Advanced Diagnosis and Accelerated Testing of Balance of System Components for Utility Scale PV Installations

October 1, 2022—September 30, 2024

David Miller

National Renewable Energy Laboratory

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Contract No. DE-AC36-08GO28308

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Suggested Citation

Miller, David. 2025. *Advanced Diagnosis and Accelerated Testing of Balance of System Components for Utility Scale PV Installations: October 1, 2022—September 30, 2024.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5K00-91818. https://www.nrel.gov/docs/fy25osti/91818.pdf.

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Project Title:	Advanced Diagnosis and Accelerated Testing of Balance of System Components for Utility Scale PV Installations
Project Period:	10/1/21 – 9/30/24
Project Budget:	$1,500,000
Submission Date:	9/30/24
Recipient: **Address:**	National Renewable Energy Laboratory 15013 Denver West Parkway Golden, CO 80401-3305
Award Number:	DE-EE00038524
Project Team:	NREL

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Acknowledgment: “This material is based upon work supported by the Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), under Award Number DE-EE00038524.”

Executive Summary:

A study of the durability of PV Balance of System components was performed. Specifically, wire cable jackets and cable connectors were examined within the direct current (DC) PV Power Transmission Chain (PTC). Degraded and failed samples have been obtained from utility PV installations to provide feedback on the degradation modes and the related damage-enabling considerations in today's PV systems. An industry interface group (including system owners, system inspectors, component manufacturers, and test labs) was used to help identify and obtain field-failed samples, for feedback (including samples and experimental design), and to facilitate the subsequent dissemination of the results of this study. Samples were empirically studied using accelerated stress testing with steady-state conditions (cable jackets) in addition to combined-accelerated stress testing (cable jackets, connectors and uncapped connectors). Steady-state accelerated testing has been performed using at least one applied stressor (e.g. UV light) to aid understanding of jacket durability relative to its application. Component- and material-focused failure analysis was conducted to develop an understanding and advise the PV industry. In-depth characterization will be applied selectively to field- and artificially aged-samples, to gain scientific understanding of the structural, chemical, electrical, mechanical, and thermal properties enabling degradation.

Community interaction (the Industry Interface Group, "IIG", consisting of the International PV Quality Assurance Task Force Task Group 10,) and the lab team (NREL) effort worked towards the goals of:

- Identification and verification of failure modes and the related considerations for PTC components in today's PV industry.
- Development of accelerated test methods suited for cable jackets and connectors.
- Development of advanced characterization methods to diagnose and elucidate degradation mechanisms for field- and chamber-degraded samples.

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Background

Balance of system (BoS) components, *i.e.,* cables and connectors, must be replaced in PV systems in the event of premature failure or if their life is less than that of the PV modules. For example, degradation of the wire harness (i.e. cable jacket) shown in Figure 1 can result in loss and/or cracking of material, compromising the electrical insulation.

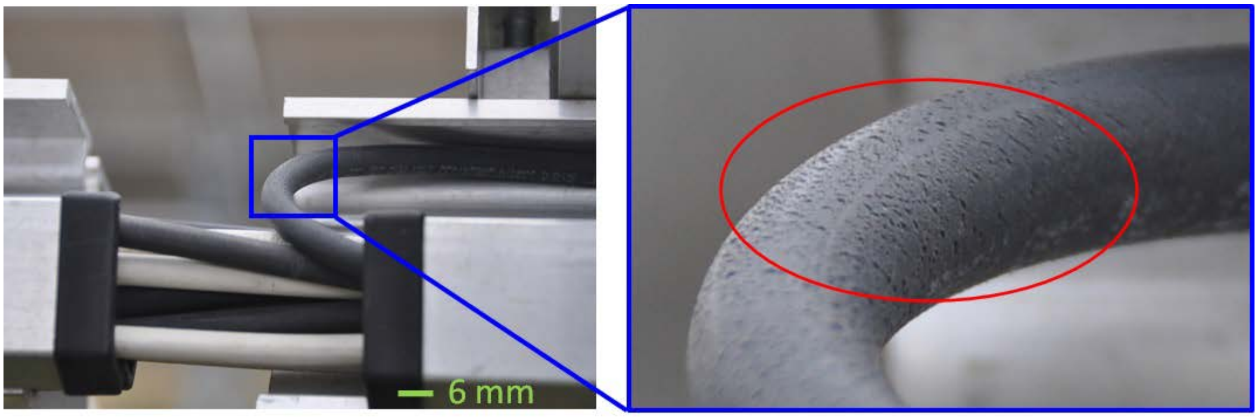


Figure 1: Cracking of cable jacket (red circle) – an industry example from a utility PV system in upstate New York.

The consequences of insulation failure can range from: system downtime (tripped inverters and lost energy production); to added operations expense(s) for replacement (preventative maintenance or in the event of electrical faults); to system destruction (ignition and fire from an arc in the event of loss of insulation) with possible collateral damage adjacent to the PV system. The scale of repair can range from the replacement of specific strings (in the case of manufacturing quality control or installation issues) to complete replacement of the electrical interconnection system (*e.g.,* for an inappropriate material or component design). The lifetime of today's wire harnesses is in the order of 30 years[1], whereas 40 – 50 year module lifetimes are now being proposed. The downward pressure for cost reduction of energy production instead motivates developers to explore lower-cost alternative suppliers and PV materials for BoS components. Additionally, technology advances have also motivated the use of new materials. For example, it has recently become required to color code system wiring relative to its electrical polarity[2], necessitating new material-formulations for cable jackets. Besides issues related to upfront cost, BoS components can further reduce electricity generation through the life of operation for installations of various sizes, Figure 2. Besides interconnect wiring, cables may also be used in metrology instruments (solar irradiance and weather) and to enable tracker operation.

[1] Mark Reusser, ICF International Inc., private communication.
[2] "NFPA 70, National Electrical Code (NEC)", National Fire Protection Association: Quincy, 2020.

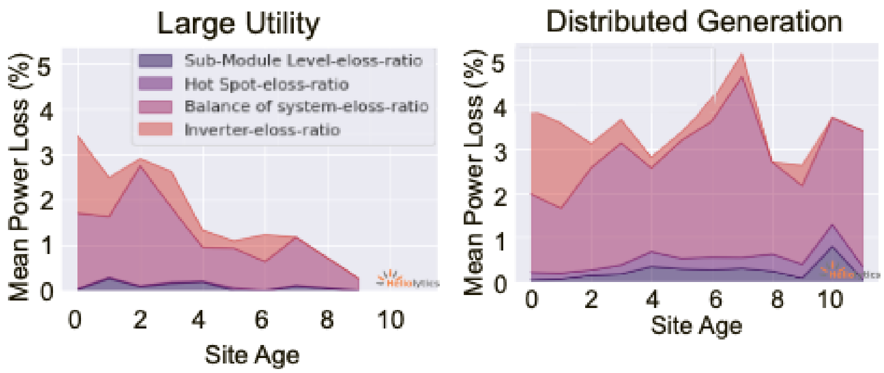


Figure 2: Comparison of the origin of power loss between PV installations of different size. The data, shown for BoS components (combined for cables, connectors, and fuses), comes from a site inspection service provider[3].

Connectors may be used in a variety of locations, *e.g.*, cable to cable (including connection to the module or elsewhere in the system), cable to branch (at T's in the system), cable to combiner box, etc. In addition to quality control, material selection, and installation practices, connectors have unique issues including susceptibility to external mechanical-loads and vibration, the mate-ability of different makes and models, and hermeticity in the event of submersion (*e.g.*, site flooding).

The durability of cables and connectors is a critical requirement for the safe operation of systems, with little specific exploration in the PV industry. The PV industry instead borrows materials, components, and approaches from other industries. There is general consensus that more needs to be learned about how to select appropriate materials for cables and connectors. The acceleration of application-specific stress conditions is also not well established.

Introduction

We seek to prevent the on-going occurrence of electricity production loss in PV installations, by working towards improvements in the performance and durability of key PTC components, i.e., cable jackets and connectors. The outputs of the study may be used by the industry to make more informed material-selection, component design, system design, installation, and operating decisions based on scientifically rigorous assessments of PTC components. Recommendations have been provided towards the improvement of industry practices and industry standards.

Three Tasks were carried out to accomplish the goals and process introduced above:

Task 1: Evaluate representative field-degraded/field-failed PTC specimens.
In Task 1, the NREL advanced characterization team will use separate field- and artificially aged PTC specimens to develop methods of examination.

[3] R. Andrews (Heliolytics Inc), "Fielded module reliability", Proc. NREL PV Reliability Work., 2021.

Task 2: Develop advanced characterization methods for degraded/failed PTC specimens.
In Task 2, NREL will use separate field- and artificially aged PTC specimens to develop methods of examination.

Task 3: Develop accelerated test methods for PTC specimens.
In Task 3, NREL will use separate studies of representative cable and connector specimens to develop methods of artificial aging.

Project Milestones
The status of all proposed Tasks is summarized through the project in Table 1. The industry survey was reviewed with Sandia then circulated on 2021/10/15. The results of the survey were reviewed with the IIG on 2021/11/16 and 2022/1/18 to foster discussion and motivate further insight on the state of the present PV industry. Sample extraction to date includes cable jackets (where the cables may be readily clipped and the jacket cut and peeled from the wire), connector pins (extracted from surrounding plastic on a mill), convolute springs (which enable the physical connection between cable connector ends and are extracted by machining the external plastic then peeling the connector pin), and indentation (*e.g.,* where cable samples were potted in wax and carefully polished at their surface to enable micro-mechanical characterization).

The design review with the IIG (PVQAT TG10) for the accelerated aging of cable jackets was on 2022/10/04. Including based on feedback from the design review, eleven separate cable samples have been procured accelerated C-AST aging. The collection of field-degraded and field-failed specimens was recognized on 2023/3/31 and their subsequent forensic examination of 50/132 specimens (exceeding 6 instances) was recorded on 2023/6/30. The field specimens were on schedule, in part because some samples were submitted to NREL by industry partners upon hearing this project had been selected for negotiations. Both the IIG (PVQAT TG10) and industry events (PVRW and PVSC) were helpful towards obtaining specimens.

Accelerated testing proceeded with cables (thorough C-AST Dynamic fixture - aging finished 2023/10/23, and simpler C-AST Kinematic fixtures – aging finished for T/N 3.3 on 2024/05/03; in addition to the use of steady state UV chamber testing.) During this project, it was realized that 3.5x runs of C-AST gives the same UV dose as 4000 hours of IEC 62788-7-2 weathering). So we extended the C-AST aging to achieve a more comparable dose. In practice, the C-AST chamber broke down (compressor then humidity fan failures) and had to be repaired, delaying the completion of the cables experiments. The added run time was used for outdoor aging of the uncapped cable connector samples in summer months prior to their C-AST experiment in FY24.

The uncapped cable connector test specimens completed 2 runs of C-AST (T/N 3.4, current stepped with each sub-sequence) on 2024/5/08. The original plan was extended by one C-AST run to achieve the NRTL connector current rating during C-AST as well as to achieve a more meaningful UV dose and environmental aging. Separate reference connector specimens (unaged, 3 generations of products from the same vendor) have been in C-AST starting 2024/5/16. Goals include to compare the references to the fielded test samples as well as the compare the durability of successive generations of connector products.

The effort did pivot in the project towards longer, more field-relevant aging of cables in addition to more prolonged accelerated testing of uncapped connectors. While this delayed the completion of the final characterizations of specimens for T/N 2.5, we appreciate DOE's flexibility here and are confident the experiments will be more meaningful and helpful to the industry. We submitted a manuscript on cables at the end of the project (T/N 3.5) and end of FY24 as originally planned. The completion C-AST aging of reference connector specimens (through two runs, with incremented current stress) will carry over into FY25Q1.

Table 1: Tasks and their completion status through FY24Q4.

Task	Description	Year 1: FY2022				Year 2: FY2023				Year 3: FY2024				Status
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
1	Evaluate field-degraded/field-failed BoS specimens.													
1.1	Perform industry survey	1.1												Complete
1.2	Obtain initial BoS field-specimens			1.2										Complete
1.3	Obtain additional BoS field-specimens						1.3							Complete
2	Perform advanced characterization of failed BoS specimens.								M2					
2.1	Demonstrate specimen extraction		2.1											Complete
2.2	Complete characterization field components							2.2						Complete
2.3	Submit manuscript on field-specimens								2.3					Complete
2.4	Complete basic characterization cable jackets after C-AST, AST									2.4				Complete
2.5	Complete characterization connectors after C-AST											2.5		In Progress
3	Conduct accelerated testing of BoS specimens.				M1								M3	
3.1	Host design review meeting for wiring harnesses				3.1									Complete
3.2	Obtain specimens for artificial aging					3.2								Complete
3.3	Complete C-AST, AST for cable jackets							→		3.3				Complete
3.4	Complete C-AST for connectors										3.4			Complete
3.5	Submit manuscript on artificial weathering												3.5	Complete

Project Results and Implications:

The Milestones from each Task in further detail to clarify their meaning, achievement, and implications. The description below is given as a summary of the project; additional details may be found in the publications and presentations from the project, below.

Results on Task 1: Evaluate representative field-degraded/field-failed PTC specimens

Subtask 1.1 – Obtain the results of an industry survey on PTC components, including input from at least 5 separate participants.

Figure 3 represents the NREL industry survey. The survey was circulated starting 2021/10/15 and received nine responses (similar to recent surveys for IEC standards). Participants were relatively well balanced between: system age (>15y), climate, module mounting. The top 4 affected components included: connectors, cables, branch connectors, and fuse blocks. The top 4 origins of degradation included: installation (8); design; manufacturing; and weathering (6 each). The frequency of occurrence was $0.1 < f < 1$ % system·y^{-1}, an order of magnitude less than less than described from system inspections (1-5 % system·y^{-1}, including field assembled connectors) by Rob Andrews (Heliolytics). An unexpected example degradation mode included cable elongation with change in temperature (where PV cables can be over-constrained, allowing longitudinal strain) by their mounting. An additional issue discussed during the IIG review was water damage and/or reduced operation, evident after storm events. Lastly, the use of separate Mechanical and Electrical installation crews came up in IIG discussion, a strategy used for PV site installation. Consequences of the staged installation approach include: a time delay between layup, assembly, and activation; recently increased occurrence of theft; and animal interactions (including nesting and outright damage). Damage and degradation modes include: connectorizing (crimping and assembly); contamination + corrosion of connectors (particularly if left uncapped); partial shading or increased V_{oc} (module damage at the cell level from incompletely assembled systems). Additional insights from the NREL industry survey may be taken from the recordings and notes of the 2021/11/16 and 2022/1/18 meetings, available at https://app.box.com/s/083kbggve2rsn0zut87vn4tfr4hzcuqj. The survey will help towards the identification and collection of relevant field-degraded BoS specimens. The summary is included here to document the occurrence and outcome of the subtask activity, which is completed.

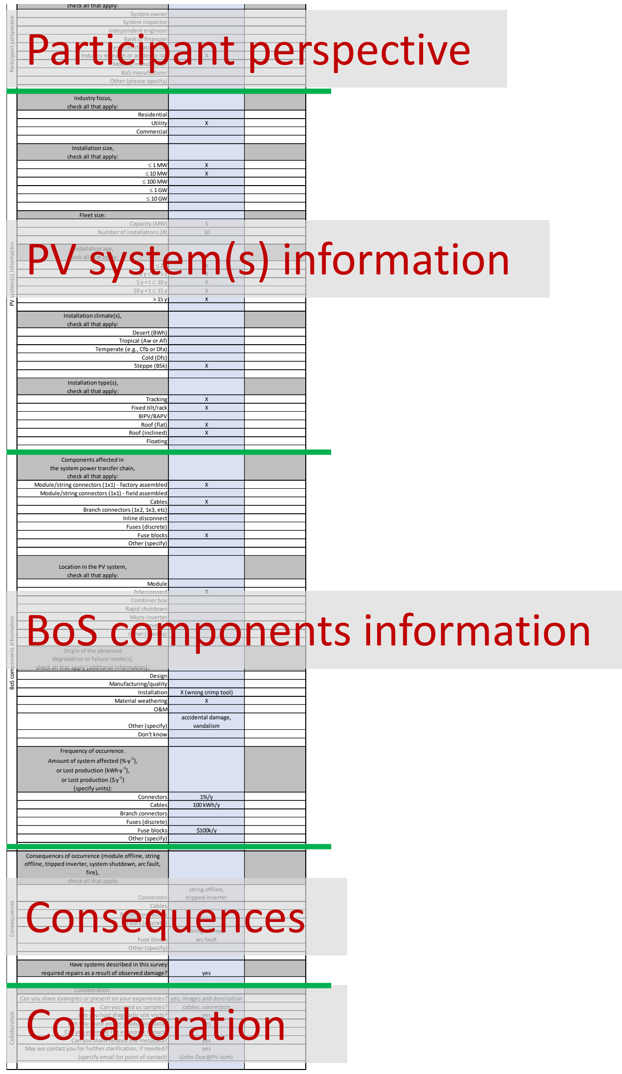


Figure 3: Image of the industry survey, identifying the sections and their emphasis (extent of detail).

PVQAT TG10, the Industry Interface Group, met monthly via the internet growing to 125 members by the end of CPS 38524. Meetings have been on the order of 20-35 live attendees; the meetings are recorded and shared online for those that are not able to attend in person. The meetings have helped to focus on components and degradation modes of concern to the industry, including previously anticipated and originally unanticipated degradation modes. Meeting topics through CPS 38524 include:

- balance of Systems Reliability (kickoff meeting, DOE CPS projects 38524, David MILLER @ NREL and 38531, Laurie Burnham @ Sandia)
- review of initial results of the BoS PTC survey (David MILLER, NREL)
- analysis of BoS degradation, from PV site inspections (Rob ANDREWS, Heliolytics)
- review of final results of the BoS PTC survey (David MILLER, NREL)
- cable ties (Sumanth LOKANATH, FTC Solar; Alexandra PETERS, Arkema)
- counterfeit connectors (David PENALVA, HelioVolta; Dominic BÜRGL Stäubli))

•connector incompatibility (Dominic BÜRGL, Stäubli; David PENALVA, HelioVolta)
•field connector experiences in India (Rajiv DUBEY, SolarMarQ)
•PV connector reliability survey (Laurie BURNHAM, SNL)
•PV branch connector accelerated testing (Mike KEMPE, NREL)
•degradation of uncapped PV connectors (PVQAT TG10)
•design review of C-AST of cables (David MILLER, NREL)
•DC cabling best practice recommendations (Jeff WANG, Stäubli)
•installer training + certification and discussion (PVQAT TG10).
•water-tree degradation from inverter switching noise (David MILLER-NREL)
•BoS PTC in floating PV (Thomas REINDL-SERIS)
•"What happens in a PV system in the event of an arc/fault?" [How do systems detect and automatically respond (for fire prevention)?] Bill SEKULIC-NREL)
•PVQAT TG10 fishbone/FMEA of cable connectors (Mike KEMPE-NREL)
•history of connectors, cables in the PV market (Bruce KING-SNL)
•metallurgical inspection of contemporary connectors (Tapasvi LOLLA-EPRI)
•connectors in automotive applications (Don PRICE-USCAR)
•specimen and site metadata for BoS (TG10)
•rapid shutdown devices (David PENALVA, Heliovolta; Peter GREENBERG, NrgWise)
•in-line fuses (Todd KARIN, PVEL; David PENALVA, Heliovolta; Ken SAUER, VDE)
•"Universal PV pin and socket standard" (Mike KEMPE, NREL)
•IEC 62852 DC PV connectors standard (Guido VOLBERG, Stäubli)
•connector body & crimp designs (Don PRICE, USCAR)
•durability of polymers used in PV cables & connectors (Soňa ULIČNÁ, NREL; Jan MASTNY, Leoni Studer AG)
•durability of metals used in PV connectors (Steven HAYDEN, NREL)
•a case study of fielded PV connectors (Steven DiGREGORIO, SNL)
•failure analysis (of cable connectors, David MILLER, NREL and Steven DiGREGORIO Sandia)
•connector technoeconomic analysis (TEA, Andy WALKER, NREL)
•creepage, clearance, and pollution for connectors (Guido VOLBERG, Stäubli)
•cable management - cable routing, conduit, and trays (James NAGEL, Heliovolta; Bill SEKULIC, NREL)
•terminology of connectors and their components (Steven DiGREGORIO, SNL)

Regarding the project goals and objectives, the IIG (PVQAT) meetings have helped to focus on components and degradation modes of concern to the industry, including previously anticipated and originally unanticipated degradation modes. To date, the IIG has helped to garner respondents and disseminate the results of two industry surveys (NREL 38524, this project; and Sandia/EPRI 38531, companion project). Working with industry partners and the IIG, NREL has obtained more than 3 separate instances (including multiple replicates) of field degraded BOS components, including cable connectors from: Baltimore, MD; Dallas, TX; Davis, CA; Fredericksburg, VA; Fresno, CA; Golden, CO; Los Angeles, CA; Prince Edward

Island (PEI), CAN; and Sacramento, CA; as well as cable jackets from: Albany, NY; Davis, CA; and

Prince Edward Island (PEI), CAN; as well as tracker cable jackets from Bengaluru, IN. This is an addition to internal samples (references for comparison) including chamber aged cable jackets and cable connectors (IEC 61215 qualification and C-AST MiMo).

Advanced characterization methods that continue to be developed and applied for the PTC-specific specimens in this study include: resistance-current integrity scans, water immersion- and spray-based high potential insulation verification, infrared thermographic imaging, X-ray computed tomography, scanning electron microscopy morphology, energy dispersive spectroscopy composition, surface roughness (profilometry), sample extraction (including mechanical machining), instrumented indentation, and polymer analysis (Fourier-transform infrared spectroscopy structure, thermogravimetric analysis, and differential scanning calorimetry). Accelerated testing has been conducted, including steady state UV weathering (IEC 62788-7-2 method A3) and C-AST aging (in three successive designs of static bending fixtures) of cable jackets. Inverter switching noise was characterized on a variety of representative PV systems, where the observed magnitude and frequency have been used towards a ripple stress circuit applied during C-AST. The custom Dynamic fixture was applied to cables in C-AST (including external mechanical perturbation and AC plus DC electrical stress), which was used in addition to the C-AST Kinematic (static) fixture. A static fixture (also including AC plus DC electrical stress) was applied to uncapped connector test specimens and is presently being applied to unaged reference connector specimens.

Subtask 1.2 – Obtain at least 3 separate instances of field-failed specimens.

As represented in Figure 4, NREL initially obtained more than 3 separate instances (including multiple replicates) of field degraded BOS components, including cable connectors (Sacramento, CA), cable jackets (Albany, NY), and tracker cable jackets (Bengaluru, IN) as well as internal samples (references for comparison) including accelerated aging cable jackets and cable connectors (IEC 61215 qualification and C-AST MiMo). Regarding the cable connectors, a wide variety of sample integrities has been observed (including deformed plastic, blistered plastic, cracked plastic, or up to one component end being mostly vaporized and no longer existing after failure). In other cases, we presume system owners identified and removed connectors based on their temperature, but the cause of degradation is not readily diagnosed prompting the creation of a test stand to characterize resistance (where current is incrementally stepped to application levels). Regarding the cable jackets, a roughened morphology (including micro-scale cracking) was observed on field degraded specimens that was not observed for specimens after the IEC 61215 qualification tests. Regarding the tracker cable jackets – no examples were anticipated at the start of this study. A greater scope was realized (including system components such as the tracker) and the meaning of early advice (multi-conductor SJOOW cables are indeed purchased for PV systems – including from the Home Depot) is clear. Progress on the Task has proceeded ahead of deadlines as we have gotten samples and offers towards samples through the IIG as well as industry partners.

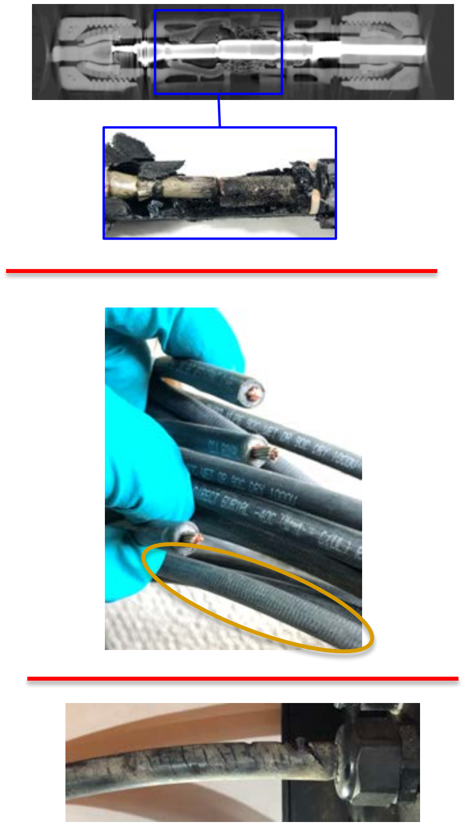


Figure 4: Examples of degraded cable connectors (top, in XCT and after removing the external plastic), cable jackets (middle, selected for study based on their appearance - circled), and tracker cable jackets (bottom, where cracking was observed at both of the connectorized ends).

Figure 5 compares the morphology of cable jackets, including: field degraded (right) and references run through separate accelerated tests (left). The field degraded specimen (from Albany, NY) shows a coarse roughness (top right) in addition to micro-scale cracking (bottom right). The specimens subjected to accelerated testing do not show the same extent of surface roughness (also quantified using AFM), rather they instead have their own unique morphology. For example, the cable jacket after UV weathering/50 thermal cycles/10 humidity freeze cycles shows bumps (“blister”, top left) also observed during damp heat testing (not shown); whereas the cable jacket after 200 thermal cycles with no hygrometric accelerated testing (bottom left) shows a smoother surface without roughening or cracking. We continued to obtain and analyze field-degraded specimens, including cable and cable connector specimens through the second year of this project. These specimens may be compared to additional specimens presently undergoing accelerated testing, including steady state IEC TS 62788-7-2 method A3 UV weathering and C-AST (using two successive kinematic fixture designs). Degraded specimens will also be compared to the formal C-AST cable experiment (“D1” and “K3” fixtures).

M1706-0004
(UV/TC50/HF10)

M2110-0049
(Field degraded)

M1706-0006
(TC200)

M2110-0049
(Field degraded)

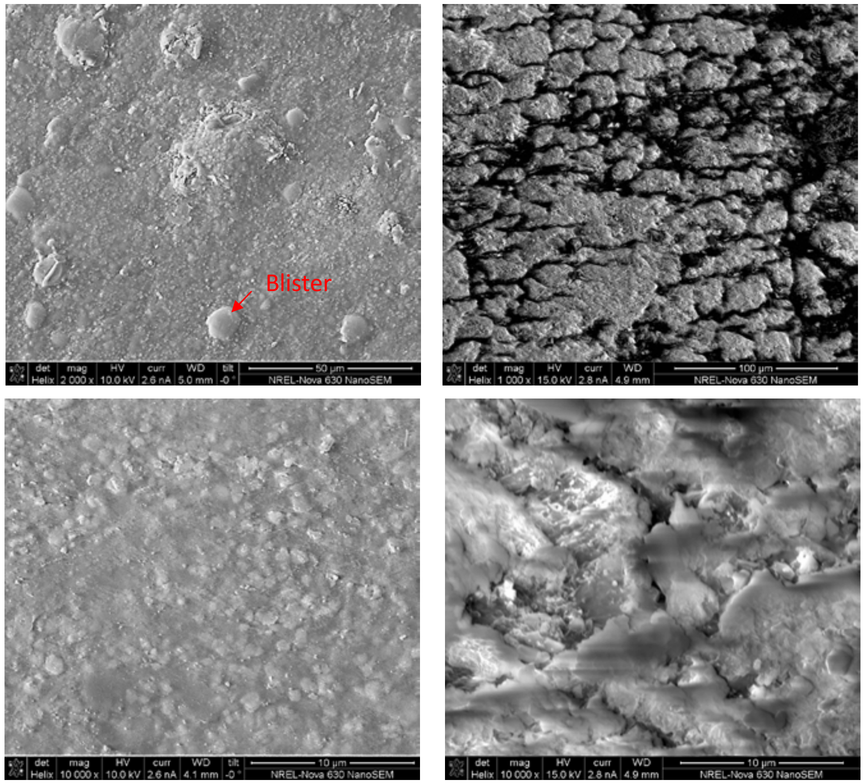


Figure 5: Comparison of cable jackets after IEC 61215 testing (left, including the test sequence of UV weathering followed by thermal cycling followed by humidity freeze as well as aging using thermal cycling only) and field degraded specimens (showing the damage to the same specimen at different magnifications).

Subtask 1.3 –Obtain at least 3 additional separate instances of field-failed specimens

As summarized in Table 2 and Table 3, a variety of degraded cable connectors specimens and cable specimens were ultimately obtained for study. The tables includes the location (typically a large city, but some specimens were only subject to accelerated testing); the number of specimens supplied by the collaborator; the climate, including the Köppen-Geiger climate classification and a corresponding colloquial description; and the manufacturer (identified with a letter index). Field specimens were typically obtained from PV installations. Accelerated aging (italicized) was performed for IEC 61215 (i.e., the Damp Heat, Thermal Cycle, and UV/TC50/HF10 tests) and combined-accelerated stress testing. Most connector specimens consisted of pin and socket pairs, although one of the components was sometimes vaporized. The cables from Bengaluru controlled one-axis trackers at that location; all other cable samples were for the distribution of electricity from PV modules. Most industry collaborators requested to remain anonymous, therefore the specific installation or township is not identified in Table 2 and Table 3. The manufacturers are anonymized in the tables at request of collaborators. Multiple manufacturers in each row in the tables may indicate multiple systems and/or incompatible connectors. Manufacturers a and b constitute most of Table 2. Specimens were examined from six climate types, however, hot-dry (BWh-desert) locations are not represented and hot-humid (Am-monsoon and Aw-savanna) locations are only modestly represented. In addition to its continental climate, the PEI site was an oceanside location.

Table 2: Cable connector specimens in this study. The C-AST specimens do not include those tested in the uncapped connectors experiment.

LOCATION	QUANTITY SUPPLIED	CLIMATE: class (description)	MANUFACTURER(S)
Baltimore, MD	8	Cfa (subtropical)	a
Dallas, TX	22	Cfa (subtropical)	b
Dallas, TX	2	Cfa (subtropical)	b
Davis, CA	6	Csa (Mediterranean)	c
Fredericksburg, VA	2	Cfa (subtropical)	c
Fresno, CA	36	Csa (Mediterranean)	a
Golden, CO	5	BSk (steppe)	a, b, d, e
Los Angeles, CA	5	Csb (Mediterranean)	a
Prince Edward Island (PEI), CAN	21	Dfb (continental)	b, d
Sacramento, CA	35	Csa (Mediterranean)	a
accelerated tests	*6*	*IEC 61215*	b
	6	*C-AST*	b, e
TOTAL	**154**	**5 + *4***	**5**

Table 3: Cable specimens in this study. The C-AST specimens do not include those tested using the fixtures for this study (K1, K2, K3 and D1).

LOCATION DURING AGING	CLIMATE: class (description)	QUANTITY SUPPLIED	MANUFACTURER(S)
Albany, NY	Dfb (continental)	3	a
Bengaluru, IN	Aw (tropical savanna)	8	b
Davis, CA	Csa (Mediterranean)	16	c, d, e, f, g, h, i
Prince Edward Island (PEI), CAN	Dfb (continental)	3	*
accelerated tests	*IEC 61215*	*6*	*j, k*
	C-AST	*1*	*l*
TOTAL	**3 + *5***	**37**	**19**

Results on Task 2: Develop advanced characterization methods for failed BoS specimens

Subtask 2.1 – Demonstrate specimen extraction for characterization of unaged cable jacket and connector specimens.

As represented in Figure 6, NREL developed methods for specimen extraction and preparation to facilitate advanced characterization. The example shows a PV cable, originally connectorized at both ends Figure 6 (top). The cable jacket can be examined from short sections cut from the original length of the cable for direct examination (e.g., SEM, EDS, profilometry, or indentation), or the jacket can be cut with a blade along its length so that it can be peeled from the cable for specific examination (e.g., TGA, DSC, or FTIR). Many cable jacket characterizations can be performed directly on a section of cable. After nondestructive examination of cable connectors (e.g., R-I scans, camera, XCT, microscope, SEM, or EDS) the external plastic can be removed by machining Figure 6 (middle, using a mill) to reveal the internal metal pins. NREL is fortunate to have technician Greg Perrin, who is a skilled machinist. Often failed connectors provide modest or even minimal diagnosis in nondestructive examination, however, scorching (at the presumed the hottest site) is evident from the metal pin and socket using many of the same characterization methods applied for nondestructive examination. Lastly, the contact spring (which enables both the electrical and mechanical connections) can be extracted from the metal socket in at least two of the major connector manufacturers, Figure 6 (bottom). Fortunately, the metal socket can often be carefully unfolded, minimally affecting the contact spring. In many specimens examined to date, the contact spring is the suspected the location of failure, suggesting a mechanical design flaw (insufficient contact force or overall robustness), manufacturing flaw (e.g., metal plating), uncapped ends, mechanical strain (from vibration and/or bending), CTE misfit (with abrasion), and live disconnect. Under the case studies activity, there are approximately five different degradation modes under investigation. Conducting several examinations in parallel helps expedite work, since work can be performed on one study while another is on hold during length stress exposures or sample shipping.

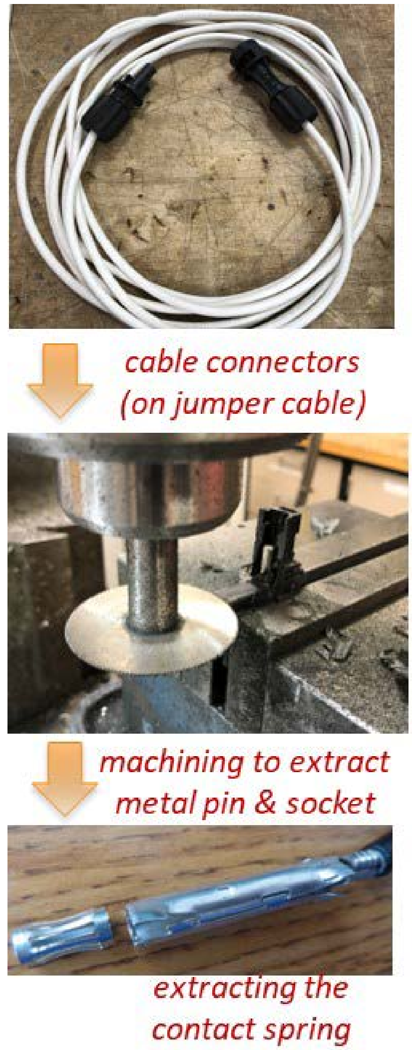


Figure 6: The specimen extraction procedure for cable connectors includes: inspection of as-received samples (top), the machining of the external plastic to reveal the external detail of the metal components (middle), and the extraction of the contact spring from the metal socket (bottom).

As shown in Figure 7, NREL performed advanced characterization on indoor aged degraded BoS samples. One interesting finding for cable jackets is that their surface roughness was greatly increased after 4000 h UV weathering using IEC 62788-7-2 method A3, Figure 7 (bottom). In contrast, prominent cracking was observed at the 4000 h read point, which may indicate a critical embrittlement for PA/PVC cables whereas the cracking was more incremental for PO cables (including damage observed at 2000 h). To date rounds of examination have also been applied to cable connectors, where interior parts may be extracted after the exterior features have been examined. Polymer analysis has not been well suited to cable connectors as most examples to date seem to feature issues related to the conductive metallic pin and socket components, where secondary degradation is only featured in the heating and deformation of the exterior plastic.

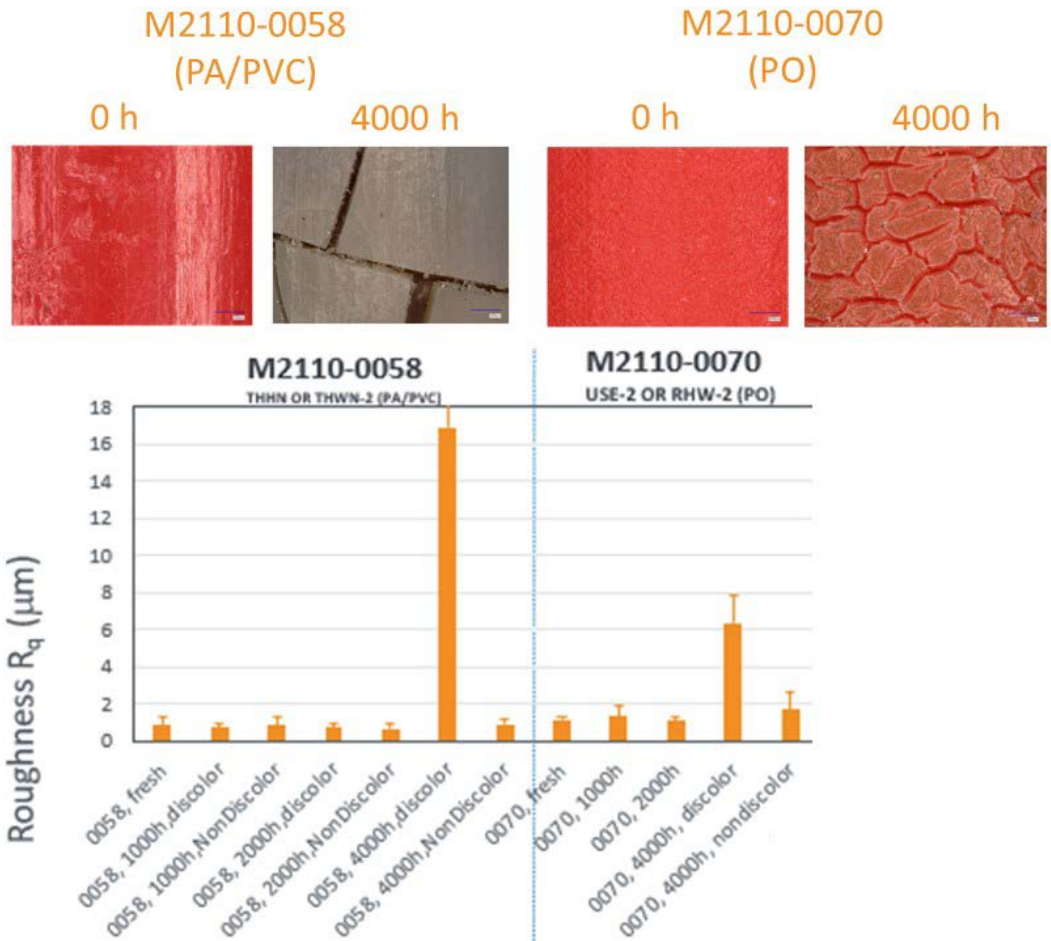
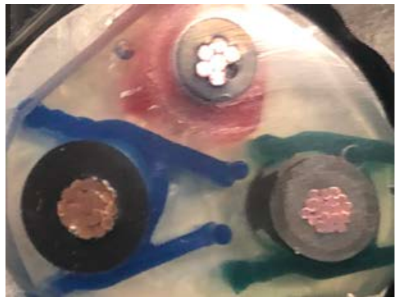


Figure 7: Comparison of the morphology (from optical microscope, top) and corresponding surface roughness (from Dektak profilometer, bottom).

As shown in Figure 8, NREL performed advanced characterization on field degraded BoS samples. Here, a microindenter was unexpectedly found at NREL that could be used towards the project. The polymer characterization has been slow to date, limited by the start of dedicated post-doc at NREL, but has allowed other characterizations to be completed for the same specimens. Samples extraction and characterization benefits from a previous DuraMAT project, specifically focused on PV branch connectors and discrete fuses, where many of the same methods were applied to specimens of different size and geometry.



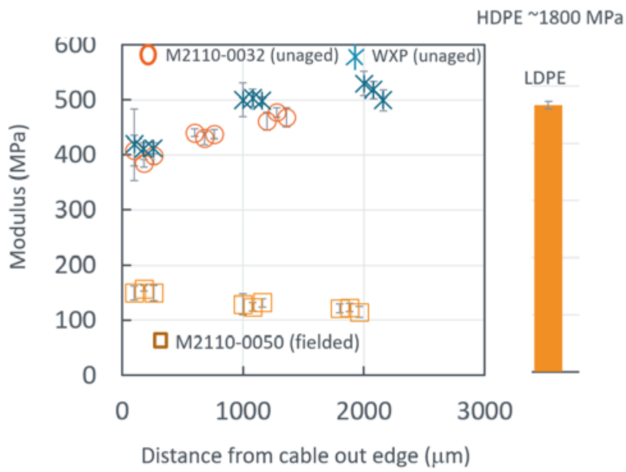


Figure 8: Degraded and reference cable jacket samples prepared in cross-section for indentation (top) and corresponding modulus results (bottom).

Subtask 2.2 – Complete diagnosis of at least 6 field-degraded/field-failed specimens.

The NREL specimen failure analysis protocol is summarized in Figure 9. The more complicated examination of cable connectors is featured in the figure to showcase the NREL forensics capabilities applied in this study. The sequence was developed over time, based on the on-going results of the study. Degraded and failed specimens were identified from tripped inverters, infrared inspection (field or aerial), and visual evidence (including cables found lying on the ground). Specimen identification and selection was entirely left up to the collaborator. Specimens were obtained from locations within the PV systems, including the module and inter-component interconnects (*e.g.*, combiner-box and inverter).

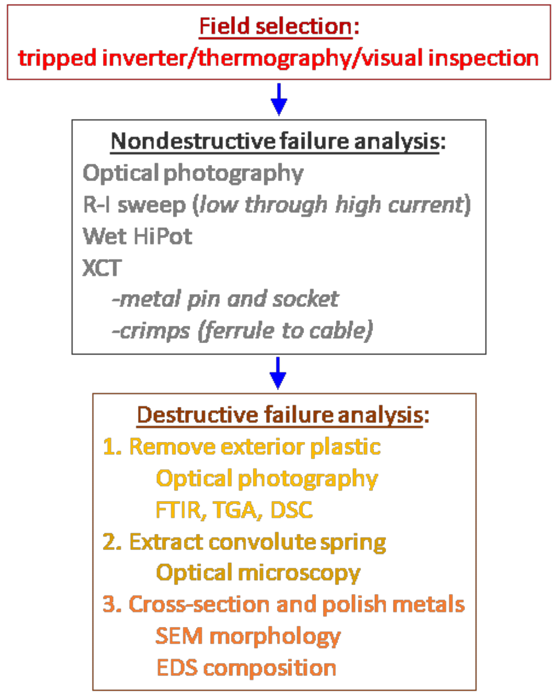


Figure 9: Summary of connector specimen examinations, including field selection (at PV installations), nondestructive methods (before disconnecting the plug and socket), and destructive characterizations (after removing the external plastic).

Nondestructive failure analysis typically started with visual appearance (α99 MII digital camera, Sony Corp., white balanced for 5500K fluorescent bulbs). A four-point style resistance measurement was obtained using an automated current sweep (LabView, National Instruments Corp.), from 0.2 A to 10 A, in 2 A increments - with a 60 s hold). Current came from a GENESYS+ GH20-75 (TDK-Lambda Corp.) power supply, voltage measurements were taken with a 2700 multimeter (Keithley Instruments LLC). From the 7 Hz data, the Immediate resistance was taken at the 3rd data point (i = 3, at 429 ms), while the Stabilized resistance was taken as the average for $365 \leq i \leq 415$. Electrical insulation was verified according to the wet leakage test (MQT 15 in IEC 61215), using a Hypot III (Associated Research Inc) tester. Resistance was determined after a 2 minute hold at 1000 V potential for specimens immersed (preferentially, for connectors with sufficiently long cable leads) and sprayed (when cable was cut short at the connector) with a water:surfactant solution. Based on appearance, resistance, and insulation, select specimens were chosen for continued examination. An X3000 system (North Star Imaging Inc.) was used for X-ray computed tomography (XCT) to obtain the three-dimensional structures of the specimen assemblies (unaged and degraded). The connectors were rotated and paused at discrete angles to collect 2D projection images. The projections were later combined to produce a 3D reconstruction of each specimen. Beam parameters of 150 kV and 40 μA were used for the X-ray source. Ten projection images were averaged at each degree to obtain a resolution on the order of micrometers. Representative images were taken from the metal components within the mated ends of pin and socket as well as from cross-sections extracted from the crimp between the ferrule and cable.

The first step of destructive failure analysis was to deconstruct each connector specimen by unscrewing and removing the end nuts, followed by machining the external plastic with a cutting wheel on a mill. The digital camera was used to photograph the internal components of the pin and socket, still plugged together and then disconnected for the first time. The metal pin from the metal socket was then mechanically unfolded to extract the convolute spring. Brightfield microscopy was performed on the spring using a white-balanced VHX-5000 microscope (Keyence Corp). The morphology and composition of the metal components were examined using a S-4800 scanning electron microscope (SEM, Hitachi High-Tech America Inc.) equipped with an UltraDry windowless silicon drift energy-dispersive X-ray spectroscopy (EDS) detector (Thermo Fisher Scientific Inc.). EDS measurements have a sample depth on the order of micrometers and a measurement detection on the order of 0.1% atomic concentration. For cross-sectional examination, the metal components were cast in hot melt wax adhesive (P/N 71-10040, Allied High Tech Products Inc.) and then polished with an automated system (MultiPrep 10-1000, Allied High Tech Products Inc.) using 30, 9, 3, 1, 0.5, and 0.1 μm diamond lapping films followed by 0.04 μm alumina slurry (Allied High Tech Products Inc.) Polished specimen were released for electron imaging using acetone.

At least 50 field specimens were examined using the failure analysis protocol in Figure 9. Most field specimens were cable connectors. Field cables were examined using the additional methods of profilometer surface roughness characterization and instrumented indentation. Some cable and connector specimens have already been examined after accelerated testing. Unaged cable and connector specimens were also examined to provide a baseline relative to field and indoor-aged specimens.

Subtask 2.3 – Submit a manuscript on field-failed specimens to a conference or peer reviewed journal.

A summary of the examination of field degraded/failed connectors was submitted to IEEE J PV on 2023/9/25 and later published in 2024, Figure 8. More than 50 out of 142 samples received were subject to detailed failure analysis. Relative to the results of the previous PVQAT TG10 survey, forensics confirmed degradation modes including: incompatible components, incomplete assembly (internally), improper crimping (field), and improper sizing (to cable). The most frequent degradation, resulting from scorched metal pins, was unexpected (not conveyed in industry feedback) and remains to be understood. This may result from design, manufacturing, uncapped ends, vibration/bending, CTE/ abrasion, or live disconnection. If the origin of degradation is understood, a test method might be proposed for the IEC 62852 standard on DC PV connectors (which does not consider the presently popular one-axis trackers) to prevent costly downtime and fires resulting from PV connectors. The study in the manuscript was also at the NIST/UL Workshop on Photovoltaic Materials Durability on 2023/12/05.

IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 14, NO. 5, SEPTEMBER 2024 793

Photovoltaic Cable Connectors: A Comparative Assessment of the Present State of the Industry

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***Abstract*—The consequences of failure for balance-of-systems components (such as photovoltaic (PV) cable connectors) include offline module string(s); low system voltage; arc, ground, insulation, and overtemperature faults; triggered fuse(s); system shutdown; and fire. The degradation modes for connectors are studied here through an industry survey and its subsequent examination, which are compared with field-degraded specimens. A total of 117 specimens were obtained from a variety of locations and climates or accelerated tests. A failure analysis for connectors from PV installations was developed (and applied to 54 specimens), including nondestructive examinations (photography, a custom resistance–current scan, and X-ray computed tomography) and destructive examinations (featuring milling of the external plastic, extraction of the internal convolute spring, and potting and polishing in cross section). Surface and through-thickness composition of the metal pins and springs was quantified using scanning electron microscopy with energy-dispersive X-ray spectroscopy. Fourier transform infrared spectroscopy was used to verify the base polymer materials and compare the chemical structure of the connector body, bushing, end nut, and o-ring. Thermogravimetric analysis and differential scanning calorimetry were used to further verify the degradation of the same polymeric components.**

***Index Terms*—Cable connectors, differential scanning calorimetry (DSC), durability, energy-dispersive X-ray spectroscopy (EDS), Fourier transform infrared spectroscopy (FTIR), International PV Quality Assurance Task Force (PVQAT), reliability, scanning electron microscope, thermogravimetric analysis (TGA), X-ray computed tomography (XCT).**

I. Introduction

POWER transfer chain (PTC) balance-of-systems (BoS) components in photovoltaics (PVs) include cable connectors, cables, branch connectors, fuses (discrete), and fuse blocks. These components may be replaced in less than 30 years, i.e., within the manufacturer's warranty period for PV modules. As system operation extends beyond 30 years, the operations and maintenance cost of PTC BoS components, therefore, becomes even more important. The consequences of failure for BoS components include offline module string(s); low system voltage; arc, ground, insulation, and overtemperature faults; triggered fuse(s); system shutdown; and fire [1], [2]. Cables and connectors on PV modules are subject to the safety and performance certification and regulations for PV modules rather than for PV systems.

Despite the severe consequences of degradation and/or failure, the study of BoS components specific to the PV industry is presently limited. For example, the components and their locations, the frequency of occurrence of failure, and the associated cost in compromised systems are not widely known, in part because of legal concerns. This study evaluates the state of the present PV industry using the following resources:

1) previous PV research and industry publications. Although the literature in the PV industry is presently limited, efforts in other industries (e.g., automotive and telecommunications) may eventually prove helpful;
2) International Photovoltaic Quality Assurance Task Force (PVQAT) Task Group 10 (TG10, an industry stakeholder team on BoS components);
3) an industry survey, primarily conducted through PVQAT and the International Electrotechnical Commission (IEC);
4) examination of degraded and failed samples obtained from PV installations. Verification of degradation modes was performed with the forensics; however, the statistical analysis of degradation modes and their occurrence within PV systems is outside the scope of the present study.

This study focuses on the degradation of cable connectors, including those used to interconnect PV modules and those used to connect module strings to inverters. Forensics of fielded samples was performed to verify industry feedback, to compliment PVQAT and the survey, which rely on the participation and perspective of a finite number of stakeholders. The forensics effort was intended to develop methods of examination as well as a forensics protocol for degraded specimens.

II. Background

The materials used in PV cable connectors typically include a polycarbonate or polyamide body with rubber (e.g., silicone or ethylene propylene diene monomer) sealing surfaces (o-rings and bushings) [3]. The metal pins typically consist of copper (or an alloy) with tin, silver, or other metallic coatings [3].

Manuscript received 25 September 2023; revised 7 May 2024; accepted 4 June 2024. Date of publication 12 July 2024; date of current version 26 August 2024. This work was supported in part by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office under Grant 38524 and in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy under Contract DE-AC36-08GO28308. *(Corresponding author: David C. Miller.)*

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This article has supplementary material provided by the authors and color versions of one or more figures available at https://doi.org/10.1109/JPHOTOV.2024.3414178.

Digital Object Identifier 10.1109/JPHOTOV.2024.3414178

Figure 10: First page from the IEEE J PV manuscript.

Subtask 2.4 - Complete diagnosis of at least 5 instances of cable components after accelerated testing.

The aging of cable specimens in the C-AST D1 fixture was completed on 2023/10/23. Six representative specimens were aged, with 1 separate replicate each between DC only current and AC+DC (to simulate inverter noise). Characterizations completed for the twelve specimens include: camera imaging, resistance measurements (2 wire), HiPot (to verify insulation), optical microscope, and surface roughness. Figure 11 summarizes the surface roughness measurements, comparing the results for unaged cables relative to the irradiated (with no contact) and the dark sides of cables (contacting the bending mandrel in response to external perturbation) for the DC only (d) and AC+DC (a) currents applied in the C-AST D1 fixture. While micro-cracking and macroscopic abrasion have been observed, a systematic difference in the nano-to-micro-scale roughness is not evident. Additional characterizations for the cable jackets include: indentation (example in Figure 12), FTIR (for polymer structure), DSC (for polymer phase change and crystallinity), and EDS (for elemental chemical composition.

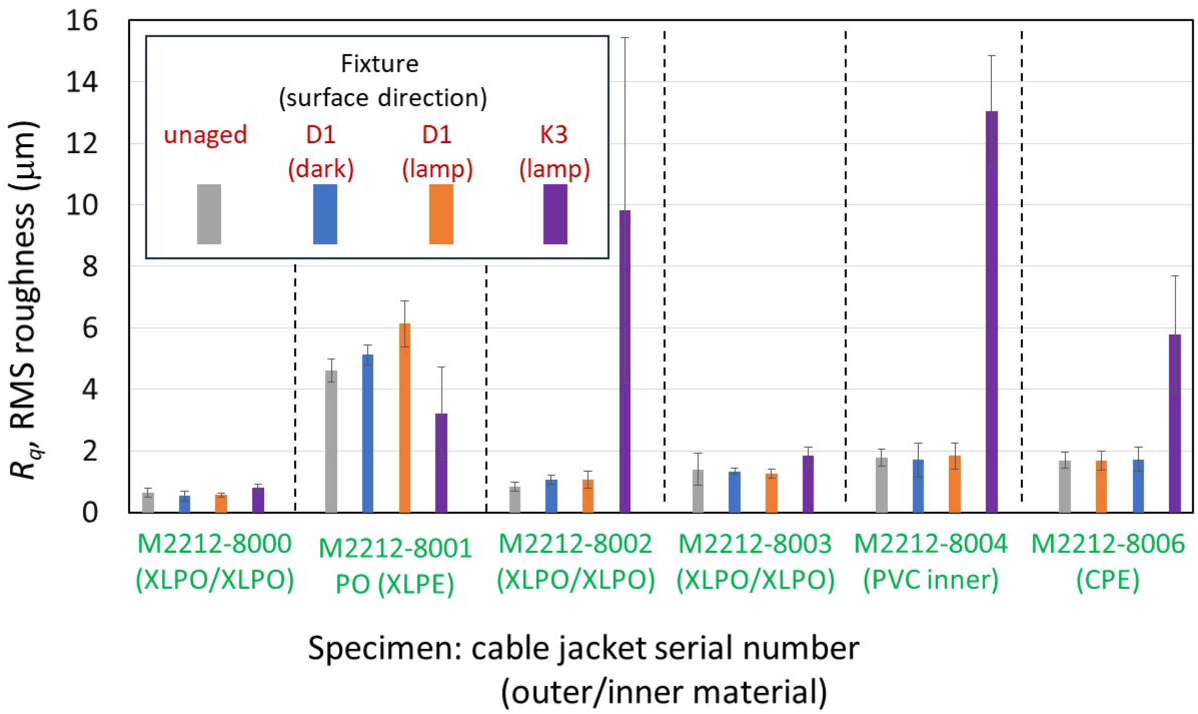


Figure 11: Summary of the root mean square roughness, Rq, for the C-AST cable specimens. Unaged jackets are compared to the D1 fixture (dark side with abrasion on the metal mandrel or lamp side) and the K3 fixture (at least twice the UV dose).

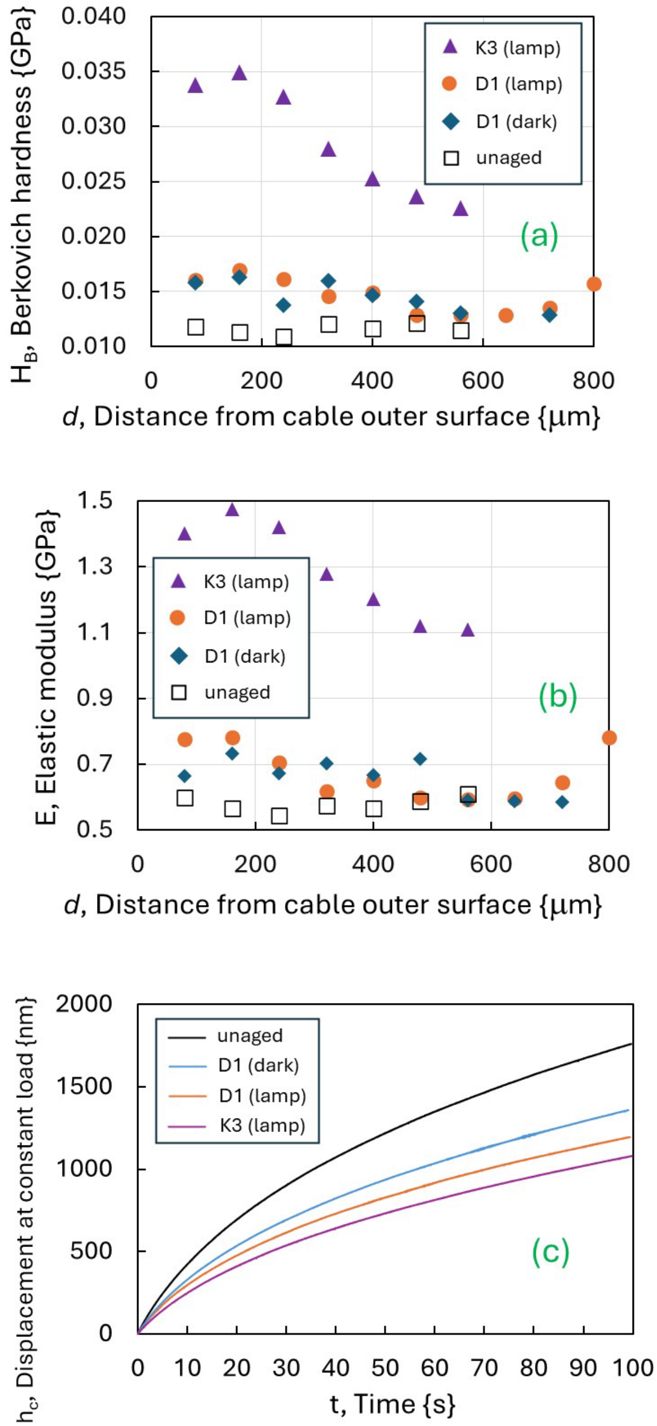


Figure 12: Comparison of the mechanical indentation of cable serial number M2212-8004 (PVC inner), including: (a) the hardness (during indentation, for 4 μm < h < 5 μm), (b) the modulus (averaged through the same depth range), and (c) the displacement-time data profile (for the creep hold, at d = 240 μm). The results are shown for specimens: unaged, after C-AST using the D1 fixture, and after C-AST using the K3 fixture.

Subtask 2.5 - Complete diagnosis of at least 5 instances of connector specimens after C-AST.

Specimens examined from C-AST include: 4 branch connectors (M2109-0102 M3, M2105-0106 M3, M2105-0105 F1, and “Experiment 3 Spring 2” from a previous study, while the C-AST uncapped connector experiment was running, but delayed in its start and completion); 6 cable connectors from the C-AST D1 cables experiment (Figure 13, M2212-8004-a, M2212-8006-a, M2212-8002-d, M2212-8003-d, M2212-8004-d, and M2212-8006-d); 6 reference cable connectors from the C-AST uncapped connectors experiment (M2302-0101 and M2302-0115 – uncapped and plugged specimens fielded at Barstow, M2302-0201 and M2302-0215 – uncapped and plugged specimens fielded at PEI, and M2302-0301 and M2302-0315 – uncapped and plugged specimens fielded at Gaithersburg); and 6 cable connectors from the C-AST uncapped connectors experiment (M2302-0102/M2302-0105 and M2302-0103/M2302-0106 fielded at Barstow, M2302-0206/M2302-0209 and M2302-0207/M2302-0210 fielded at PEI, and M2302-0303/M2302-0306 and M2302-0306/M2302-0309 fielded at Gaithersburg). M2212-8004d is used to represent the examination process, which includes nondestructive characterizations (R-I and HiPot) and imaging in addition to characterizations after samples deconstruction and extraction. SEM morphology and composition analysis have focused on the branch connectors and the C-AST uncapped connectors experiment (from the field and after C-AST).

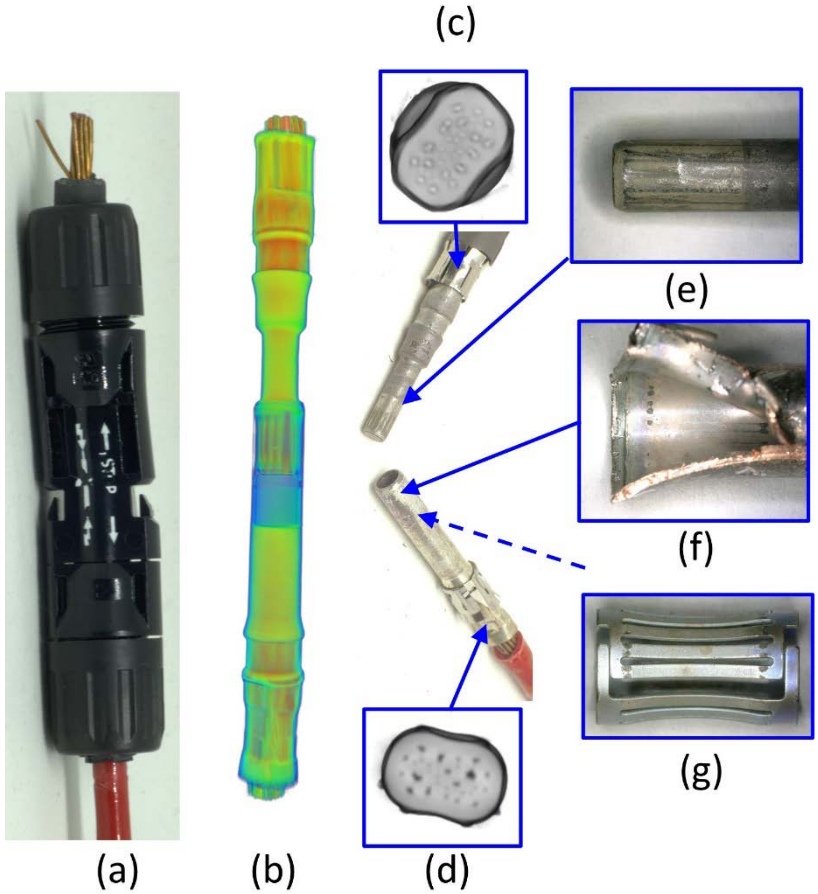


Figure 13: Forensics of specimen serial number M2212-8004d, from the fixture to cable in the C-AST D1 fixture, including: (a) camera photograph of after it was taken out of the experiment, (b) XCT scan prior to deconstruction, (c) detail of the crimp from XCT, (d) detail of the crimp from XCT, (e) detail of the pin after deconstructing and separating the connector, (f) detail of the inside of the socket after deconstructing and separating the connector, and (g) detail of the contact spring after it was extracted from the socket. S/N M2212-8004d was a connector used at the end of the corresponding D1 cable specimen.

Highlights from the forensics of the branch connectors include: Local spots were observed were the Sn outer coating was thin and may have been scraped through, as evidenced by the intermediate Ni layer showing through. The coating materials (Ni, Sn) were not deposited or depleted at edges of louver springs on the contact spring. Carbon was deposited at inner radius between the louvers on the ends of the contact spring, presumably from elevated electric field. Highlights from the forensics of the uncapped connectors include: The pin, socket, and contact spring were discolored (from corrosion of Sn outer layer) in humid locations (PEI and Gaithersburg). Mineral contamination was observed in the desert location (Barstow). Artifacts of insect/small organisms (including spider webs and eggs) were observed inside socket and contact spring in all locations.

Results on Task 3: Develop accelerated test methods for BoS specimens

Subtask 3.1 Host experiment design review meeting for wiring harnesses (cable jackets).

As shown in Figure 14 and Figure 15, the C-AST dynamic fixture was conceptualized and fabricated at NREL based on the feedback from the PVQAT TG10 design review on 2022/10/04. Twenty-nine persons joined for the presentation, which focused on the cable specimens to be examined and the design of the dynamic fixture. Regarding specimens, feedback included to examine Al conductor cable (which has gained market share for system wiring, practically necessitating examination of 8 AWG samples – often the minimum size of Al cable) and to compare jackets with and without flame inhibitor additives (which may affect field degradation). Red was regarded as the least durable jacket color (black being the most durable) and appreciation was expressed towards examining specimens rated for 2kV in addition to cables rated for 600V. The mechanical stressor (which includes external mechanical perturbation using cylinders of the prescribed minimum bend radius) was well-received. The manufacturing processes for cables can result in anisotropic material characteristics, therefore the strain from the perturbation will be designed (separation gap between cylinders) to give a lateral strain comparable to the hoop strain from bend radius.

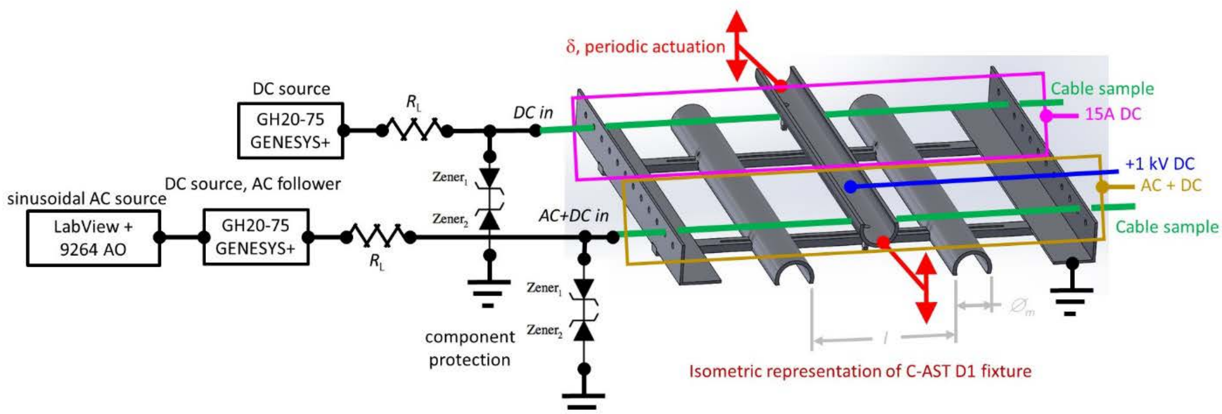


Figure 14: Schematic showing the additional features of the “dynamic” fixture (D1), including external perturbation in addition to direct current which may be superimposed with alternating current to simulate inverter switching noise. Key aspects of the electrical circuits are shown including sources, protective diodes, and electrical grounding.

Figure 15: Initial image of C-AST dynamic fixture, with the unaged specimens in the formal experiment.

Subtask 3.2: Obtain at least 5 separate instances of wire harness (cable jacket) specimens for accelerated testing.

As summarized in Table 4, NREL obtained cable specimens for examination in C-AST aging. A variety of black polyolefin jackets was obtained, expected to give a range of durability, including a “known durable” make and model. The “known vulnerable” for the dynamic fixture is the red building wire, where PA/PVC cable is known to be used as a contingency, *e.g*., either inadvertently in outdoor portions or when the rated cable supply is used up during a residential PV installation. Successive generations of flame inhibitors were examined using the dynamic fixture, as jackets with and without additives were not available without a custom order (thousands of feet of cable). Al conductor could not be sourced at this time in the US; therefore one sample was used to compare to the multi-conductor field tracker cable previously obtained from India. Additional samples were also purchased that may be examined using the C-AST K3 fixture. The six cables examined on the dynamic fixture (including six replicates subject to just DC current in addition to six more replicates subject to AC ripple + DC current) were also examined using six more replicates on the K3 fixture, Figure 16.

Table 4: Summary of the specimens in this study that were aged using C-AST.

NREL S/N	C-AST FIXTURE	JACKET (ACTUAL)	COLOR	SIZE (AWG)	VOLTAGE RATING	OUTDOOR RATING	NOTE
M2212-8000	D1, K3	XLPO outer; XLPO inner	black	8	2 kV, "PV"	SUN RES, "PV"	IEC benchmark
M2212-8001	D1, K3	XLPE	gray	8	2 kV, "PV"	"PV"	NEC benchmark
M2212-8002	D1, K3	XLPO outer; XLPO inner	black	8	2 kV, "PV"	SOLAR	similar to IEC benchmark
M2212-8003	D1, K3	XLPO outer; XLPO inner	black	8	2 kV, "PV"	SOLAR	similar to IEC benchmark, except flammability
M2212-8004	D1, K3	PA outer; PVC inner	red	8	600 V	not specified	known misapplication (building wire)
M2212-8006	D1, K3	CPE outer; EPDM inner	black	≤18	300 V	not specified	for tracker cable (multiconductor)
M2212-8005	K3	TPE (all jackets)	black	≤18	≥300 V	not specified	for tracker cable (multiconductor)
M2212-8007	K3	XLPE	red	8	2 kV, "PV"	SUN RES, "PV"	similar to NEC benchmark
M2212-8011	K3	XLPE	red	8	2 kV, "PV"	SUN RES, "PV"	similar to NEC benchmark

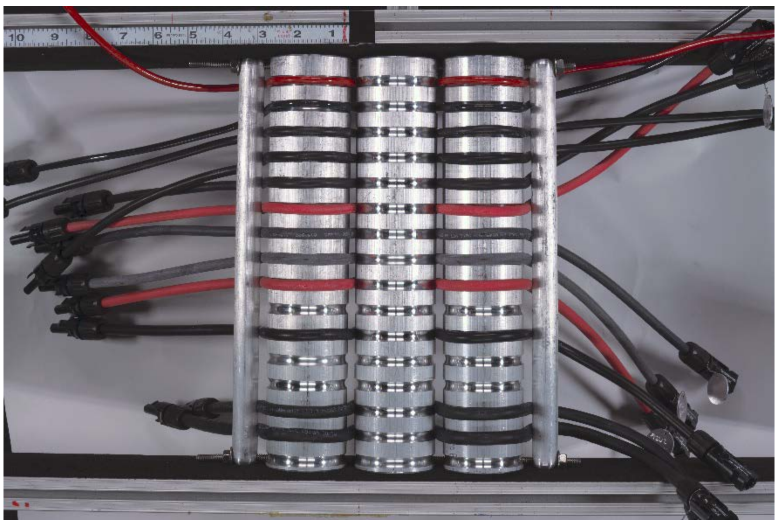


Figure 16: Initial image of K3, the 3rd C-AST kinematic fixture, with the unaged specimens in the formal experiment.

Subtask 3.3 – Complete accelerated testing for at least 5 instances of cable components, including two rounds of C-AST and all auxiliary accelerated tests.

Accelerated testing using the hardware and capabilities in Figure 14, Figure 15, and Figure 16 was initiated for cable specimens on 2023/2/16. The C-AST dynamic (“D1”) fixture (Figure 14, Figure 15) using the AC + DC electrical waveform, and the periodic mechanical perturbation was completed on 2023/10/23. While we would have liked to achieve continuous aging, 10 out of 12 of the cable specimens failed roughly half-way through the experiment, Table 5. Failure occurred at the cable connectors (on both the fixture and specimen side - the connectors are used to allow the specimens to be removed for measurement at read points) rather than cutting the cables. Furthermore, failure occurred at 24 A average current, rather than the 40 A rated current, NRTL certified for the reputable connector make and model. The experiment reenforces that PV cable connectors are presently more delicate than PV cable jackets. The static K3 fixture in Figure 16, continued through one more round (approximately three months in duration) of C-AST. The fixture uses static cylindrical mandrels to bend cable specimens, where additional mechanical strain is achieved by the temperature cycles applied in the C-AST sequences. The K3 fixture was compared to the D1 fixture (specimens also subject to AC + DC electrical waveform and the periodic mechanical perturbation) and K2 fixture (which achieved 3.5 runs of C-AST, comparable to the UV dose from 4000 h of IEC 62788-7-2 A3 weathering).

Table 5: Summary of the C-AST D1 cable experiment

	C-AST RUN 1					C-AST RUN 2					C-AST RUN 3				
	SEQUENCE:					SEQUENCE:					SEQUENCE:				
NUMBER FAILURES:	Winter	Spring	Tropical-a	Tropical-b	Desert	Winter	Spring	Tropical-a	Tropical-b	Desert	Winter	Spring	Tropical-a	Tropical-b	Desert
CABLE ENDS	0	0	0	0	1	0	0	8	2	0	0	0	0	0	0
FIXTURE	0	0	0	0	1	0	0	3	1	1	0	0	0	0	4
DC±AC or DC CURRENT at HIGH IRRADIANCE {A}	0 0		9.0±5 9.0	9.0±5 9.0	24±10 24	0 0		24±10 24	15±8 15	10±6 10	0 0		10±6 10	10±6 10	10±6 10
DC±AC or DC CURRENT at LOW IRRADIANCE {A}	0	9.0±5 9.0	9.0±5 9.0	9.0±5 9.0	13±6 13	0 0	13±6 13	13±6 13	7.5±4 7.5	5±3 5	0 0	5±3 5	5±3 5	5±3 5	5±3 5
START DATE	2023/2/16	2023/2/17	2023/2/23	2023/3/17	2023/4/11	2023/4/24	2023/4/25	2023/5/03	2023/5/26	2023/6/26	2023/7/07	2023/7/10	2023/7/14	2023/9/13	2023/10/12

Subtask 3.4 – Complete C-AST for at least 5 instances of connectors, from all accelerated tests.

The accelerated testing of PV connector specimens followed the cable specimens, Figure 17. Leveraging industry feedback in the IIG (PVQAT TG10), this focused on uncapped connectors (i.e., as may occur between the mechanical and electrical installation of PV systems, suspected to result in connector failure with requisite replacement of the corresponding PV modules). The goals of the experiment were to distinguish and technically understand capped and uncapped connectors (both aged in the field) using C-AST. To allow sufficient field aging prior to accelerated testing, specimens were aged outdoors from 2023/4 to 2023/8 in Barstow, CA; Gaithersburg, MD; and PEI, CA, where the exact day varies between the sites. As summarized in Table 6, to help identify a threshold for failure, the average applied current will be incremented through the C-AST run (from 5 A, 10 A, 15 A, then 20 A for the Spring, Tropical-a, Tropical-b then Desert sequences, respectively; then again from 12.5 A, 30 A, 35 A, then 40 A for the Spring, Tropical-a, Tropical-b then Desert sequences, respectively). As summarized in Table 7, the experiment is presently being repeated using unaged reference connectors (previous, same, and subsequent models) to help interpret the result for the test (outdoor uncapped) connectors. While the C-AST run schedule fell behind (from an added run for cables, then compressor and circuit breaker failures), therefore the C-AST reference connectors experiment will complete in FY25Q1.

(a) (b) (c)

Figure 17: Uncapped connector experiment, including: (a) schematic of outdoor fixture, (b) photograph of the connectors in the outdoor fixture (in 1 x1 configuration, returned from Gaithersburg, MD), and (c) photograph of the connectors in the indoor C-AST fixture (after being assembled into 1 x 3 configuration). Specimens have already been returned and reexamined after outdoor aging in Barstow, CA; Gaithersburg, MD; and PEI, CAN and are presently in C-AST aging.

Table 6: Summary of the C-AST uncapped connectors experiment. Preliminary results are given before forensics have been completed.

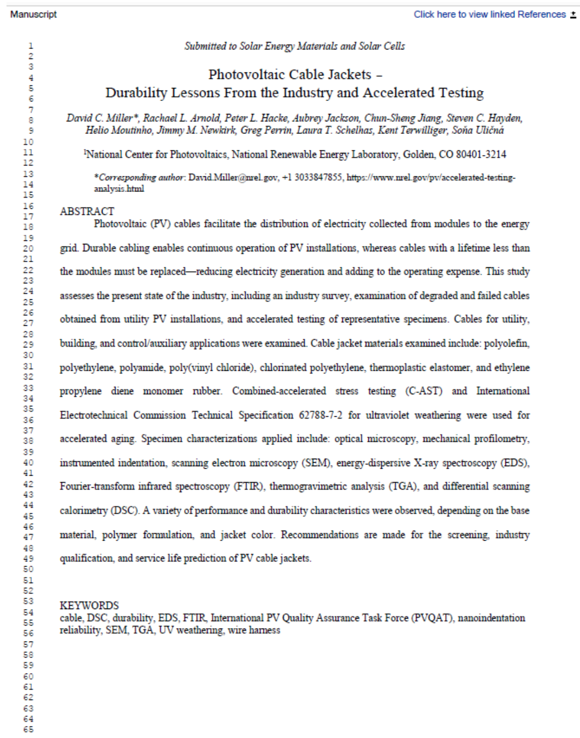
		C-AST RUN 1					C-AST RUN 2				
LOCATION	NUMBER FAILURES:	SEQUENCE:					SEQUENCE:				
		Winter	Spring	Tropical-a	Tropical-b	Desert	Winter	Spring	Tropical-a	Tropical-b	Desert
Barstow, CA	uncapped										2
	plugged										
	jumper/fixture								4	1	
PEI, CAN	uncapped								2	1	
	plugged										
	jumper/fixture								1	1	1
Gaithersburg, MD	uncapped					1			1		1
	plugged									1	
	jumper/fixture								4	2	1
DC±AC CURRENT at HIGH IRRADIANCE {A}		0		10±6	15±8	20±10	0		30±10	35±2	40±0
DC±AC CURRENT at LOW IRRADIANCE {A}		0	5±3	5±3	7.5±4	10±5	0	12.5±6.3	15±7.5	17.5±8.8	20±0
START DATE (EXPERIMENT 1: FIELDED CONNECTORS)		2023/11/07	2023/12/14	2023/12/20	2024/1/24	2024/2/16	2024/2/28	2024/3/01	2024/3/06	2024/4/03	2024/4/30

Table 7: Summary of the C-AST reference connectors experiment. Preliminary results are given before forensics have been completed.

		C-AST RUN 1					C-AST RUN 2				
SPECIMENS	NUMBER FAILURES:	SEQUENCE:					SEQUENCE:				
		Winter	Spring	Tropical-a	Tropical-b	Desert	Winter	Spring	Tropical-a	Tropical-b	Desert
generation a (past)	reference										
	jumper										
	fixture									2	1
generation b (present)	reference										3
	jumper										
	fixture								2	4	1
generation c (future)	reference								1	2	
	jumper										
	fixture								1	3	
DC±AC CURRENT at HIGH IRRADIANCE {A}		0		10±0	15±0	20±10	0		30±10	35±2	40±0
DC±AC CURRENT at LOW IRRADIANCE {A}		0	5±0	5±0	7.5±0	10±5	0	12.5±6.3	15±7.5	17.5±8.8	20±0
START DATE (EXPERIMENT 2: UNAGED REFERENCE CONNECTORS)		2024/5/16	2024/5/17	2024/5/22	2024/6/27	2024/7/25	2024/8/13	2024/8/14	2024/8/20	2024/9/12	2024/10/10

Subtask 3.5 – The NREL project team will submit a manuscript on artificial weathering of PTC components to a peer reviewed journal.

The final Milestone for this project was a journal manuscript on cable jackets, Figure 18. The document primarily focused on the most recent C-AST D1 and K3 fixtures, but made reference and comparison to the earlier C-AST and IEC 62788-7-2 UV weathering experiments. The earlier work was referenced through the posters (published online) and the supplementary information (a companion slide deck, that will also be published through OSTI). Specimen characterizations covered in the manuscript include: optical microscopy, mechanical profilometry, instrumented indentation, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (XPS), Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC). The primary topics for the paper included the materials used in cable jackets, the degradations observed (accelerated testing and field aged cables), and the durability testing used with PV cables.



Manuscript
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Submitted to Solar Energy Materials and Solar Cells

Photovoltaic Cable Jackets –
Durability Lessons From the Industry and Accelerated Testing

David C. Miller, Rachael L. Arnold, Peter L. Hacke, Aubrey Jackson, Chun-Sheng Jiang, Steven C. Hayden, Helio Moutinho, Jimmy M. Newkirk, Greg Perrin, Laura T. Schelhas, Kent Terwilliger, Soňa Uličná*

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ABSTRACT

Photovoltaic (PV) cables facilitate the distribution of electricity collected from modules to the energy grid. Durable cabling enables continuous operation of PV installations, whereas cables with a lifetime less than the modules must be replaced—reducing electricity generation and adding to the operating expense. This study assesses the present state of the industry, including an industry survey, examination of degraded and failed cables obtained from utility PV installations, and accelerated testing of representative specimens. Cables for utility, building, and control/auxiliary applications were examined. Cable jacket materials examined include: polyolefin, polyethylene, polyamide, poly(vinyl chloride), chlorinated polyethylene, thermoplastic elastomer, and ethylene propylene diene monomer rubber. Combined-accelerated stress testing (C-AST) and International Electrotechnical Commission Technical Specification 62788-7-2 for ultraviolet weathering were used for accelerated aging. Specimen characterizations applied include: optical microscopy, mechanical profilometry, instrumented indentation, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC). A variety of performance and durability characteristics were observed, depending on the base material, polymer formulation, and jacket color. Recommendations are made for the screening, industry qualification, and service life prediction of PV cable jackets.

KEYWORDS
cable, DSC, durability, EDS, FTIR, International PV Quality Assurance Task Force (PVQAT), nanoindentation reliability, SEM, TGA, UV weathering, wire harness

Figure 18: First page from the manuscript submitted to SOLMAT.

Conclusions:

- Common degradation modes for connectors confirmed in this study include: an incomplete connection (not externally apparent), incompatible components (overheated in a steppe climate or corroded in a maritime location), and scorched components (most commonly observed and occurring at the connection between the metal pin and socket).
- The mode of scorched metal components was unexpected may result from (TBD): design, manufacturing, uncapped ends, vibration/bending, live disconnection, and/or CTE-misfit (abrasion). The cause will be examined in a follow-on study.
- In accelerated testing, connectors were found to be more delicate than cables. The durability of connectors is recommended for further examination and was subsequently prioritized in this project.
- The base materials of PE, PO, PA, PVC, CPE, EPDM, and TPE were confirmed relative to industry sources and literature. A greater variety of resins, fillers, colorants, chemicals, and cross-linking methods (temperature and e-beam) was found for PV cables relative to other packaging components.
- Observed degradation modes included: discoloration, delamination, and cracking. Both photodegradation and thermal aging observed from accelerated testing. Bad practices seen for field specimens included direct UV exposure (*e.g.*, where conduit or routing trays were not used), external abrasion (including from cable routing, vegetation maintenance, and animals) and the use of red colorant to indicate cable polarity.

- The variety and complexity of materials used in cable jackets necessitates vigorous durability testing, including extended sequential (IEC TS 63209-1) and combined-stress (IEC TS 63556) tests. The accelerated testing of cable connectors will be examined a follow-on project, with the goal of recommending improvements to capture the mode of scratched components.

All Milestones were completed. (See Table 1.)

Budget and Schedule:

Table 8 summarizes project spending for CPS A/N 38524 through 2024/12/31, from the most recent RPPR2 spreadsheet (updated 2024/10/11). In particular, the table reflects the No Cost Extension of the project towards the C-AST aging of the unaged reference connectors. An alternate tool (NREL MCCS PI Dashboard) suggests the remaining project unreserved funds are $28,782 as of 2024/10/14. These remaining funds will be used to complete the experiment in Table 7 and subsequent characterization of the connector specimens.

Table 8: Spending summary for CPS A/N 38524 through FY25Q1, from the RPPR2 summary spreadsheet (III. Spendplan worksheet in 38524 PV Miller FY24Q4.xls).

Project Spend Plan			Federal Share		
Quarter	From	To	Initial Plan	Actuals & Updated Plan	Cumulative
1	10/01/21	12/31/21	$ 121,208.00	$ 72,833.06	$72,833.06
2	01/01/22	03/31/22	$ 121,208.00	$ 68,892.45	$141,725.51
3	04/01/22	06/30/22	$ 121,208.00	$ 116,034.15	$257,759.66
4	07/01/22	09/30/22	$ 121,208.00	$ 125,850.11	$383,609.77
5	10/01/22	12/31/22	$ 125,548.00	$ 113,285.43	$496,895.20
6	01/01/23	03/31/23	$ 125,548.00	$ 150,958.42	$647,853.62
7	04/01/23	06/30/23	$ 125,548.00	$ 127,597.03	$775,450.65
8	07/01/23	09/30/23	$ 125,548.00	$ 138,971.49	$914,422.14
9	10/01/23	12/31/23	$ 128,244.00	$ 91,043.62	$1,005,465.76
10	01/01/24	03/31/24	$ 128,244.00	$ 123,638.23	$1,129,103.99
11	04/01/24	06/30/24	$ 128,244.00	$ 126,238.51	$1,255,342.50
12	07/01/24	09/30/24	$ 128,244.00	$ 214,531.43	$1,469,873.93
13	10/01/24	12/31/24		$30,126.07	$1,500,000.00

Scope Issues:

Regarding “Obtain additional BoS field-specimens”, NREL received the originally intended number of separate instances of field degraded samples early into this project. DOE requested at the time of start of this project was to obtain cable connector samples from the field site inspections under Sandia/EPRI CPS #38531. Note this request is outside of our own control We note that in addition to the Sandia project, more samples from separate case studies could have been obtained from the IIG if needed.

While accelerated testing was delayed to achieve more application relevant aging and with chamber breakdowns, the results of C-AST aging stand out as a success – we were able to distinguish types and materials for cable jackets as well as to distinguish between locations for uncapped connectors. The presentation of the results at conferences and workshops also proved not entirely predictable. Sandia submitted for a technical session (similar to a small workshop) at the RE+ conference in Las Vegas, NV from 2023/9/11 - 2022/9/14. We hoped to present at the event, however, it did not get selected for the RE+ conference. We updated our poster (from IEC 62788-7-2 A3 weathering only) from the PVRW 2023 for presentation at the Asian PVSEC from 2023/11/06 – 2023/11/10 (to now compare A3 weathering to C-AST); the posters were published in OSTI as an NREL "reports", NREL/CP-5900-87918 and NREL/PO-5K00- 86969. We also presented the findings of the recently submitted PV connectors manuscript at the NIST/UL workshop on 2023/12/05. We gave an oral presentation on PV connectors at the PVRW (2024/2/29), then the monthly DuraMAT webinar (2024/5/13 https://www.youtube.com/watch?v=Zti2Pf-nEt0, now also published in OSTI as an NREL "report", NREL/CP-5900-87599).

The project pivoted towards PV connectors, for reasons including the substantive industry interest (as the #1 cause of fires in PV systems), the observation of the lesser robustness of connectors relative to cables, during accelerated aging, and the opportunity to independently verify degradation and failure modes identified by the industry. PV connectors journal manuscript, including from the PVQAT effort, was published in IEEE J PV at https://ieeexplore.ieee.org/document/10596700. We presented on connectors at the EPRI cable connectors workshop (2024/7/17). The characterization and forensics of the uncapped connectors experiment leaves content of strong interest that might be presented during the follow-on AOP project, starting in FY25.

Path Forward:

A follow-on project is anticipated as CPS 52774 (to Sandia) and 52802 (subcontract to NREL) for FY25-FY27. From the findings of the present project, NREL's effort will prioritize durability of cable connectors (found to presently be less durable than cables). We hope to demonstrate and give recommendations for chamber accelerated testing that may identify the scorched pin/socket. From PVQAT TG10, we became aware of issues with the durability of rapid shutdown devices (RSD), including several recent fires in rooftop PV systems. We will work with C-AST aging of RSDs to help identify component(s) commonly failing to give recommendations to improve the situation. We anticipate there will be an opportunity to examine cable ties after accelerated testing to give perspective on different grades of component material. Working with Sandia, we expect there will be opportunities to learn more about the durability of cables.

Publications Resulting from This Work:

This section lists products resulting from work under this program. These products include publications in refereed journals (Table 9), and conference papers and presentations (Table 10).

Table 9: Refereed journal articles produced under this program. Articles are listed in alphabetical order by first author. Each entry is followed by a link to the open access version of the article and to the article on the publisher's site. Some articles are collaborations between institutions or programs, as detailed in acknowledgements section of those articles.

Paper	Open Access Link	Journal link
P1. David C. Miller, Rachael L. Arnold, Peter L. Hacke, Aubrey Jackson, Chun-Sheng Jiang, Steven C. Hayden, Helio Moutinho, Jimmy M. Newkirk, Greg Perrin, Laura T. Schelhas, Kent Terwilliger, Soňa Uličná, "Photovoltaic Cable Jackets - Durability Lessons From the Industry and Accelerated Testing".	anticipated: https://www.nrel.gov/docs/fy25osti/91451.pdf	submitted, in review
P2. David C. Miller, Rachael L. Arnold, Peter L. Hacke, Chun-Sheng Jiang, Steven C. Hayden, Helio Moutinho, Jimmy M. Newkirk, Greg Perrin, Laura T. Schelhas, Kent Terwilliger, Soňa Uličná, Chuanxiao Xiao, "Photovoltaic Cable Connectors - A Comparative Assessment of the Present State of the Industry"	https://www.nrel.gov/docs/fy24osti/87599.pdf	https://doi.org/10.1109/JPHOTOV.2024.3414178

Table 10: Conference products, such as proceedings papers and presentations, created under this program. Products are listed in alphabetical order by first author. Each entry is followed by the conference name, the product type, and a link to the product if one is available.

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
C1. David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Steven C. Hayden, Aubrey Jackson, Helio Moutinho, Jimmy Newkirk, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná, Weston Wall, Chuanxiao Xiao	PV Connector Reliability: Lessons from Advanced Diagnosis and Accelerated Testing of Balance of System Components for Utility Scale PV Installations	Sandia-EPRI PV Connector Workshop	Oral Presentation	7/17/2024	https://energy.sandia.gov/programs/renewable-energy/photovoltaic-solar-energy/projects/pv-connectors/workshops-and-presentations/
David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Steven C. Hayden, Aubrey Jackson, Helio Moutinho, Jimmy Newkirk, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná, Weston Wall, Chuanxiao Xiao	Photovoltaic Cable Connectors: A Comparative Assessment of the Present State of the Industry	DuraMAT webinar	Webinar Presentation	5/13/2024	https://www.youtube.com/watch?v=Zti2Pf-nEt0, https://www.nrel.gov/docs/fy24osti/87599.pdf

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
David MILLER, Laurie BURNHAM, Bruce KING, Andy WALKER	PV Balance of Systems Component Reliability (CPS's 38524 and 38531)	DOE SETO Peer Review	Oral Presentation	3/27/2024	?
David Miller	Scorched metal pins were frequently observed on field degraded PV cable connectors in addition to several known degradation modes	DOE SETO Peer Review	Poster Presentation	3/26/2024	https://app.box.com/s/n8myewgcvbw9ung10j9okw93k68m2626
David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Steven C. Hayden, Helio Moutinho, Jimmy Newkirk, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná, Weston Wall, Chuanxiao Xiao	Photovoltaic Cable Connectors: A Comparative Assessment of the Present State of the Industry	NREL PVRW 2024	Oral Presentation	2/29/2024	https://pvrw.nrel.gov/past-proceedings
David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Steven C. Hayden, Helio Moutinho, Jimmy	Photovoltaic Cable Connectors: A Comparative Assessment of the Present State of the Industry	NIST-UL Workshop on Photovoltaic Materials Durability	Oral Presentation	12/5/2023	N/A

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
Newkirk, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná, Weston Wall, Chuanxiao Xiao					
David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Helio Moutinho, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná	Accelerated aging of PV cables - the development of methods towards combined-accelerated stress testing	Asian PVSEC 2023	Poster Presentation	11/6/2023 - 11/10/2023	https://www.nrel.gov/docs/fy24osti/86969.pdf
David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Helio Moutinho, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná	Accelerated aging of PV cables - the development of methods towards combined-accelerated stress testing	NREL PVRW 2024	Poster Presentation	3/2/2023	https://www.nrel.gov/docs/fy24osti/87918.pdf

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
C1. David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Steven C. Hayden, Aubrey Jackson, Helio Moutinho, Jimmy Newkirk, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná, Weston Wall, Chuanxiao Xiao	PV Connector Reliability: Lessons from Advanced Diagnosis and Accelerated Testing of Balance of System Components for Utility Scale PV Installations	Sandia-EPRI PV Connector Workshop	Oral Presentation	7/17/2024	https://energy.sandia.gov/programs/renewable-energy/photovoltaic-solar-energy/projects/pv-connectors/workshops-and-presentations/
David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Steven C. Hayden, Aubrey Jackson, Helio Moutinho, Jimmy Newkirk, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná, Weston Wall, Chuanxiao Xiao	Photovoltaic Cable Connectors: A Comparative Assessment of the Present State of the Industry	DuraMAT webinar	Webinar Presentation	5/13/2024	https://www.youtube.com/watch?v=Zti2Pf-nEt0, https://www.nrel.gov/docs/fy24osti/87599.pdf

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
David MILLER, Laurie BURNHAM, Bruce KING, Andy WALKER	PV Balance of Systems Component Reliability (CPS's 38524 and 38531)	DOE SETO Peer Review	Oral Presentation	3/27/2024	?
David Miller	Scorched metal pins were frequently observed on field degraded PV cable connectors in addition to several known degradation modes	DOE SETO Peer Review	Poster Presentation	3/26/2024	https://app.box.com/s/n8myewgcvbw9ung10j9okw93k68m2626
David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Steven C. Hayden, Helio Moutinho, Jimmy Newkirk, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná, Weston Wall, Chuanxiao Xiao	Photovoltaic Cable Connectors: A Comparative Assessment of the Present State of the Industry	NREL PVRW 2024	Oral Presentation	2/29/2024	https://pvrw.nrel.gov/past-proceedings
David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Steven C. Hayden, Helio Moutinho, Jimmy	Photovoltaic Cable Connectors: A Comparative Assessment of the Present State of the Industry	NIST-UL Workshop on Photovoltaic Materials Durability	Oral Presentation	12/5/2023	N/A

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
Newkirk, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná, Weston Wall, Chuanxiao Xiao					
David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Helio Moutinho, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná	Accelerated aging of PV cables - the development of methods towards combined-accelerated stress testing	Asian PVSEC 2023	Poster Presentation	11/6/2023 - 11/10/2023	https://www.nrel.gov/docs/fy24osti/86969.pdf
David Miller, Rachael Arnold, Peter Hacke, Chun-Sheng Jiang, Helio Moutinho, Greg Perrin, Laura Schelhas, Kent Terwilliger, Soňa Uličná	Accelerated aging of PV cables - the development of methods towards combined-accelerated stress testing	NREL PVRW 2024	Poster Presentation	3/2/2023	https://www.nrel.gov/docs/fy24osti/87918.pdf