Fill Factor Loss in Fielded Modules Due to Metallization Failures, Characterized by Luminescence and Thermal Imaging” poster presentation, 29th NREL Silicon Workshop, Winter Park, CO, Aug. 4-7, 2019.
68. Dana Sulas-Kern, “Degradation of fielded modules characterized by luminescence and thermal imaging,” Oral Presentation, PVRW 2020.
69. Sulas-Kern, D.B.; Johnston, S.; Owen-Bellini, M.; Terwilliger, K.; Meydray, J.; Spinella, L.; Sinha, A.; Schelhas, L.; Jordan, D.C. “UV-Fluorescence Imaging of Silicon PV Modules After Outdoor Aging and Accelerated Stress Testing,” Presented at the 47th IEEE Photov. Spec. Conf. (Virtual Meeting, Jun 15 – Aug 21, 2020), Poster presentation.
70. Sulas-Kern, D.B.; Johnston, S.; Jordan, D.C.; Moutinho, H.; Young, M.; Meydbray, J.; Jiang, C.S.; Al-Jassim, M.; Norman, A.; Alam, M.A.; Asadpour, R.; Owen-Bellini, M.; Terwilliger, K.; Sinha, A.; Schelhas, L.; Bhoopathy, R.; Zhang, S.; Hamieri, Z. "From Modules to Atoms-Characterization of Silicon Photovoltaic Module Reliability Guided by Luminescence and Thermal Imaging" invited oral presentation, Materials Research Society (MRS) Virtual Fall Meeting, December 3 2020.
71. J. Wohlgemuth, "PV standards activities of the IEC," poster presentation at the 2019 PVRW, Lakewood, Colorado, February 26, 2019.
72. J. Wohlgemuth, “PV Reliability,” invited tutorial at 46th IEEE PVSC, Chicago, June 2019.
73. John Wohlgemuth, Ingrid Repins, “Revision of the PV Module Qualification Standard (IEC 61215),” Invited oral presentation, NIST/UL Workshop on Photovoltaic Materials Durability, Gaithersburg, Maryland, December 12-13, 2019.
74. C. Xiao, “Kelvin Probe Force Microscopy Study of Silicon Solar Cell Degradation”, Oral presentation, 29th NREL Silicon Workshop, Winter Park, CO, Aug. 4-7, 2019.
75. C. Xiao, Chun-Sheng Jiang, Steve Johnston, Mowafak Al-Jassim, In Situ Stressing Capability of Electrical AFM for Study of Silicon Solar Cell Degradation, Materials Research Society Fall Meeting, Boston, Nov 25-30, 2018.
76. C. Xiao, C.S-Jiang, S. P. Harvey, D. Sulas, X. Chen, J. Liu, J. Pan, H. Moutinho, A. Norman, P. Hacke, S. Johnston, and M. Al-Jassim, "Large-Area Material and Junction Damage in c-Si Solar Cells by Potential-Induced Degradation," poster presentation for 2019 PV reliability workshop, Lakewood, Colorado, February 26, 2019.

77. Chuanxiao Xiao, Chun-Sheng Jiang, Ashley Gaulding, Michael G Deceglie, Dana Sulas-Kern, Mowafak Al-Jassim, Steve Johnston, Ingrid L Repins, “Junction characterization of LeTID cells from utility-scale photovoltaic system by Kelvin probe force microscopy”, PV Reliability Workshop, poster presentation, 2021.

8.5 Students Supported

1. Rachel Arnold, Undergraduate intern, University of Colorado
2. Joanna Bomber, Undergraduate Intern, Colorado School of Mines
3. Matthew Brown, Undergraduate Intern, University of Colorado
4. Daniel Celvi, Undergraduate intern, Colorado School of Mines
5. Hazen Goodyear, Undergraduate Intern,Colorado School of Mines
6. Hamsini Gopalakrishna, PhD student, Arizona State University, thesis advisory team
7. Alex Hattori, Undergraduate Intern, Massachusetts Institute of Technology
8. Derek Holsapple, Undergraduate intern, Metropolitan State University
9. Ryo Huntamer, Undergraduate Intern, University of California, Merced
10. Clare Lanaghan, SULI undergraduate intern, Iowa State University
11. Trevor Lockman, Graduate Intern, Colorado School of Mines
12. Jessica Mello-Kalbermatt, Undergraduate Intern, University of Colorado, Boulder
13. Alexandria McPherson, Undergraduate intern, Colorado School of Mines
14. Jimmy Newkirk, undergraduate intern, University of Colorado, Boulder
15. Yasas Patikirige, PhD student, Colorado School of Mines
16. Aidan Ravnik, Undergraduate intern, Colorado School of Mines
17. Sai Tatapudi, PhD student, Arizona State University (subcontract)
18. Sarah Toth, PhD student, University of Colorado, Boulder
19. Patrick Thornton, PhD student, Stanford University, (subcontract)
20. Michael Thuis, Undergraduate Intern, Colorado School of Mines

8.6 Webinars and Web Postings (Chronological Order)

1. Hosted PVQAT TG12: “Techno-Economic Assessment of Soiling Losses and Mitigation Strategies” (2020/5/19).
2. S. Kurtz, “New Standards for Improving PV Reliability and Investability and Why a Scientific Basis is both Essential and Impossible,” part of the NSF I/UCRC Center on Next Generation Photovoltaics series, (1/15/19).
3. D. Jordan, Solar PV Mythbusting – How reliable are Photovoltaics really?, Colorado Renewable Energy Society, Golden, Colorado, (1/19), https://www.youtube.com/watch?v=Z8k7Y8EGLa4 .

4. "Particle Size Distributions for PV Soiling Assessment," (7/16/19) https://pvqataskforceqarating.pbworks.com/w/page/109737652/Soiling%20and%20Dust%20Webinar
5. "Modeling Atmospheric Dry Deposition," (11/12/19), https://solideas.com/projects/pvquality/webinars/2019-11-12-PVQAT-Webinar-details.pdf
6. Hosted PVQAT TG12 webinar: "Effect of DC:AC Ratio on Soiling Loss and Degradation" (2020/10/15).
7. Hosted PVQAT TG12: "PV Cleaning" (2020/7/21).
8. Hosted PVQAT TG5: "Recent Results of the PVQAT TG5 Study 2" (2020/9/15).
9. Ingrid Repins, Cherif Kedir, Tristan Erion-Lorico, Itai Suez, "Data for: Stabilization of Light-Induced Effects in Si Modules for IEC 61215 Design Qualification," Public data repository entry, 26-08-2020, https://data.mendeley.com/datasets/b2k4jcd656/1
10. M. Woodhouse, I. Repins, D. Miller, P. Hacke, "LID and LeTID Impacts to PV Module Performance and System Economics" (12/14/20) https://www.duramat.org/webinars.html (Joint presentation with reliability core and Duramat.)
11. Links to video proceedings of each session of the Photovoltaic Reliability Workshop are now found at https://www.nrel.gov/docs/fy21osti/80055.pdf
12. Hosted PVQAT TG12 webinar: "PV Soiling: Accumulation and the Technoeconomics of Cleaning" (07/13/2021).
13. Hosted PVQAT TG12 webinar: "Soiling Analysis — quantification using production data" (05/18/2021).
14. Hosted PVQAT TG12 webinar: "Soiling Sensors: Recent Field Experience" (02/09/2021).
15. Hosted PVQAT TG12 webinar: "Field Soiling –and- Artificial Abrasion of Coatings" (2021/11/09).

8.7 Major Awards, Honors, and Press or Popular Media Mentions (Chronological Order)

1. Dirk Jordan (for "Photovoltaic Failure and Degradation Modes"), Most downloaded paper (top 20 in number of downloads in last two years), Progress in Photovoltaics, 10/26/18.
2. Xiao, Jiang, et al, 2019; paper chosen for *Solar RRL* front cover, April 2019.
3. Best poster award at IEEE Photovoltaics Specialists Conference; for "Effects of Reactive Power on Photovoltaic Inverter Reliability and Lifetime," Ramanathan Thiagarajan, Adarsh Nagarajan, Peter Hacke, Ingrid Repins, June 2019.
4. Tim Silverman, "Presidential Early Career Award for Scientists and Engineers," (PECASE), the highest honor bestowed by the U.S. government on outstanding scientists and engineers beginning their independent careers, July 2019.

5. Dana Sulas, Steve Johnston, Dirk Jordan, et al, paper chosen for Solar RRL front cover, August 2019.
6. Dana Sulas, Director's Award, awarded by NREL to recognize one-time exceptional achievements, September 2019.
7. Paper by Deceglie et al. ("Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System", IEEE JPV 2020) is quoted and discussed in PVEL's 2020 Module Reliability Scorecard.
8. Best poster award, IEEE PVSC, 2021: Steve Johnston, Chuanxiao Xiao, Michael G. Deceglie, Ashley Gaulding, Chun-Sheng Jiang, Harvey Guthrey, Dana B. Kern, George F. Kroeger, Mowafak Al-Jassim, Ingrid L. Repins, "Letid-affected Cells From A Utility-scale Photovoltaic System Characterized By Deep Level Transient Spectroscopy".
9. MG Deceglie et al. Light and elevated temperature-induced degradation (LeTID) in a utility-scale photovoltaic system, 3rd place PVRW 2021
10. A Gaulding et al. Differences in printed contacts leads to susceptibility of silicon cells to series resistance degradation, 2nd place poster award at PVRW 2021
11. Solar Energy Journal Best Paper Award (2021), Awarded by the International Solar Energy Society for the paper I. Repins et al. "Stabilization of Light-Induced Effects in Si Modules for IEC 61215 Design Qualification", October 26, 2021
12. 1906 Award, Awarded by the International Electrotechnical Commission to Ingrid Repins, Dec 8, 2021

8.8 Workshops Held (Chronological Order)

1. *2018 International PV Soiling Workshop*, October 31 - November 2, 2018; Golden, CO
2. *2019 Photovoltaics Reliability Workshop*, February 26-28; Lakewood, CO
3. 2019 International PV Soiling Workshop; October 28-30, 2019; Ben Guerir, Morocco; Co-hosted by IRESEN.
4. 2020 NREL Photovoltaics Reliability Workshop, Lakewood, Colorado, Feb 25-27, 2020.
5. NREL Photovoltaic Reliability Workshop; February 22-26, 2021 (on-line).

8.9 Standards (By Standard Number)

1. IEC TS 60904-13 – Photovoltaic devices – Part 13: Electroluminescence of photovoltaic modules, Peter Hacke - Project Lead, Standard published, December 2018.
2. IEC 61215 series, Terrestrial photovoltaic (PV) modules – Design qualification and type approval, new edition. Published February, 2020. Ingrid Repins of NREL is project leader.
3. IEC 61215-1-2/AMD1 ED2 Amendment 1 "Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-2: Special requirements for testing of thin-film Cadmium Telluride (CdTe) based photovoltaic (PV) modules," Committee draft for vote circulated by the IEC, July, 2021. NREL participating on the Project Team.

4. IEC 61215-1-3/AMD1 ED2 Amendment 1 “Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-3: Special requirements for testing of thin-film amorphous silicon based photovoltaic (PV) module,” Committee draft for vote circulated by the IEC, July, 2021. NREL participating on the Project Team.
5. IEC 61215-1-4/AMD1 ED2 Amendment 1 “Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-4: Special requirements for testing of thin-film Cu(In,Ga)(S,Se)2 based photovoltaic (PV) modules,” Committee draft for vote circulated by the IEC, July, 2021. NREL participating on the Project Team.
6. IEC 61730-1/AMD1 ED2 Amendment 1 - Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction. CDV passed IEC vote, March, 2021. NREL participating on Project Team.
7. 61730-2 Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing. CDV passed IEC vote, March, 2021. NREL participating on Project Team.
8. IEC 62093 ED2 - Balance-of-system components for photovoltaic systems - Design qualification natural environments. Approved by the IEC for FDIS, June 2021. NREL participating on Project Team.
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