DuraMAT
Durable Module Materials Consortium

Evaluating the Durability of Balance of Systems Components Using Combined-Accelerated Stress Testing

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Updated from Miller et. al., Proc. DuraMAT Work. 2022, Tuesday, 2022/8/30.

IEA PVPS Task 13 Meeting; Sub-Task 1.3: The impact of load factors; the future of accelerated testing

Remote presentation to: Saalbau Griesheim, Frankfurt am Main, DE

Thursday, 2022/10/06 03:55-04:15 MT

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The Motivation for the BoS Study

- BoS components include: cable connectors, cables, **branch connectors**, *fuses (discrete)*, fuse blocks.

- Quantifiable replacement rate for t < 25y! 50y use TBD.
  -2 DOE AOP projects presently examining: components, occurrence, cost.
  (CPS/N: 38524 @ NREL; 38531 @SNL)

Example of PV fires in Italy.
Fiorentini et. al., PVRW 2020.
https://www.nrel.gov/docs/fy21osti/80055.pdf

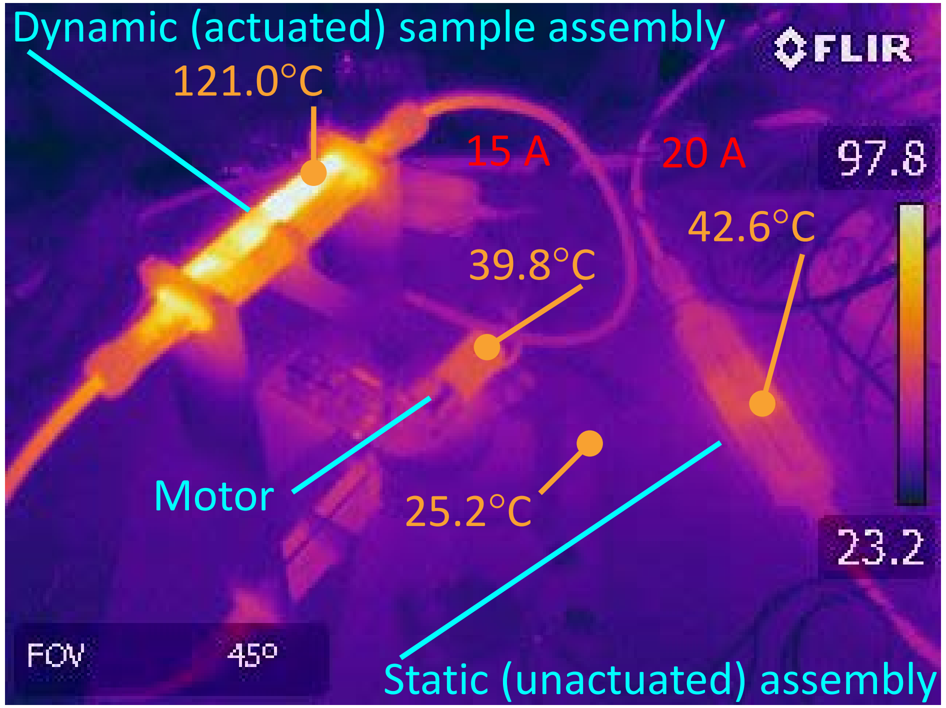
- Consequences of degradation and failure include:
  offline-modules, -strings, -inverters;
  system shutdown; arc fault; and fire!!!

Look For in This Presentation

In C-AST (today) and benchtop (previously):

-External mechanical perturbation greatly affected the result-

- How is accelerated testing implemented?
- What component(s) are affected?
- How to further validate the result?



Miller et. al., IEEE J PV, https://doi.org/10.1109/JPHOTOV.2022.3205154.

Branch Connectors: The Scenario

Examples of PV branch connectors.

- Utility provider experienced ~30% failure rate in their power transfer chain, attributed to branch connectors.
  - -“Failure” means overheating, softening, physical distortion.
  - -Distinct ΔT in thermographic imaging.
  - -Worst consequences: broken circuit, arc, fire.
- Component makes & models kept confidential in this presentation.

Branch Connectors: The Approach

Examples of PV branch connectors.

- Compare **C-AST** (here) to UL standard tests (Mike KEMPE).
- # and contribution of damage susceptible components unknown.
  Evaluate all adjoining components: cable connectors, branch connectors, fuse.

- Develop fixture and software using benchtop experiments (1 replicate, previously).
- **Use custom C-AST fixture for mechanical actuation (6 replicates).**

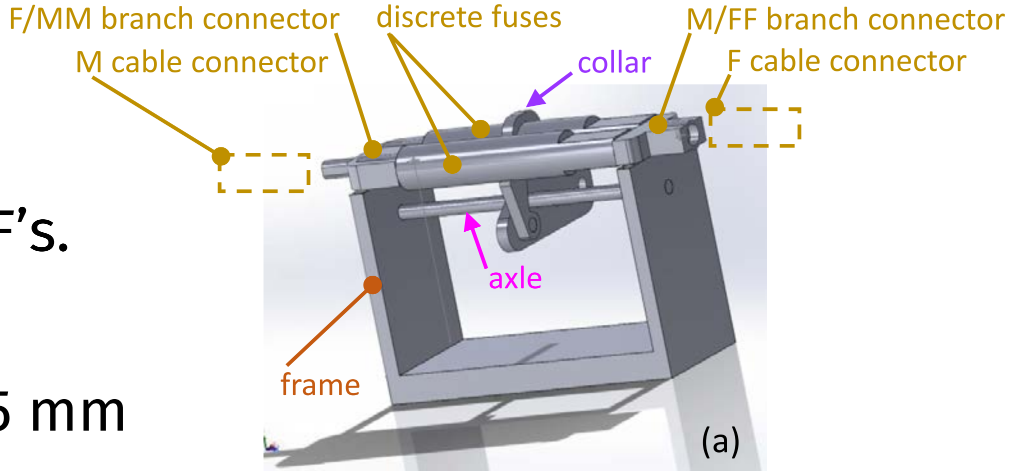
An Integrated Push/Pull Mechanical Fixture Was Used for “Dynamic” Specimens

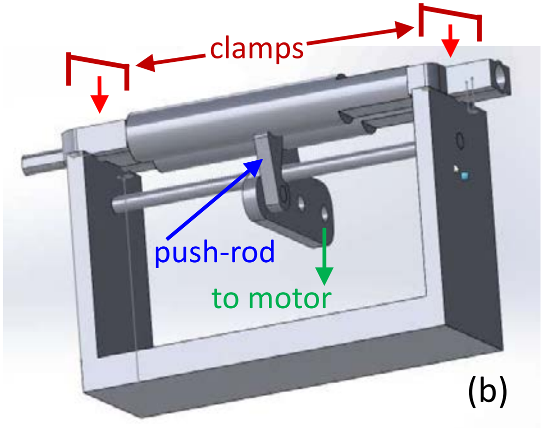
- PV installations: cantilevered from cable → multiple DoF’s.
- “Collar and push-rod” design concept selected.
- Deflection used: 3 mm (initial) → 1 mm (benchtop) → 0.5 mm (C-AST, *this presentation*).

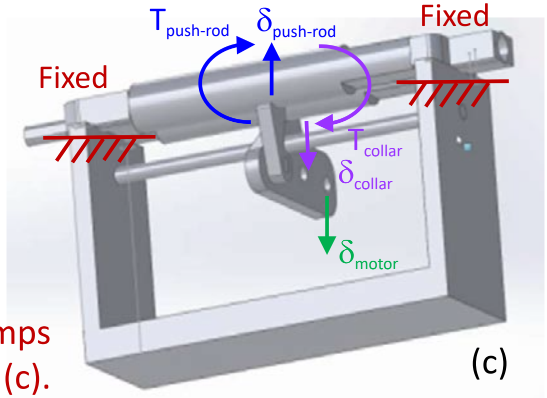
- Benchtop version run with 0.27 Hz rotary DC motor.
- C-AST: perturbation depends on sequence.

EXPERIMENT	SEQUENCE NAME	PERTUBATION DURATION {s}	REST PERIOD (BETWEEN PERTURBATIONS) {s}	CYCLE PERIOD {s}	DUTY CYCLE (ON:TOTAL) {%}	# CYCLES·RUN^{-1} {dimensionless}
benchtop	continuous	1.9	1.9	continuous	50	to failure
C-AST	Winter-1	1	7	8	13	7985
C-AST	Winter-2	2,438	0	2,438	100	5
C-AST	Spring	1,817	0	1,817	100	49
C-AST	Tropical	3	6	9	33	4790
C-AST	Desert	90	0	90	100	2776

Comparing the mechanical actuation in the benchtop and C-AST experiments.

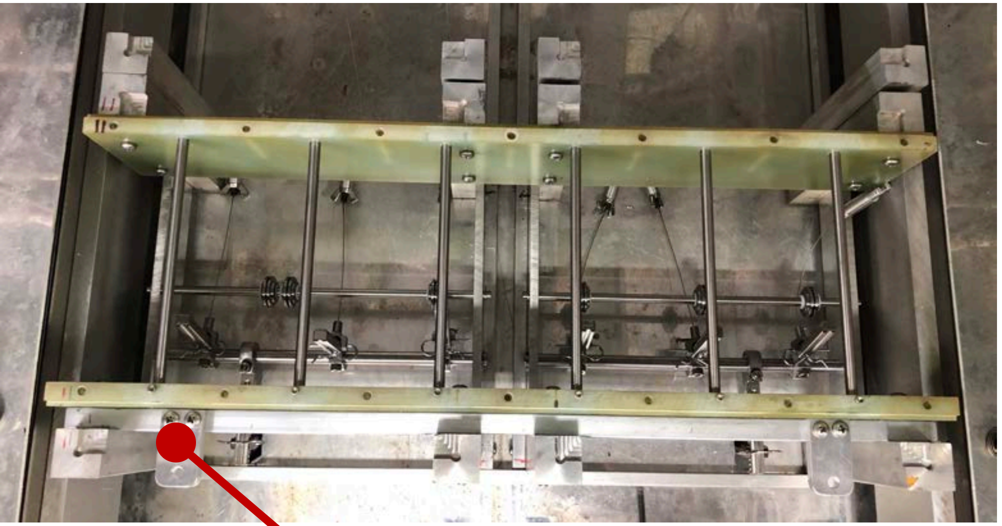






Solid model representation, including: the location of the BoS components in (a); the location of end clamps used to hold the specimen assembly in (b); the mechanical effects of moving components in (c).

The Approach for the C-AST Experiments



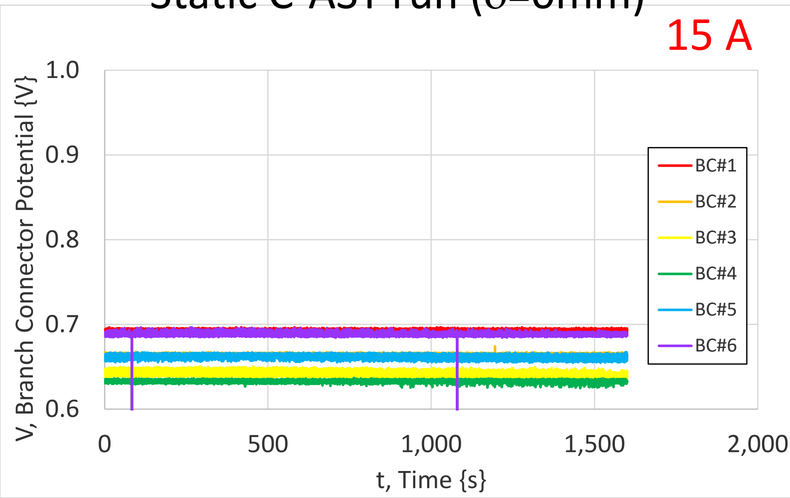
The 1x6 C-AST fixture uses a system of displacement adjustable pulleys.

- Separate static and dynamic specimen runs, in same 1x6 fixture.
- Start at 10 A, in case of strong environmental effect.
- Repeat at 15 A (dynamic benchtop failure current).
- 4 complete C-AST runs
  (Winter → Spring → Tropical → Desert).
- Data sets: Live, binned, read point.

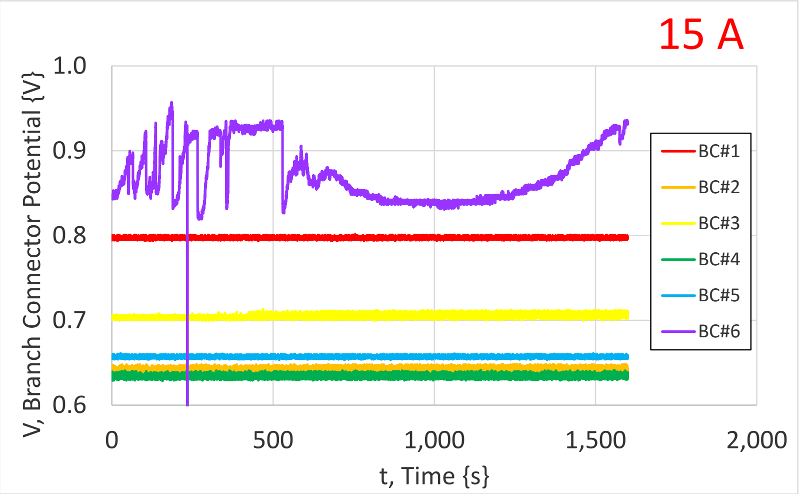
C-AST Live I-V: Mechanical Actuation Readily Affected Test Results

- Live measurements obtained at 10 Hz, 500 Hz, 10kHz.
- Voltage varied for current-controlled dynamic samples.
- Specimen temperature ∝ V (resistive heating).
- 2-3 assemblies typically ran hotter than others.
- *Transient* behavior observed for hottest specimens (10’s of seconds).

Static C-AST run (δ=0mm)



Dynamic C-AST run (δ=0.5 mm)



Live in-situ voltage monitoring (burst mode), early in the C-AST Tropical sequence.

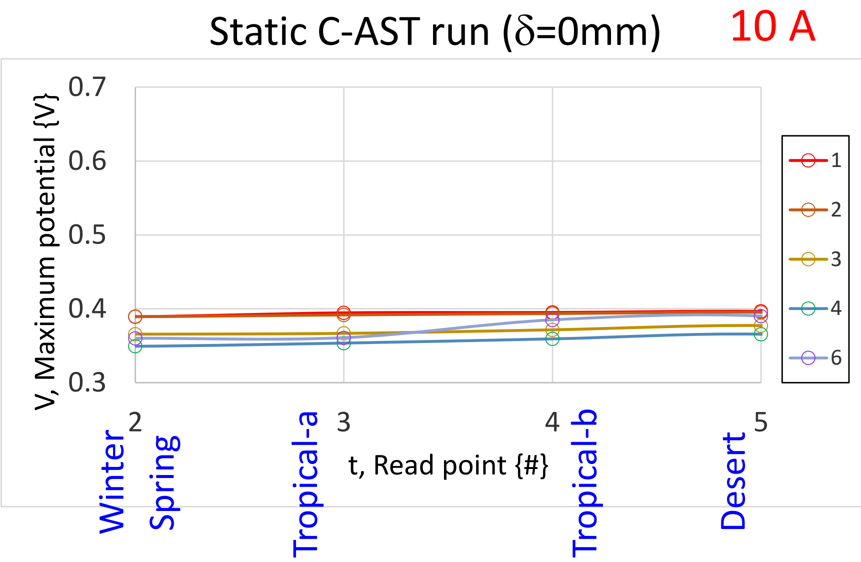
C-AST Binned I-V: Mechanical Actuation Readily Affected Test Results

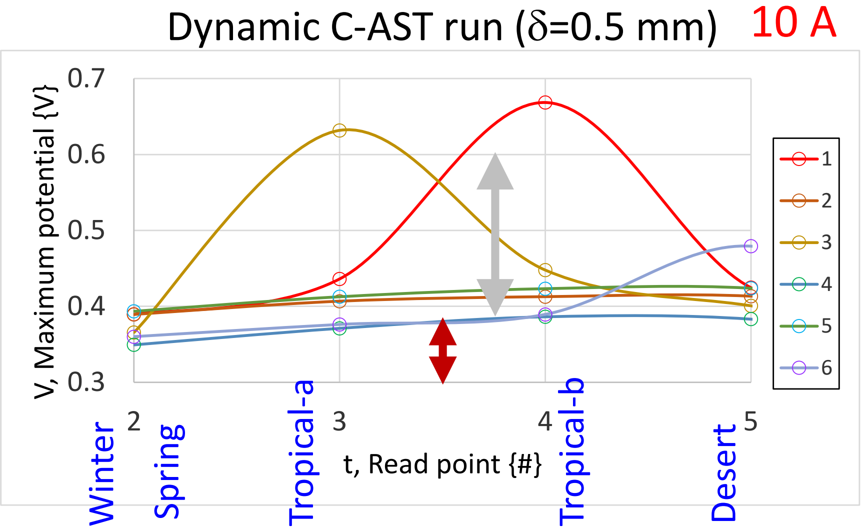
- In-situ monitoring analyzed in 1-minute bins.
  - -Instantaneous (hottest) events not captured.

- *Stochastic*: V_{max} varied with read point for specimen assemblies.

- Tropical & Desert sequences stand out.
  - -Both: elevated T
  - -Tropical: elevated RH %, water spray, greater # mechanical cycles

- Winter & Spring sequences give minimal effect.
  - -Winter: no light (or current).
  - -Spring: intermediate light (and current).





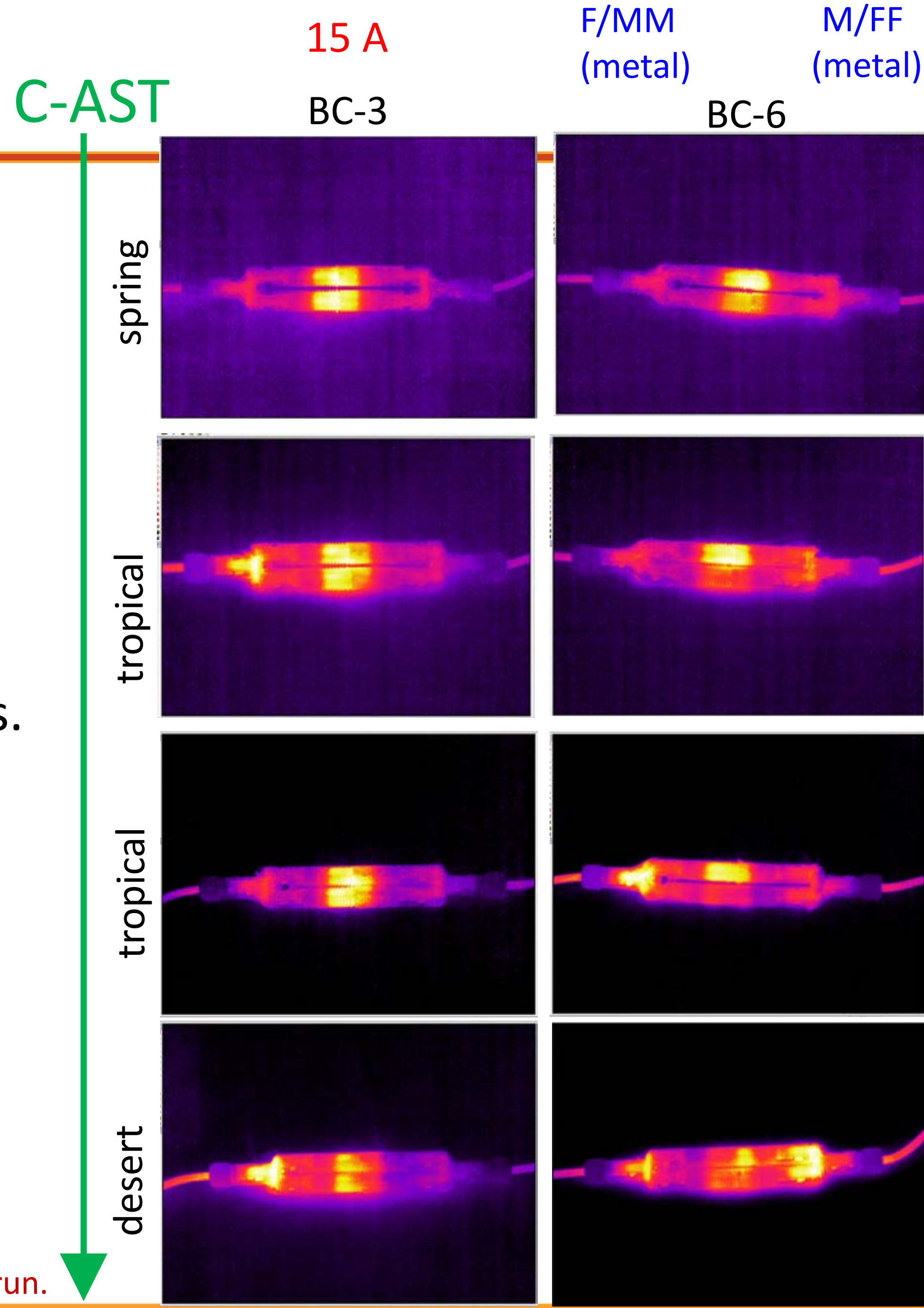
Sensitivity to the combined factors of temperature and humidity (C-AST Tropical sequence) as well as elevated temperature (C-AST Desert sequence) are implied from the binned in-situ voltage monitoring.

Read Point Characterizations: Accumulated Degradation Observed

- Characterizations at the end of each C-AST sequence:
  - R_{series} (2 wire multimeter).
  - T_{max} (from IR image).

- R_{series}, T_{max} increased from Desert-1 (10 A) onwards (not shown).
  - Suggests damage accumulation.
  - Limited correspondence between read points and in-situ results.

- Location of T_{max} evolved through 15 A dynamic run.
  - Initially hottest in filament cartridge in discrete fuses
  - 5/6 specimens effected:
    - 3/6: F/MM (metal pin) hottest.
    - 2/6: M/FF hottest.



Representative IR images through dynamic 15 A C-AST run.

The Destructive Failure Analysis Procedure Following XCT

1. Remove (mill) external plastic.
   - -Retain for polymer F/A (FTIR, DSC).
   - -Inspect internal metal components relative to XCT.
   - -Methods: camera, optical microscopy, SEM/EDS.

2. Extract (unfold) convolute spring from F metal pins.
   - -Inspection, methods as above.

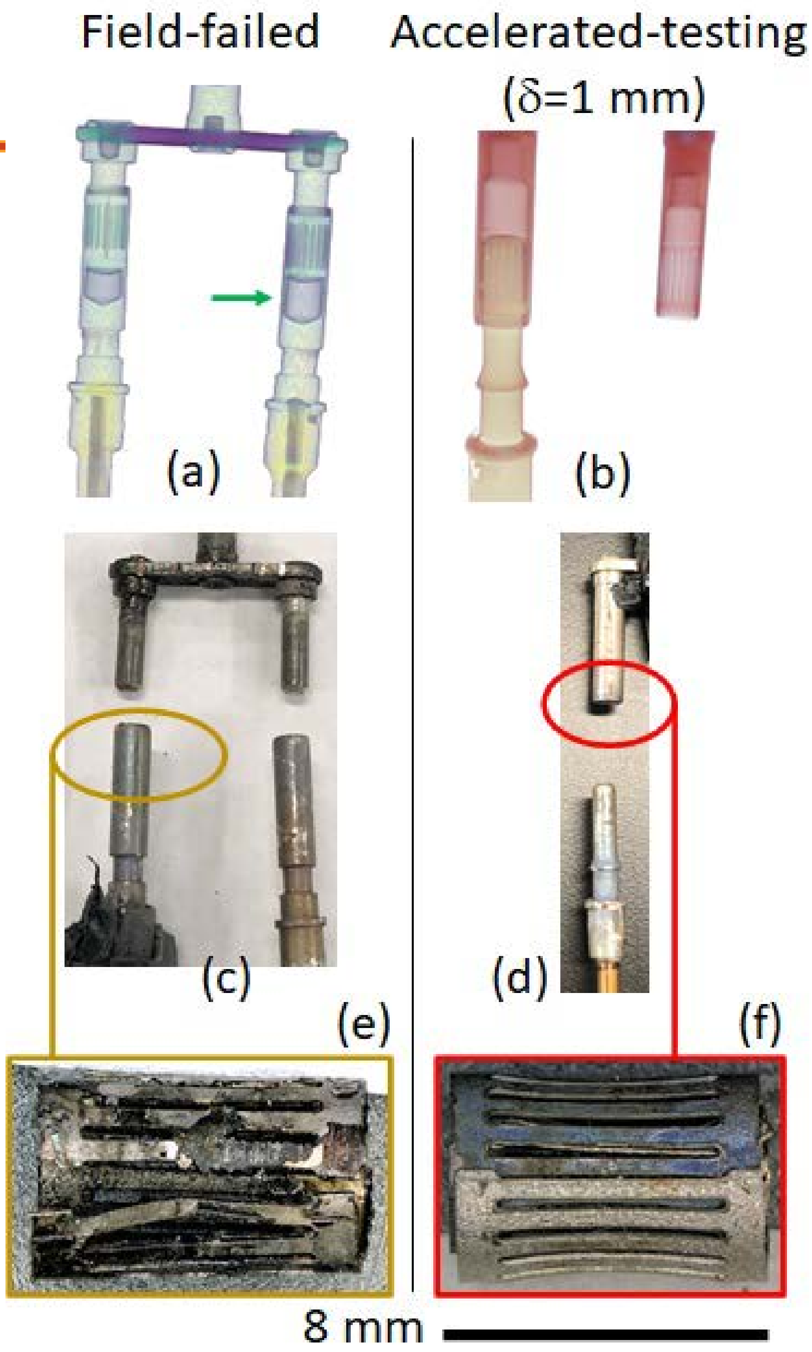
convolute spring, extracted from unaged metal pin

~8 mm

Failure Analysis Points to Convolute Spring Component, Identifies Multiple Degradations.

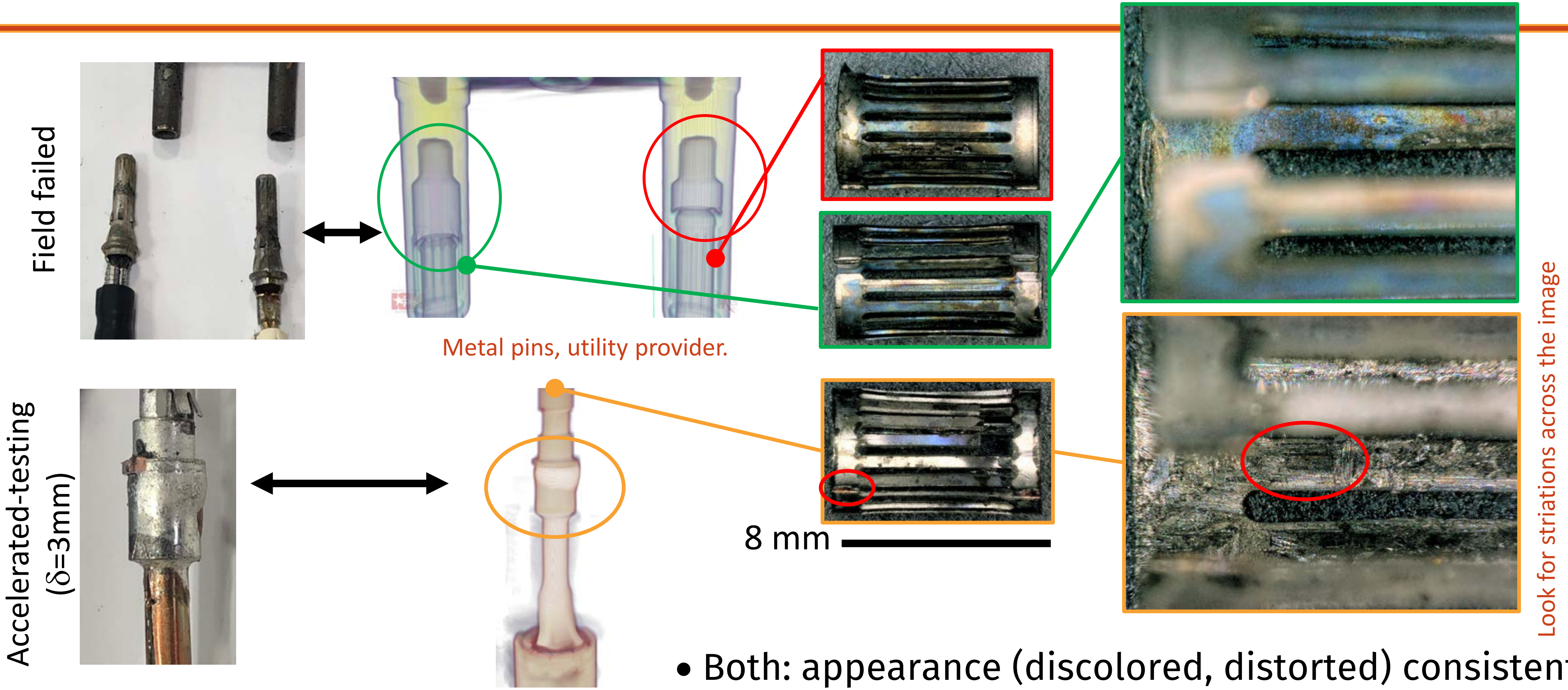
- Iterative F/A performed before and after removing external plastic, then convolute spring.
- Hottest location much easier to identify without the plastic!

- Field and benchtop specimens failed at convolute spring (different than utility provider's suggested location).
- Degradation modes observed:
  - -Melting and reflow of solder.
  - -Oxidation (with surface discoloration)
  - -Vaporization (e.g., from localized electrical arcing).
  - -Corrosion.
  - -Inelastic deformation (longitudinal and circumferential).
  - -Abrasion (?large δ only?).



Comparison of field-failed (left) and benchtop-failed (right, for δ=1 mm) specimens, including: XCT prior to removing the exterior plastic, (a) and (b); visual appearance after removing the exterior plastic, (c) and (d) ; and optical micrographs of the convolute springs, (e) and (f).
From Miller et. al., IEEE J PV, https://doi.org/10.1109/JPHOTOV.2022.3205154.

Optical Micrscopy: Oxidation of Spring, with Mechanical Wear for δ = 3 mm



Metal pins, utility provider.

Metal pins, benchtop δ = 3 mm.

- Both: appearance (discolored, distorted) consistent with XCT.
- Discoloration suggests oxidation of convolute springs. (ΔT).
  - -More localized discoloration in benchtop specimen.
- Striations (ends, interior) suggest wear during accelerated test.

from https://www.nrel.gov/docs/fy22osti/81456.pdf

Remember From This Presentation

-External mechanical perturbation greatly affected the result.-

- How is accelerated testing implemented?

  -sample integrated push/pull mechanical fixture

- What component(s) are affected?

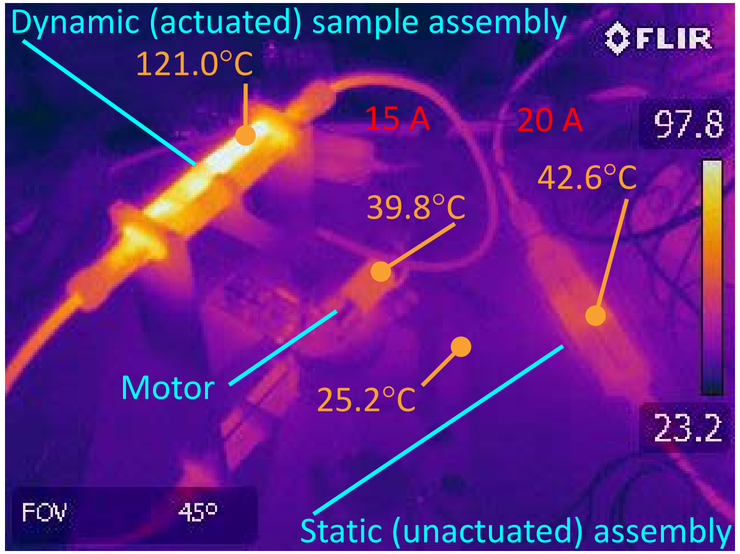
  -static: fuse (internal).

  -with actuation: BC /fuse (observed for field).

- How to further validate the result?

  -Iterative failure analysis (nondestructive → destructive).

  -Multiple degradation modes observed!



Miller et. al., IEEE J PV, https://doi.org/10.1109/JPHOTOV.2022.3205154

Pros and Cons of C-AST

Pros:

- Ability to a-priori screen degradation modes. 10’s of examples already for PV backsheets, encapsulants, cells, interconnects, now BoS.
- C-AST or test sequences can enable degradation that steady state cannot. Strong recent examples.

Cons:

- No consensus on application (rack, BAPV), environments (tropical, desert, …), use level to target.
  - Stressor levels and duration of sequences would benefit from continued development.
  - $3\sigma + 3\sigma + 3\sigma + \ldots \rightarrow$ -might be- $\rightarrow \geq 5\sigma$.
- Presently limited to MiMos and coupon specimens.
  - Full-sized modules can have their own manufacturing & quality issues.
  - Equipment and operating expense.
- Validation and rate modeling not yet fully addressed.
  - Requires extended outdoor weathering (auto paint ≥2y), steady state accelerated aging (UV, T, %RH).

Presenter's Question

RE: Accelerated testing, what are your recommendations for content to cover in the IEA Activity 1.3 Task 13 PVPS report?

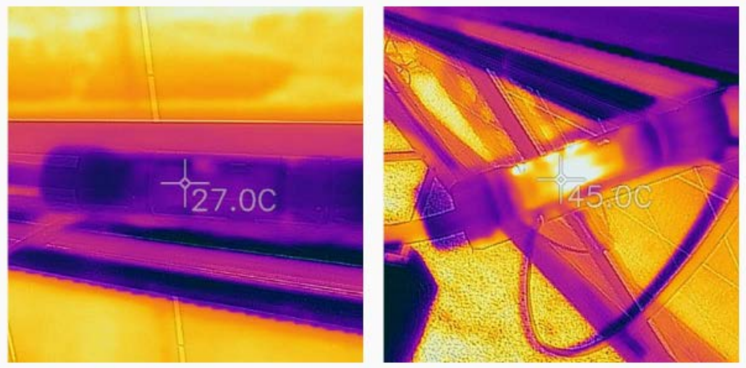
BoS Reliability Projects and PVQAT TG10

- There are separate 3y AOP projects at NREL, Sandia about BoS components, including: connectors, cables, cable ties, …

- Monthly PVQAT TG10 web group meetings on the state of the industry as well as feedback on testing and results.

- Collaborators needed for on-site PV installation inspections.

- Collaborators needed for degraded/failed specimens.



Infrared inspection of intact (left) and degraded (right) cable

Cracking of tracker cable at the controller box.

- All participants welcome!!!

Please inquire to: Laurie BURNHAM lburnha@sandia.gov; David MILLER David.Miller@nrel.gov

Also: https://energy.sandia.gov/programs/renewable-energy/photovoltaics/pv-systems-and-reliability/pv-connectors/

PVQAT International PV Quality Assurance Task Force

Acknowledgements

👍 Thanks to:

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The views expressed in the presentation do not necessarily represent the views of the DOE or the U.S. government. Instruments and materials are identified in this paper to describe the experiments. In no case does such identification imply recommendation or endorsement by LBNL, NREL, SLAC, or SNL.

NREL STM campus (Dennis Schroeder)

👉 Please submit your questions/comments or contact: David.Miller@nrel.gov

NREL/PR-5K00-84230

Aging Using Combined-Accelrated Stress Testing (C-AST)

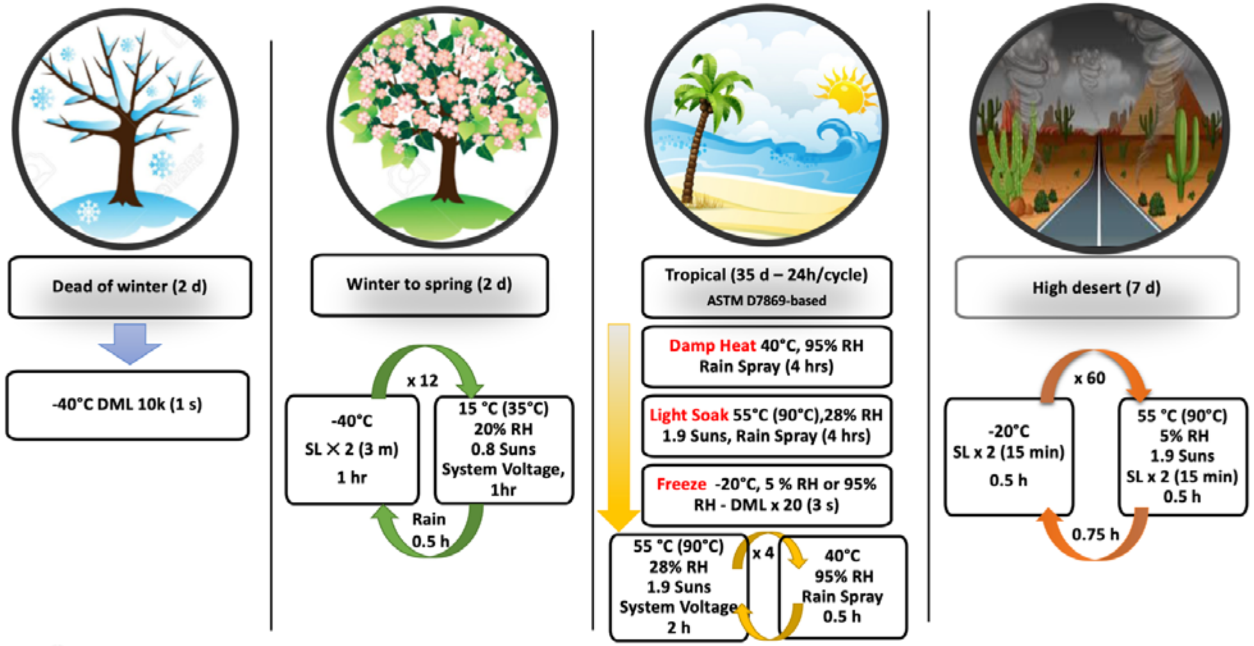
- Approach: steady-state weathering enables rate modeling; combined stressors (and/or sequence) allows a-priori screening of degradation modes.
  - -Spataru et. al., Proc. WCPEC, 2018, 3943-3948, 10.1109/PVSC.2018.8547335.

- Tropical sequence is based on ASTM D7869 (degradation of clearcoat automotive paints in Miami)
  - -Nichols et. al, J Coat. Technol Res., 10, 2013, 153–173, https://doi.org/10.1007/s11998-012-9467-x.

- Four sequences/C-AST run.

- Stressors:
  - -UV-VIS radiation (levels: high, middle, none)
  - -Temperature (-40 – 90 °C, $\text{MiMo}_{\text{specimen}}$, up to 95 °C for BoS)
  - -RH (0-95%, chamber)
  - -Water spray (intermittent)
  - -External mechanical perturbation (by sequence)
  - -Electrical current (by levels, with light)
  - -Electrical potential (±1000 V)

- In-situ characterization (this study):
  - -I, V, T (per specimen)



Summary of the Winter → Spring → Tropical → Desert sequences in C-AST.