NREL
Transforming ENERGY

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

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*Updated from UL-NIST 2023, PVRW 2024 workshops

DuraMAT webinar
Monday, 2024/5/13, 1:00-200 MT
https://www.duramat.org/news-and-events/webinars

Today's Presentation

Background (motivation, PVQAT survey on industry)

Experimental details (samples, failure analysis protocol, methods examples)

Results:

- Field degraded connectors: *primary*, metallic & polymeric components)
- Accelerated aged connectors: *secondary*, metallic & polymeric components)

Wrapping up (solutions, summary, acknowledgements)

Questions and comments welcome, e.g., end of each section.

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Motivation

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

- BoS components include: **cable connectors**, cables, branch connectors, fuses (discrete & blocks), RSD's.

- Quantifiable ($\leq$ x %$\cdot$y^{-1}) replacement rate for t < 30y! *50y use TBD*.
  -2 DOE projects presently examining: components, occurrence, cost.
  (CPS/N: 38524 @ NREL; 38531 @SNL). References: see PVRW 2024.

- Consequences of degradation and failure include:
  offline-modules, -strings, -inverters;
  system shutdown; arc fault; and fire!!!
- Concerns: *availability, safety, and technology adoption.*

Fielded Connectors: Common Degradation Modes and Scorched Metal Pins

Q:"What degradation modes dominate PV cable connectors in today's industry?"

A: PVQAT (*survey & specific meetings*): **incompatible makes**, **improper assembly**, **uncapped ends**, … also … incomplete connection, improper sizing, and improper mechanical fastening.

- Featured today: incomplete connection, incompatible makes, **scorched plug & socket**.
  - -**Scorched metal pins**: majority of field samples, unexpected, remains to be reconciled.

Field degraded & failed cable connectors:

- Nondestructive failure analysis.
- Destructive failure analysis.
  - -Metallic  and polymeric  components.

PVQAT Survey: Dominant Degradation/Failure Modes

- **Connector incompatibility**: plug and socket are cross-mated between different manufacturers and/or models. Present preventative NEC, IEC standards initiatives.

- **Improper assembly**: not built correctly. Often field assembly @ home run, including: stripping jacket, crimp tool, fitting of parts, torquing to specification.

- **Uncapped ends**: ends left open to the environment. Separate mechanical and electrical installation steps common. Contamination and corrosion suspected.

- **Incomplete connection**: connector not properly engaged, but visible seem fitted.

- **Improper sizing of connector to cable**: compromised seal against H_2O.

- **Improper mechanical fastening to system**: (1) connectors cantilevered from the cable. May void the manufacturer's warranty. (2) cable ties crush the connector.

- **Live disconnection**: active connector separated, then reconnected for continued use.

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The Degraded Connector Specimens Used in Forensics Examination

Highlights:

- Samples obtained from new and prior collaborators, including PVQAT TG10.
  - -Detailed forensics: >50/118 samples.

- Mostly two manufacturers (a & b).
  - -Market share (quantity).
  - -Design (straight spring)?

- Mostly *warm* climates.
  - -Donated specimens, not targeted locations.
  - -Desert and monsoon/savanna climates missing.

- Compare to accelerated tests.

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
Golden, CO	5	BSk (steppe)	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	**118**	**5 + *4***	**5**

Forensic Examination in This Study

• A protocol for nondestructive then destructive failure analyses was developed from this project.

Nondestructive: keep plug/socket connected, as-received.

Destructive: iterative.

Highlights:

⇒ Custom R-I sweep all connectors, including short leads.

• XCT allows metal pins and crimp to be examined without cutting the specimen.

• Traditional epoxy potting and polishing is useful.

-Unconventional- methods applied here (milling plastic, extracting convolute spring for greater area of examination, and hot melt wax for ease of specimen handling).

Field selection:
tripped inverter/thermography/visual inspection

↓

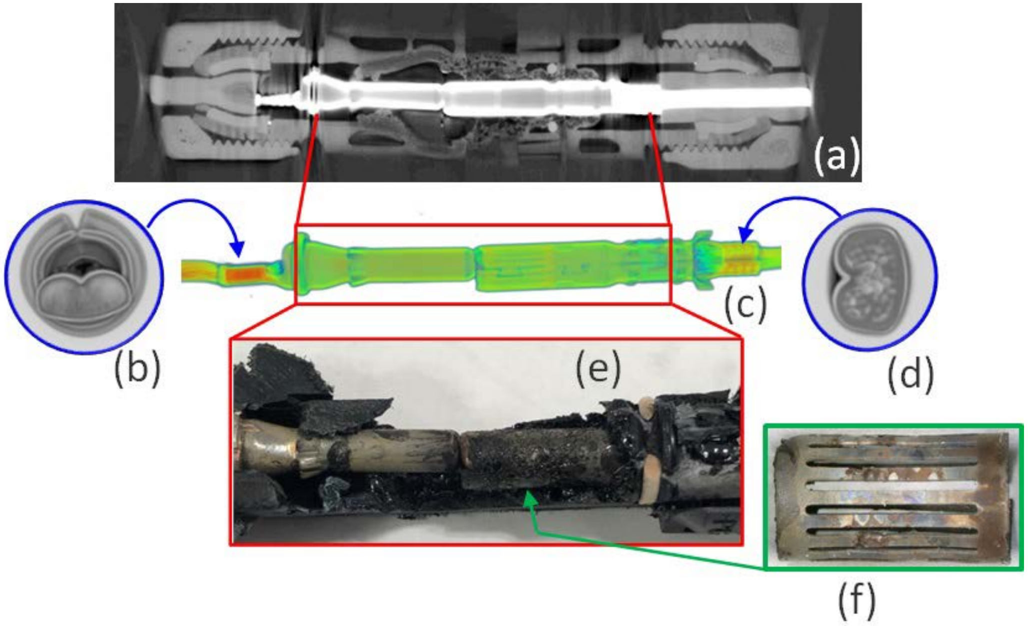
Nondestructive failure analysis:
Optical photography
R-I sweep (*low through high current*)
Wet HiPot
XCT
-metal pins
-crimps (pin to cable)

↓

Destructive failure analysis:
1. Remove exterior plastic
   Optical photography
   FTIR, TGA, DSC
2. Extract convolute spring
   Optical microscopy
3. Cross-section and polish metals
   SEM morphology
   EDS composition

An Early Specimen Motivated R-I Characterization

- •Outward blister (mm's) on plastic socket.
- •Externally: plug and socket fit together without physical separation.
- •R of 90 mΩ in 2-wire measurement.
- •Crimped metal folded over, no extruding wire strands, no extra space inside crimp.



A field-degraded connector: (e) photograph of deconstructed pin and socket as well as XCT cross-sections of: (a) the entire connector; (c) the detail of the metal pin and socket; (b) and (d) crimp site on the metal pins; and (f) the convolute spring.

- •"Incomplete connection".
- •Field assembly suspected – metal pin(s) not seated correctly/inactive alignment features.
- •Primary damage occurred between metal pins rather than in the crimps.
- •Early basis for R-I sweep (10's of A as in PV system, rather than 1 mA test current).

Features Observed in Field Degraded Connectors

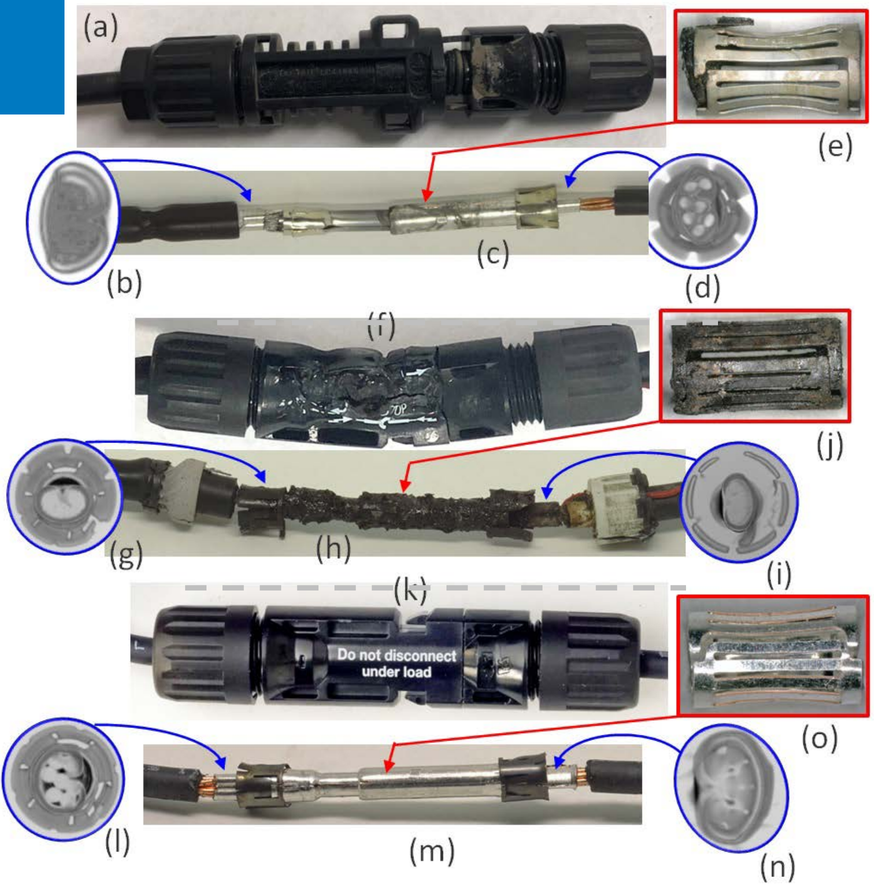
- (a)-(e): incompatible end, compromised electrical connection.

- (f)-(j): cracks and vias extend into plastic body. Failure identified visually; not identifiable from module I-V and power history!

- (a) and (f): loose end nut on the right.

- (k) and (n): unaged (reference).

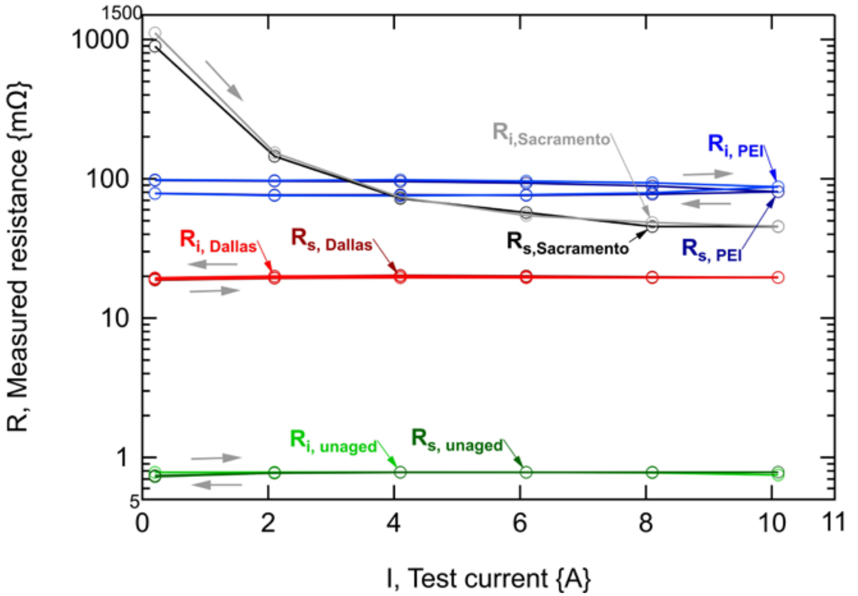
- Other specimens: vaporized end (plug or socket), large blister(s), locking pins no longer fully seated, change in plastic surface gloss.



Photos of connectors, including external appearance and springs after deconstruction.

R-I Sweep May Be Used to Diagnose Degraded Connectors

- R_{unaged}: 0.73 mΩ at 0.2 A, 0.78 mΩ at 10 A.
- Elevated R (10's of mΩ) observed for field degraded samples.
- PEI: hysteresis from high to low R.
- PEI, Dallas, other specimens: measurable difference between initial and stabilized (1 min) R.



Resistance-current sweeps for field and unaged specimens of the same model. The results are shown for initial and stabilized readings at each measured current.

- 2≤ΔR≤4 mΩ criteria for accelerated aging in standards.
- 6% ΔR consistent with 4°C temperature rise for bulk Cu. R anticipated to increase with current, e.g., from Joule heating.
- ↓R for PEI … from thermal depletion of surface oxide or improved of contact (CTE misfit)?
- Examples show usefulness of 4-wire R-I sweeps as damage quantification & diagnostic tool.

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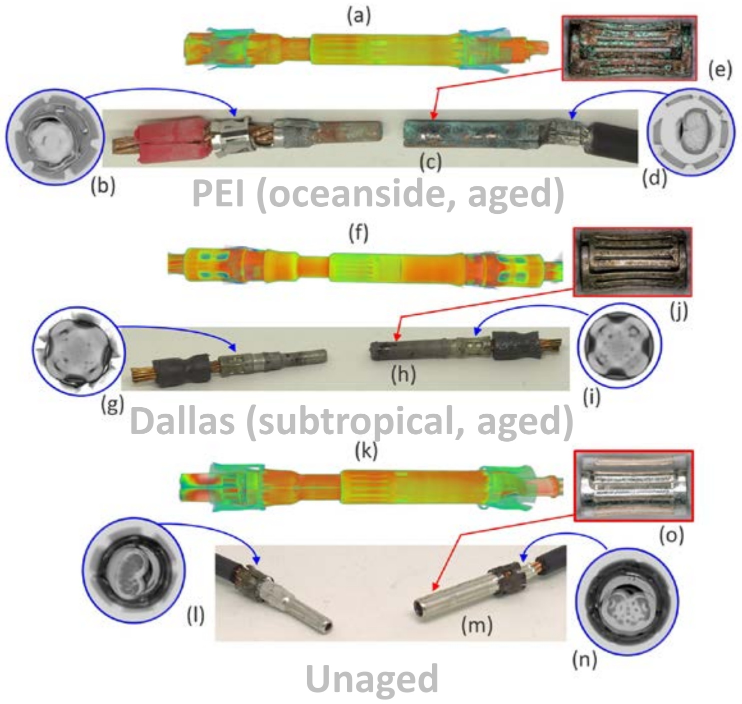
Failure Analysis of Fielded Cable Connectors

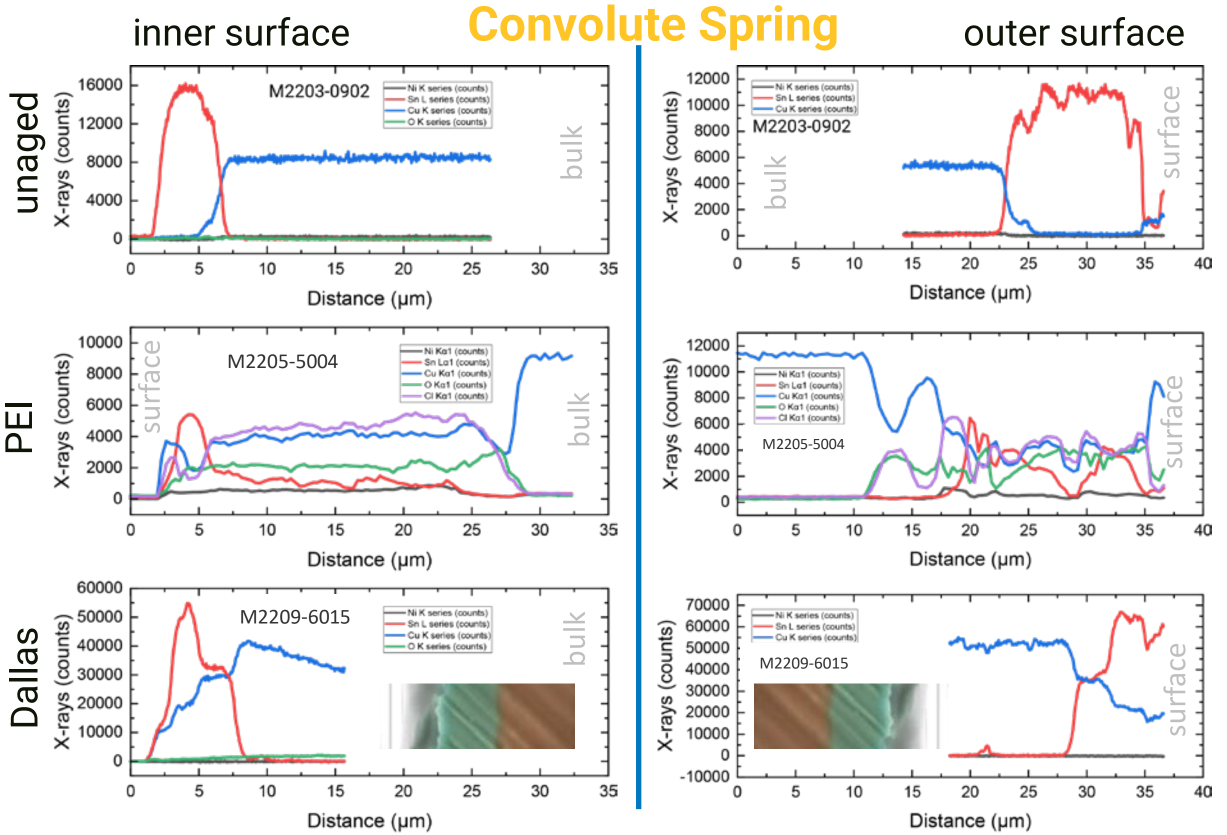
- Study of three connectors through destructive failure analysis.
- ~1y field use (where applicable).
- Metallic and polymeric components examined separately.
- Journal manuscript on F/A protocol and field degraded connectors in review.

- PEI: Incompatible connectors.
  Hermeticity compromised; corroded metal pins.
- Dallas: Scorched metal pins (common).
- We suspect improper field assembly (crimp, sizing, uncapped) is out there, but seldom identified in our specimens.



Failure Analysis of Fielded Cable Connectors: Case Study of Metallic Components

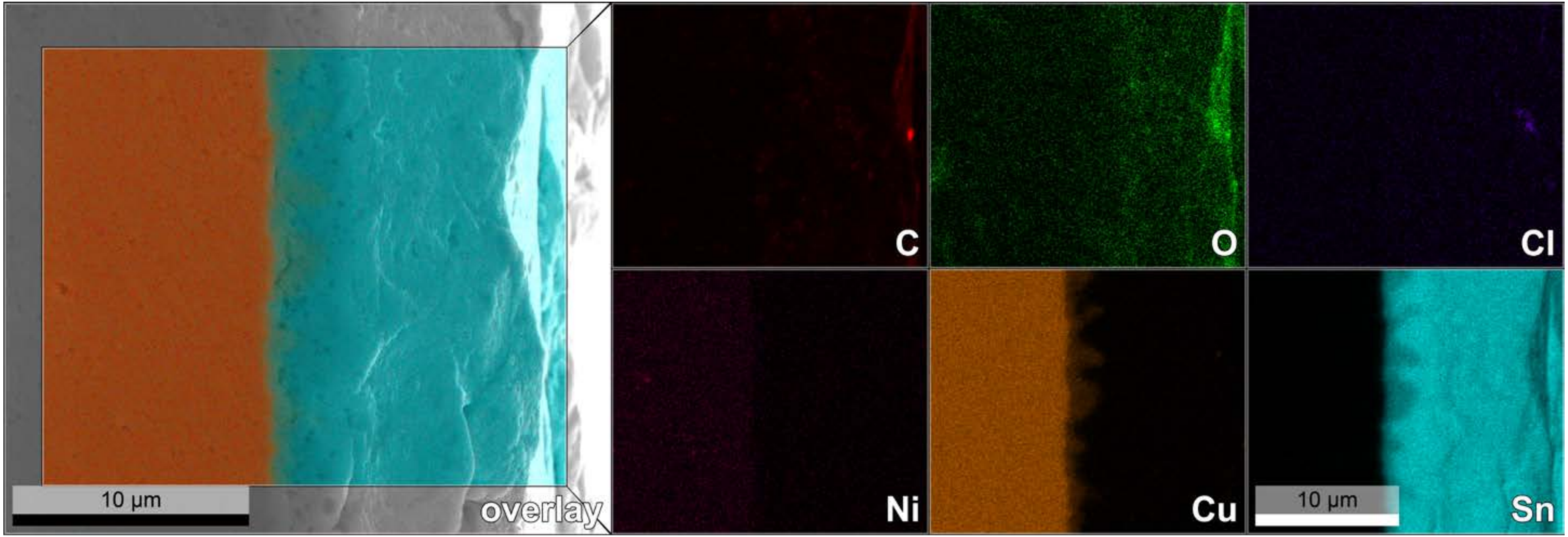
- Unaged reference (M2203-0902)
  - 10 um outer coating layer of Sn
  - 5 um inner coating layer of Sn
  - little mixing between layers
  - Z of Be too low for EDS detection
- PEI, oceanside, aged (M2205-5004)
  - thick (25 um) scale layer, inside & out
  - mixed Ni/Sn/Cu as well as heavy O and Cl traces
  - Ni may be transferred at elevated T
- Dallas, subtropical, aged (M2209-6015)
  - ca. 7 um Sn on surface, concentration gradient
  - equimolar Cu mixed-phase 3-4 um at -Sn/Cu interface, inside & out -23.6±0.1 % at. Sn intermetallic ε phase
  - gradient mixed-phase: Sn/Cu ratio decreases after 3-4 um plateau toward surface



Failure Analysis of Fielded Cable Connectors: Case Study of Metallic Components

Convolute Spring

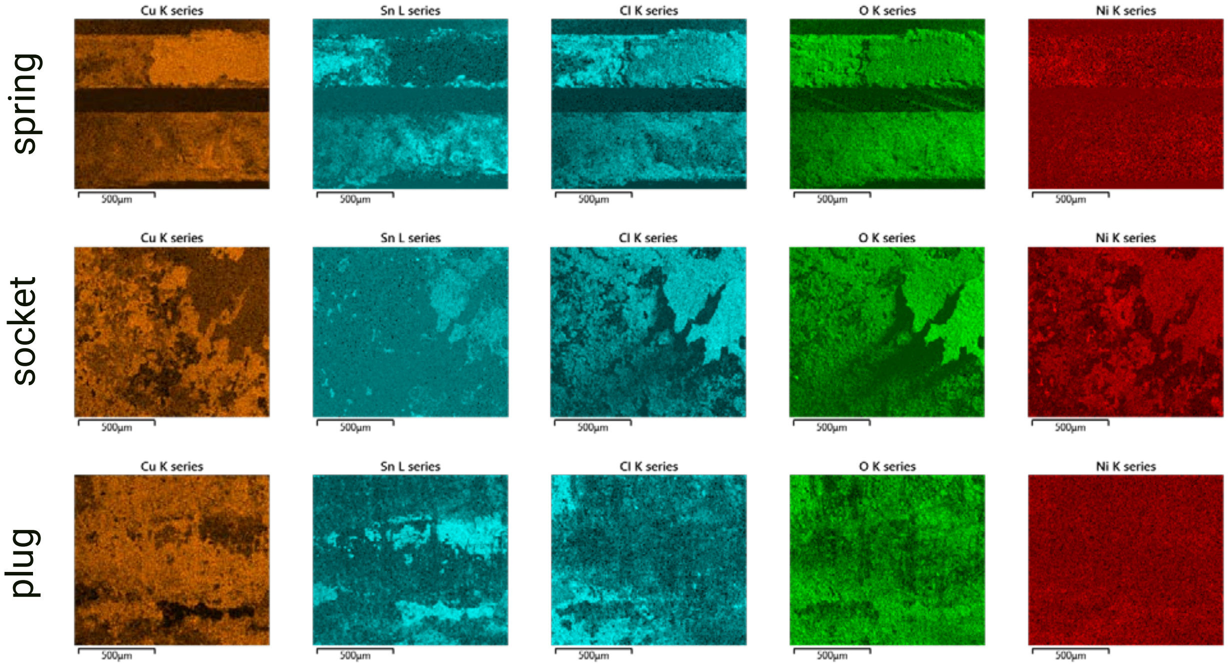
Unaged reference (M2203-0902)



Failure Analysis of Fielded Cable Connectors: Case Study of Metallic Components

Elemental mapping confirms scale compositions

- PEI, oceanside, aged (M2205-5004)
    - Cl signal colocalized with both Cu and Sn regions
    - O signal everywhere Cl is present
    - Ni also detectable from surface



Cable Connectors: Key Characteristics of Polymeric Components

- Components examined: sealing o-ring & bushing; structure end nut & body.
- Goal: seal against H_2O, prevent corrosion of metals.

Typical in-use concerns:

- Dimensional stability… material, type, glass & melt transitions.

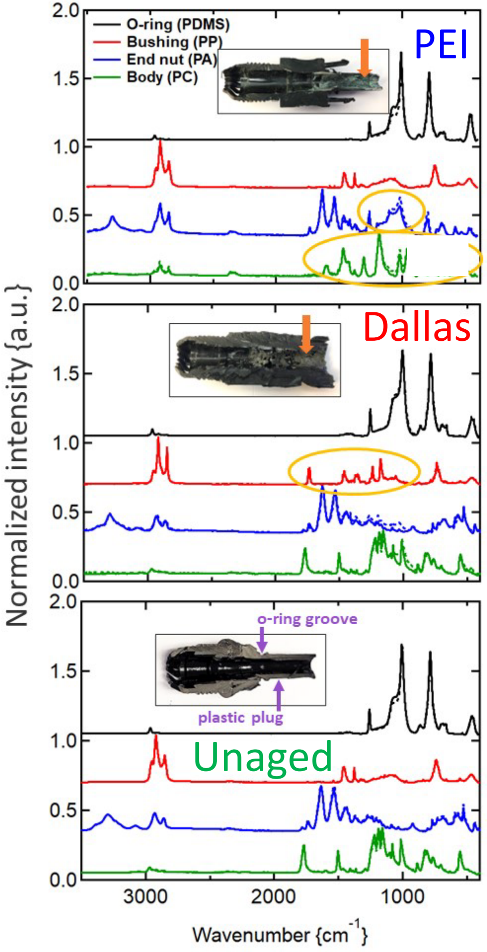
**primarily PA6/6.*

Adverse operation concerns:

- Thermal decomposition. Here @ 2% mass loss, $>T_{application}$.

POLYMER MATERIAL	POLYMER STRUCTURE	POLYMER TYPE	O-RING	BUSHING	END NUT	BODY	T_g, GLASS TRANSITION {°C}	T_m, MELT TEMPERATURE {°C}	T_d, DECOMPOSITION TEMPERATURE {°C}
silicone (PDMS)	semicrystalline	thermoset, elastomer	a, b, e	a, b, e	N/A	N/A	<-90	-45	400
polypropylene (PP)	semicrystalline	thermoplastic	N/A	b	N/A	N/A	-5	155	260
polyamide (PA)*	semicrystalline	thermoplastic	N/A	N/A	a, b	b	60	260	380
polycarbonate (PC)	amorphous	thermoplastic	N/A	N/A	N/A	a, b	145	N/A	450
polyphenylene ether and polystyrene	amorphous	thermoplastic copolymer	N/A	N/A	e	e	140/90	N/A	360

The Damaged Components and Connector Failure Modes From Polymer Forensics



- PEI: PC body degraded, blue-green deposit from metal pin.
- Dallas: PP bushing degraded (lowest T_d polymer), gray discoloration, deformation of PC body from over-heating, T_d 450 °C.
- Both: silicone O-ring not affected by field use.
- Damage to polymeric components is secondary, occurring from overheating after metal pins compromised near their connection.

FTIR spectra for the polymeric components from the connectors: PEI, Dallas, and unaged. Notable differences in the spectra signature is identified with a circle. The cut connector body is shown in the insets.

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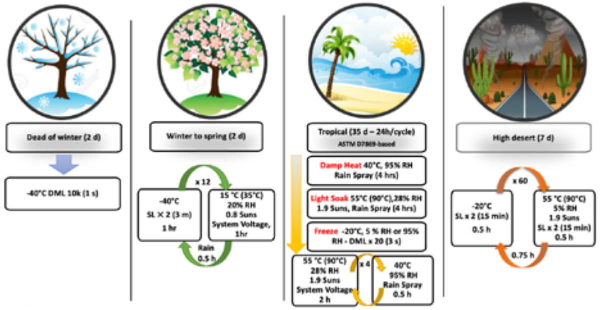
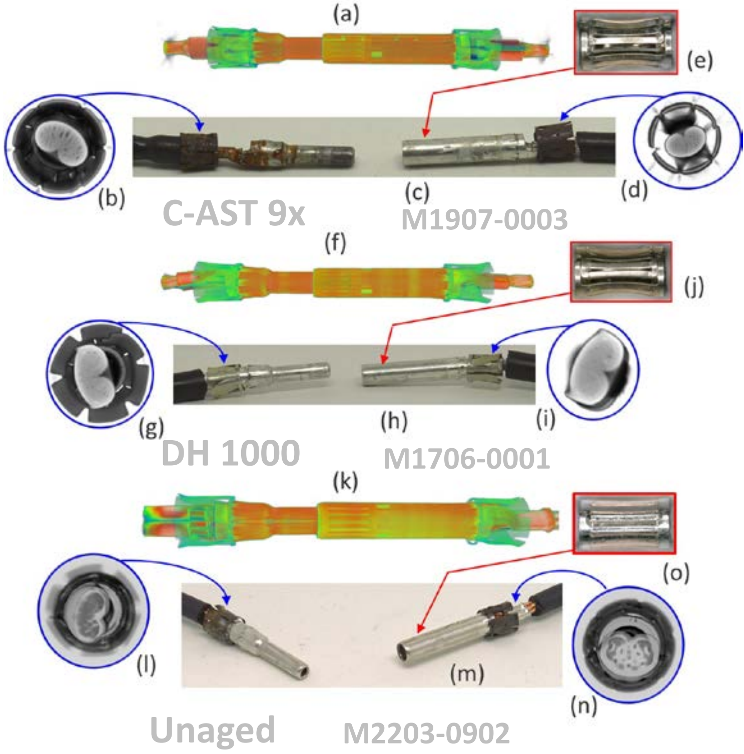
Failure Analysis of Cable Connectors After Accelerated Aging

<u>Tests</u>:

- **C-AST** (below)
- **Damp Heat** (85°C/85%RH, steady state @ V_{oc}).



Summary of the C-AST sequences (+1000 V, at MiMo current)



Failure Analysis of Cable Connectors After Accelerated Aging: Case Study of Metallic Components

Unaged (M2203-0902)

- Reference sample

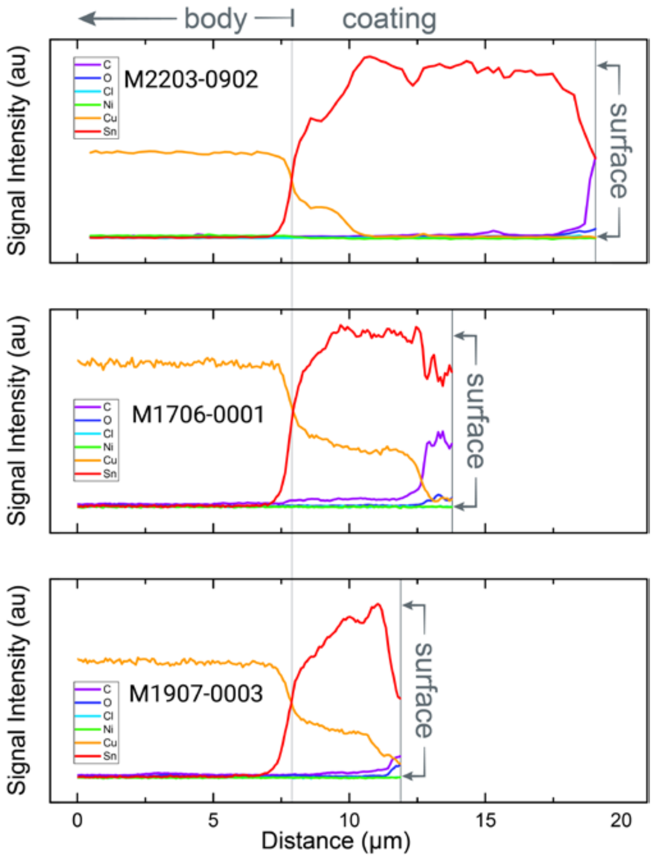
DH 1000 (M1706-0001)

- Diffusion of Cu bulk into Sn surface layer.
- 12 µm → 8 µm thick Sn surface layer.

C-AST 9x (M1907-0003)

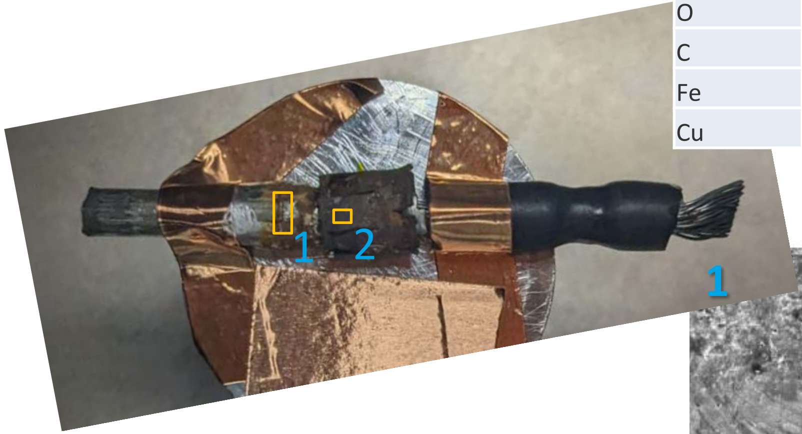
- Diffusion of Cu bulk into Sn surface layer
- 12 µm → 6 µm thick Sn surface layer.

Convolute Spring



Failure Analysis of Cable Connectors After Accelerated Aging: Case Study of Metallic Components

- C-AST 9x (M1907-0003): What Is Corroding?

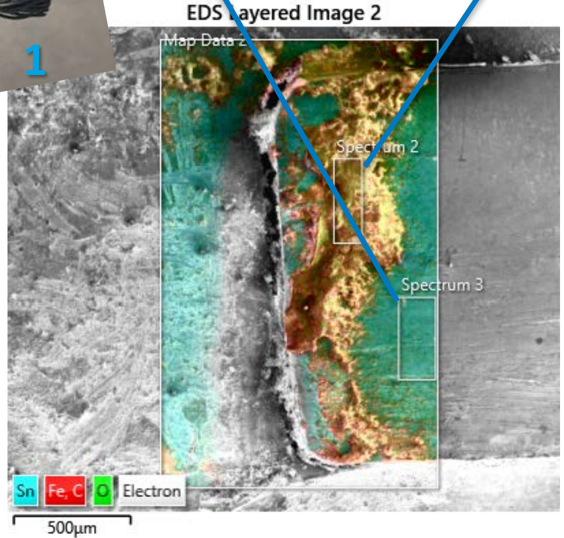


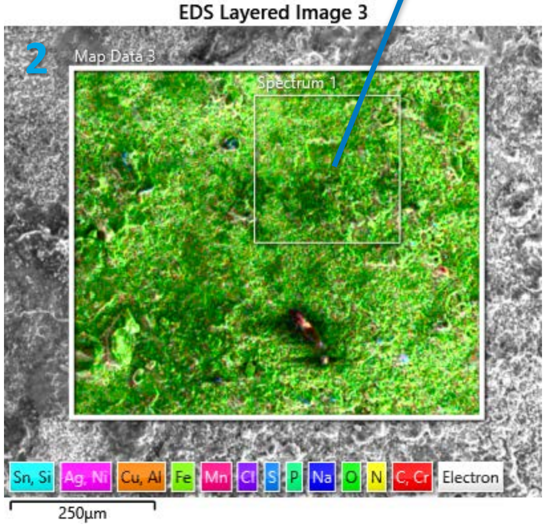
- Fe is from retainer spring near connector end nut/cable.

Element	Weight %	σ
Sn	62.47	0.24
O	25.94	0.23
C	5.52	0.12
Fe	4.62	0.08
Cu	0.93	0.08

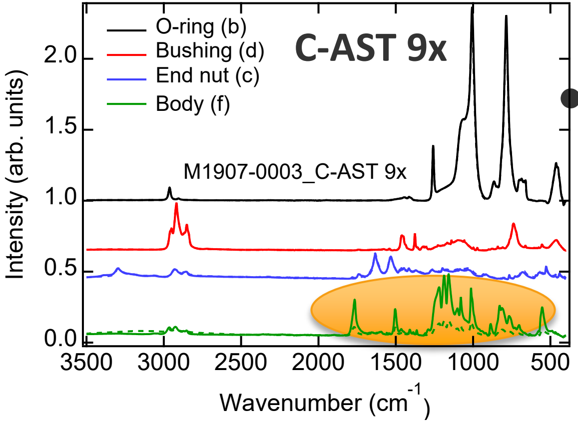
Element	Weight %	σ
Fe	45.71	0.23
O	35.65	0.22
C	17.82	0.28

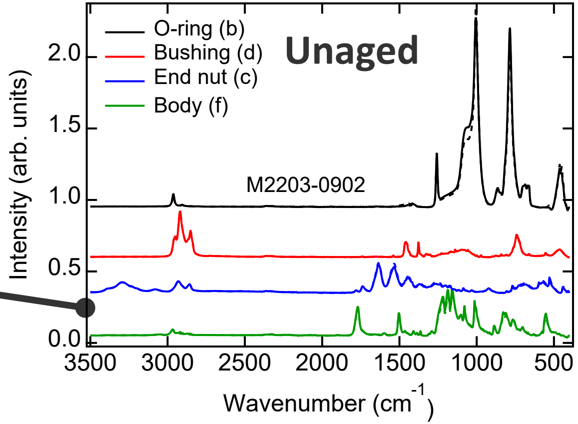
Element	Weight %	σ
Fe	62.87	0.12
O	27.48	0.08
C	8.65	0.14
Mn	0.37	0.02
Si	0.23	0.01
Cl	0.14	0.01

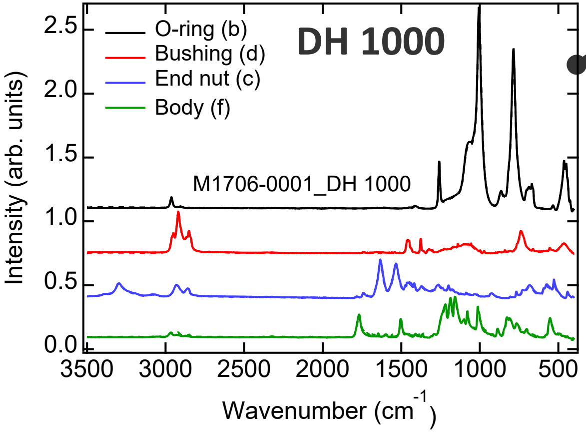




Failure Analysis of Cable Connectors After Accelerated Aging: Case Study of Polymeric Components







C-AST 9x:

- Degradation of the connector PC body, suspect from heating following metal pin corrosion.

Initial mechanical/hermeticity failure (not bulk degradation polymer) suspected.

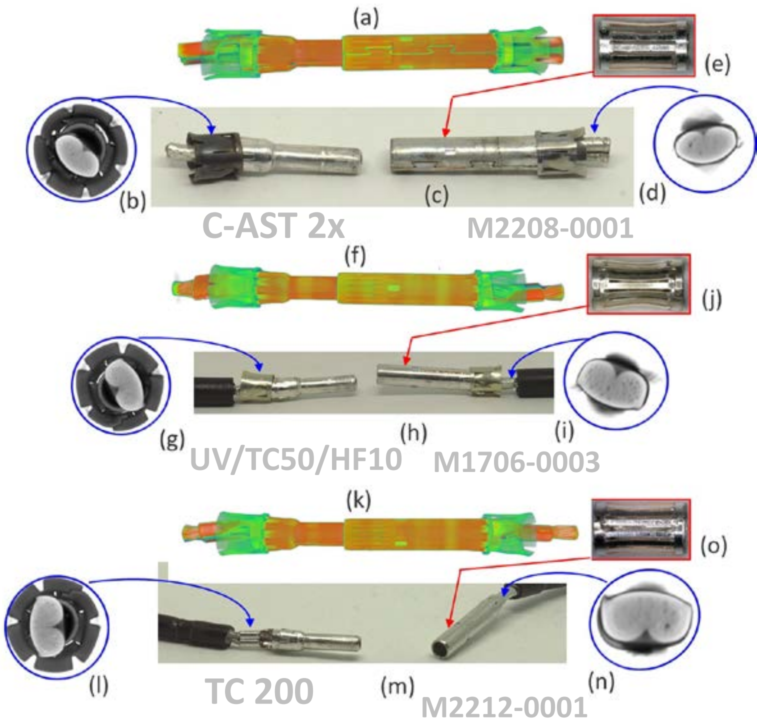
All:

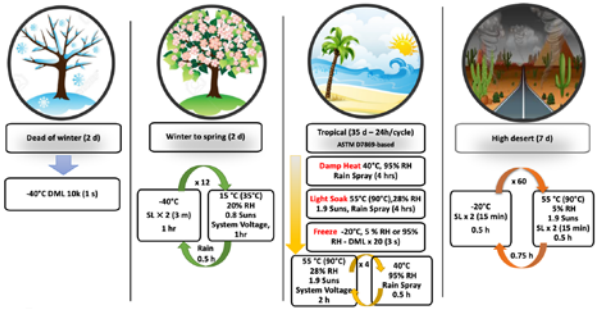
- Silicone O-ring and PP bushing not chemically affected.

Failure Analysis of Cable Connectors After Accelerated Aging

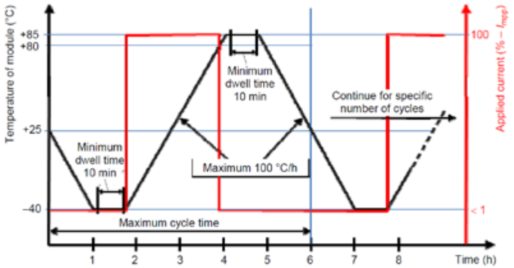
<u>Tests</u>:

- **C-AST** (below)
- **Thermal Cycle** (below),
- **UV conditioning/Thermal Cycle** (below)**/Humidity Freeze** (starting from 85°C/85%RH).





Summary of the C-AST sequences



The Humidity Freeze test is similar (with 85 °C/85% RH) to the Thermal Cycle test (from IEC 61215-2)

Failure Analysis of Cable Connectors After Accelerated Aging: Case Study of Metallic Components

TC200 (M2212-0001)

- 9 µm Sn surface layer
- Negligible Intermetallic layer mixing (similar profile to unaged)

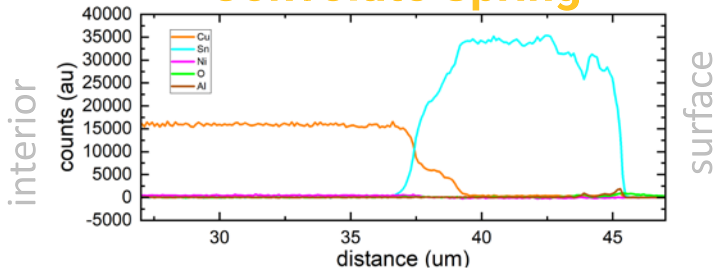
UV/TC50/HF10 (M1706-0004)

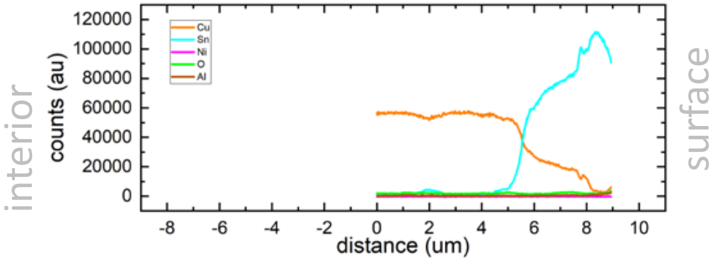
- 4 µm Sn surface layer
- Intermetallic layer mixing
- Localized damage
- Surface oxidation. From HF10? (compare to -0001)

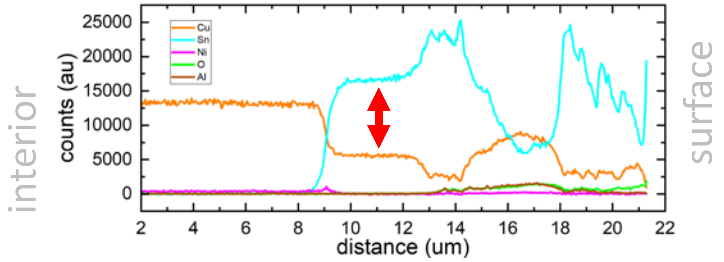
C-AST 2x (M2208-0001)

- 12 µm mixed-metal surface layer
- Extensive metallic mixing past interface; 61.5 Sn (%at) is not an intermetallic phase.
- Now more vulnerable to corrosion

Convolute Spring

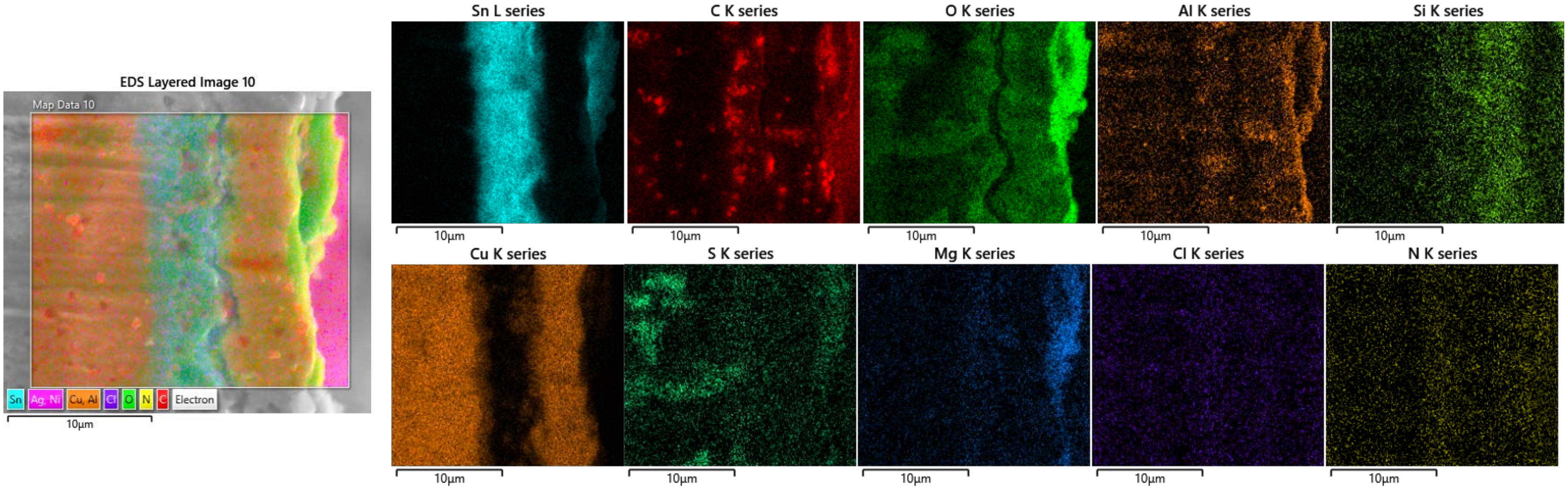






Failure Analysis of Fielded Cable Connectors: Case Study of Metallic Components

- Cross-section of the metal socket on M1706-0006 (TC 200)

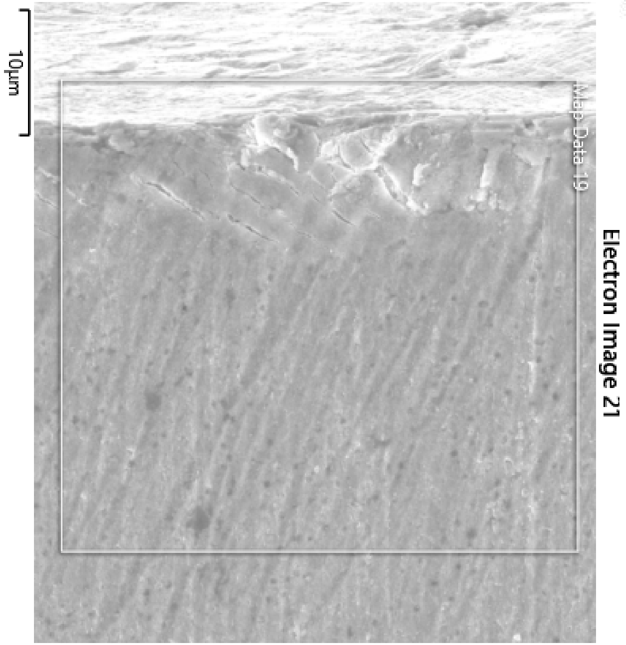


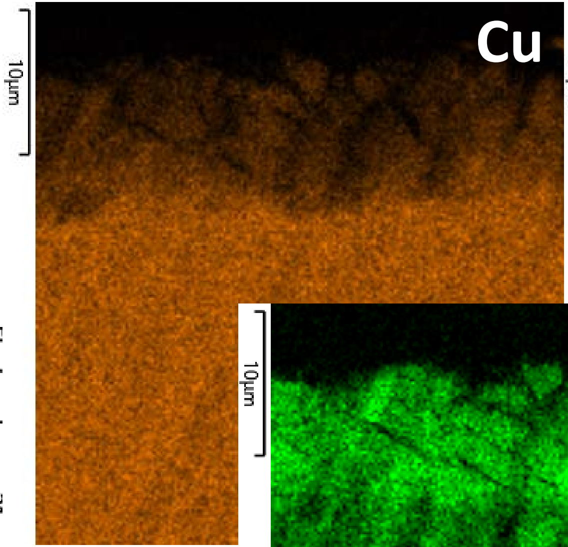
- Sn surface layer is structurally compromised.
- Oxidized Cu (?@ pin/socket contact?), contaminated with Mg, present on top of Sn.
- Sulfur signal in body; C inclusions.

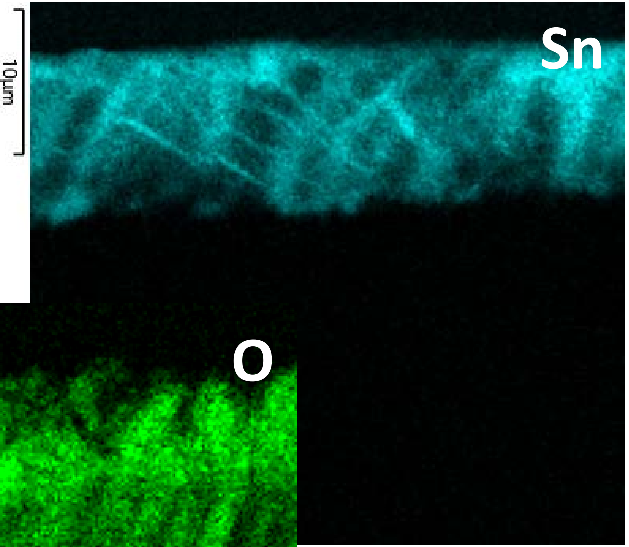
Failure Analysis of Fielded Cable Connectors: Case Study of Metallic Components

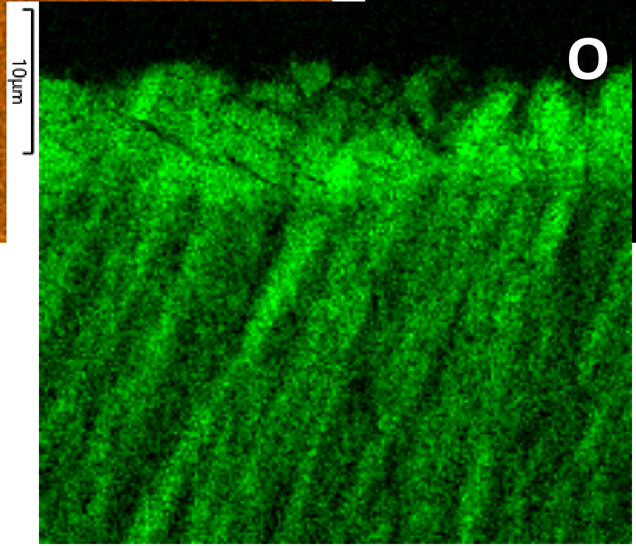
- Cross-section of the metal socket on M1706-0006 (TC 200)

- Mechanical cracks in Sn outer layer.









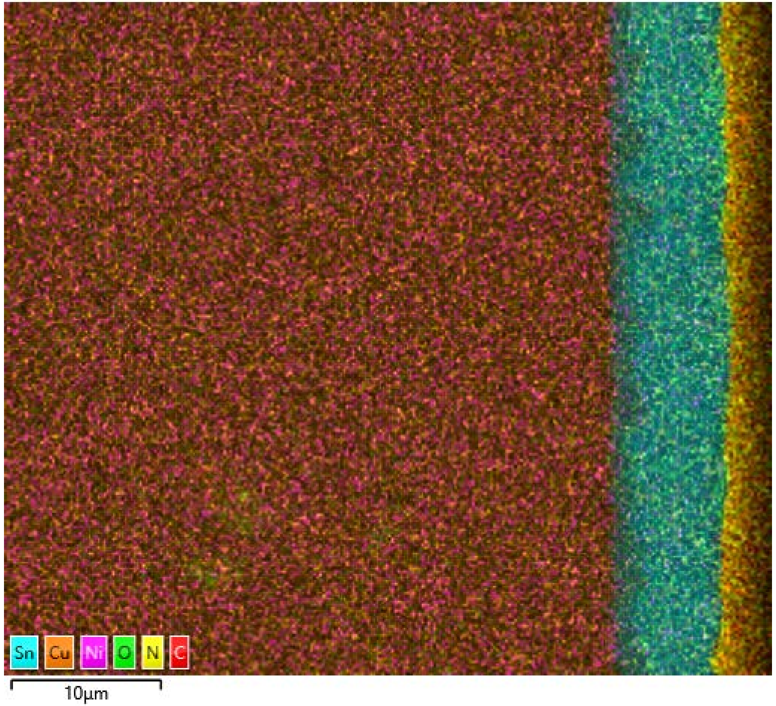
- Sample *not* at pin/socket contact region.

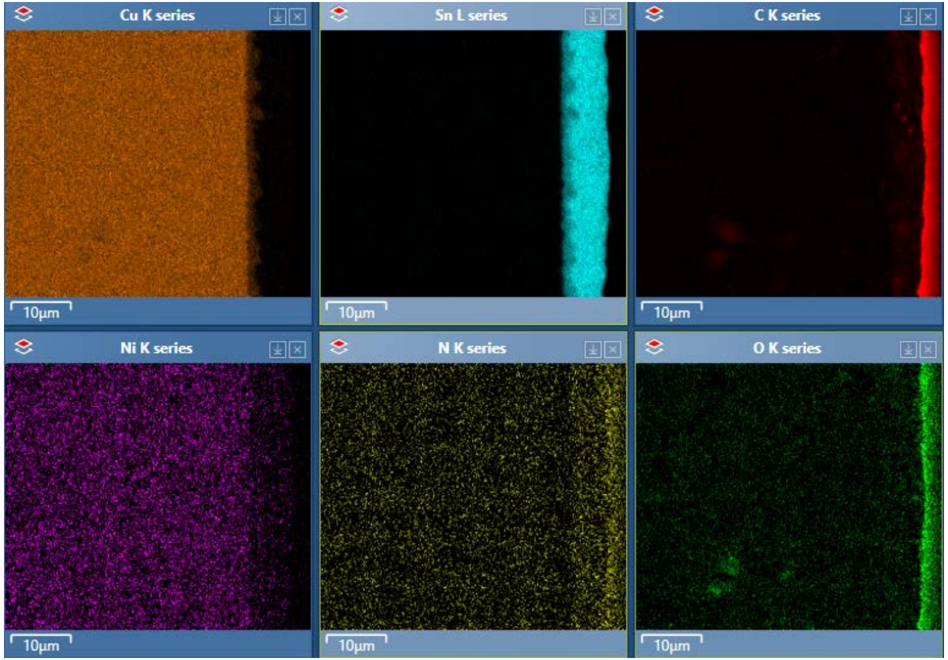
Failure Analysis of Fielded Cable Connectors: Case Study of Metallic Components

Convolute Spring

TC200 (M2212-0001)

EDS Layered Image 1





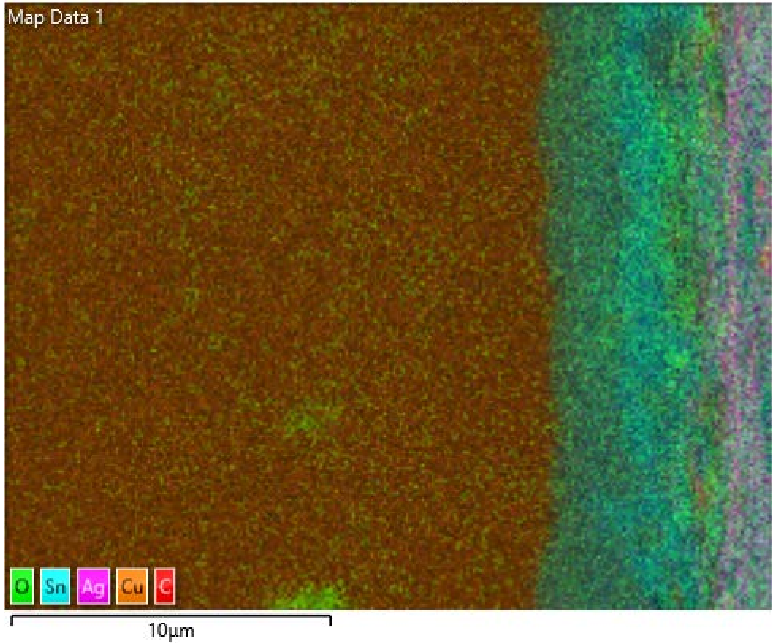
Nickel in bulk Cu, not Cu/Sn interface (some manufacturers)
Ni:Cu is 2.6 for M2208-0001, M2212-0001, M2203-0902. < 10% at. as in strengthened Cupronickel alloy

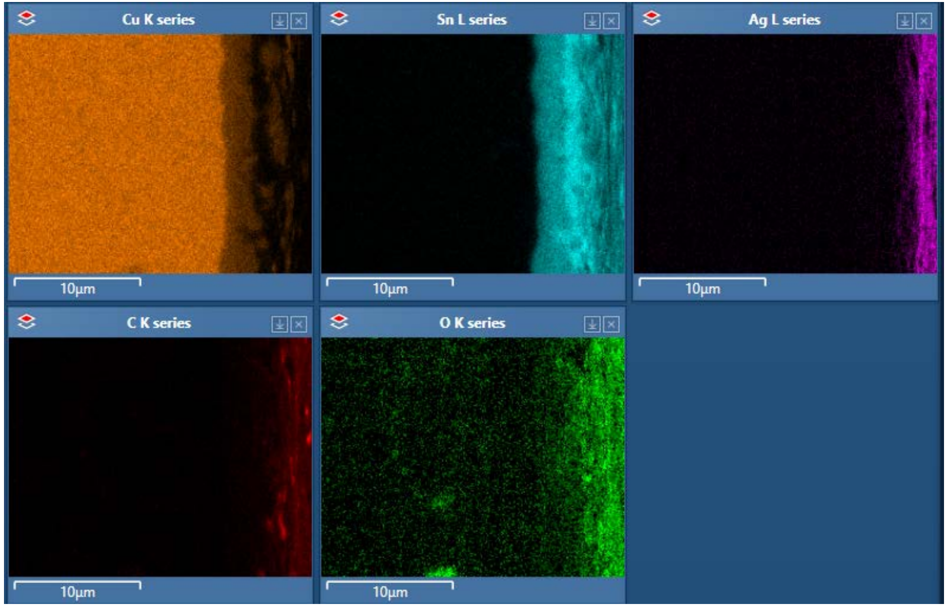
Failure Analysis of Fielded Cable Connectors: Case Study of Metallic Components

Convolute Spring

UV/TC50/HF10 (M1706-0004)

EDS Layered Image 1





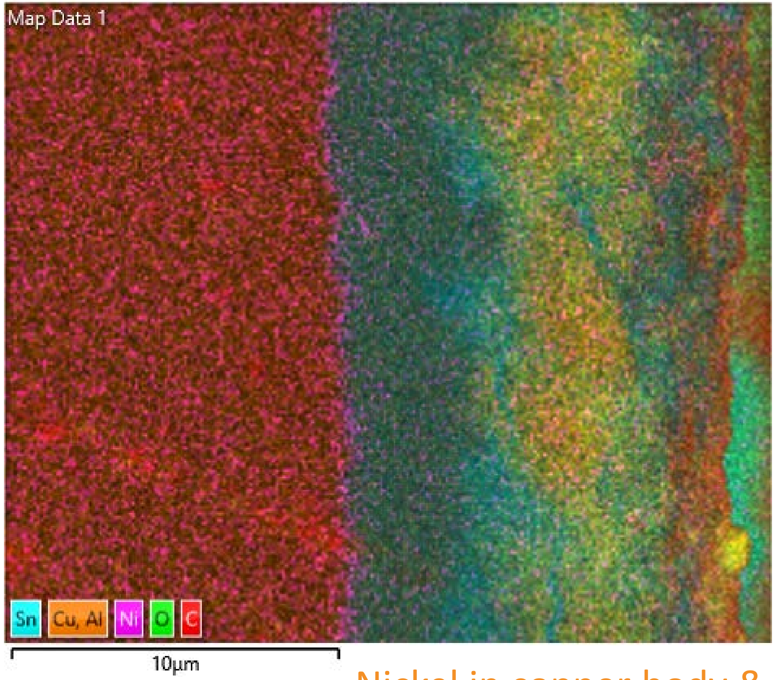
No nickel detected

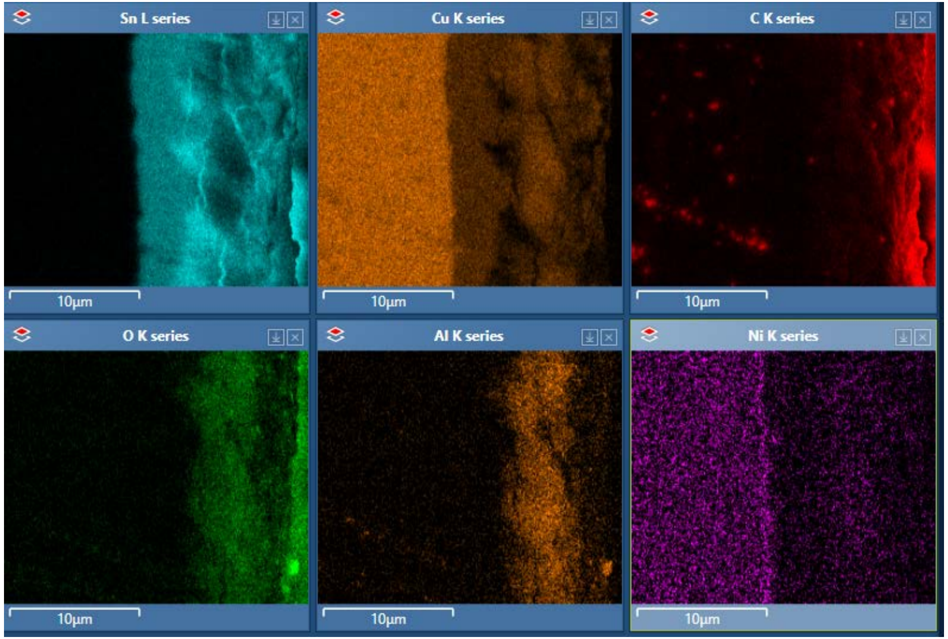
Failure Analysis of Fielded Cable Connectors: Case Study of Metallic Components

Convolute Spring

C-AST 2x (M2208-0001)

EDS Layered Image 1



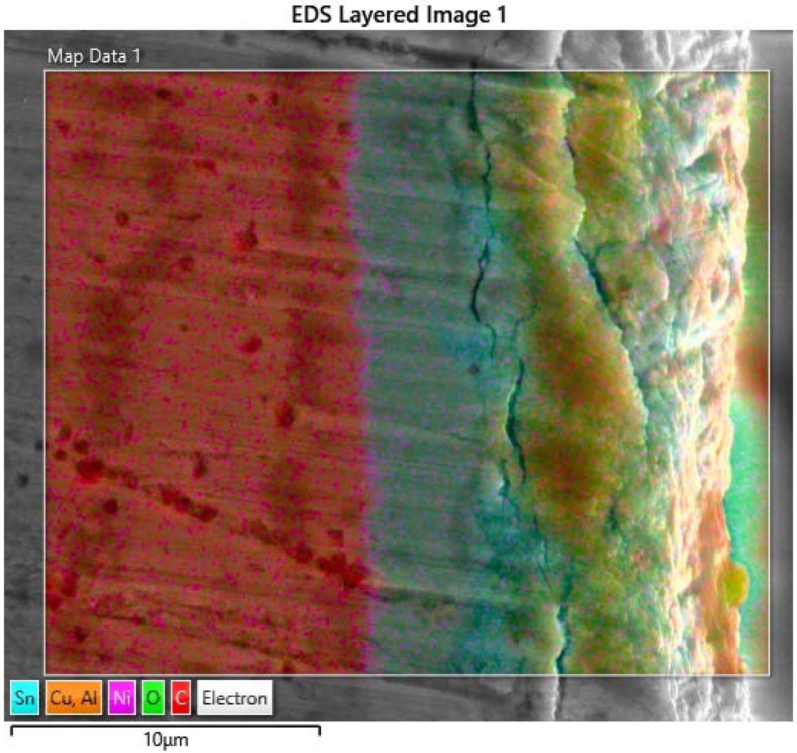


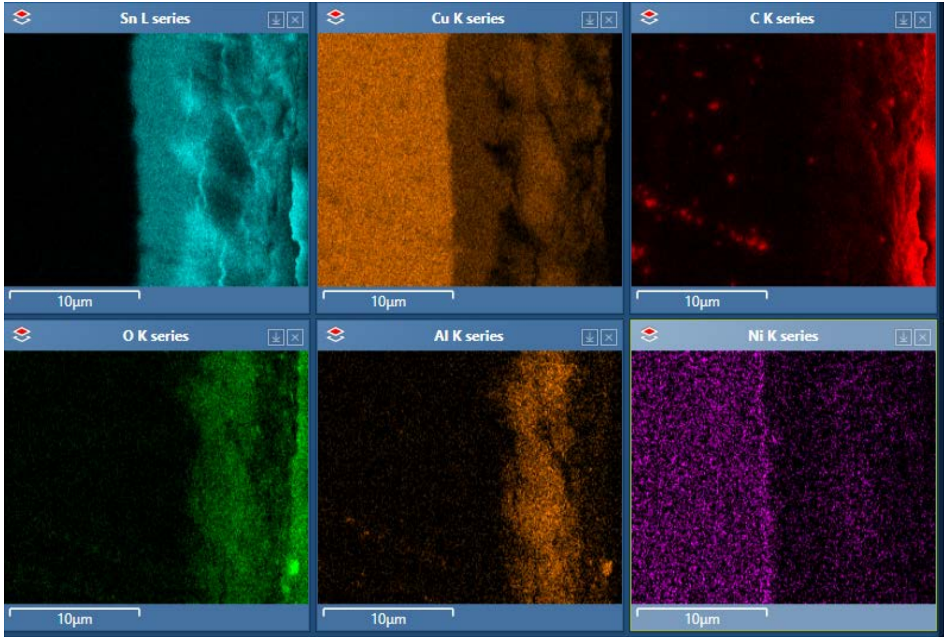
Nickel in copper body & spike at interface | Extensive scale present
Al, C may be sample preparation artifact (polishing grit)

Failure Analysis of Fielded Cable Connectors: Case Study of Metallic Components

Convolute Spring

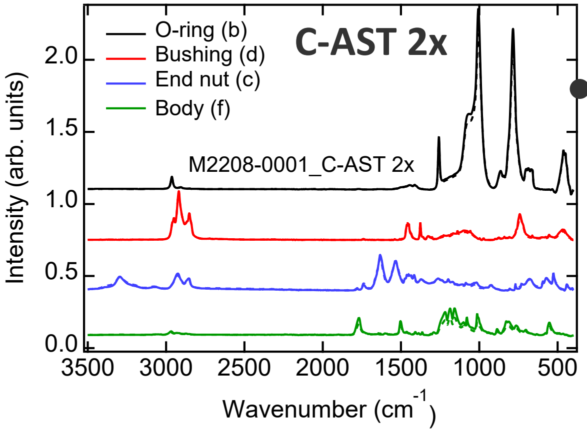
C-AST 2x (M2208-0001)

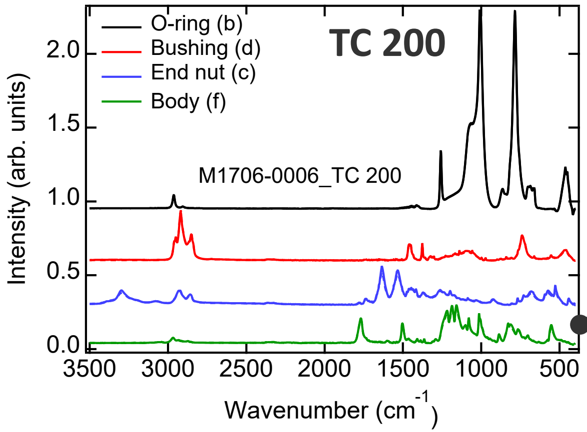


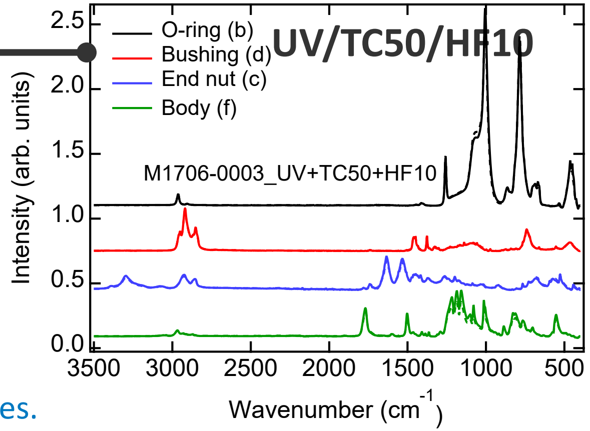


Nickel in copper body not consistent between samples.
Multiple material vendors? (Specific Cu alloys observed in other models/components, e.g., aluminum bronze).

Failure Analysis of Cable Connectors After Accelerated Aging: Case Study of Polymeric Components







- No visual degradation of polymer, these samples.
- No chemical changes detected here in FTIR.

Today’s Presentation

Background (motivation, PVQAT survey on industry)

Experimental details (samples, failure analysis protocol, methods examples)

Results:

Field degraded connectors: *primary*, metallic & polymeric components)

Accelerated aged connectors: *secondary*, metallic & polymeric components)

Wrapping up (solutions, summary, acknowledgements)

Questions and comments welcome, e.g., end of each section.

Prevention of Common Degradation/Failure Modes

Please say solutions that come to mind.

- Connector incompatibility: Model-specific jumper presently required, greater # connectors. NEMA, IEC Universal Plug & Socket standards.
- Improper assembly: Training, certification, informative outreach. NABCEP CE Conference. IRA apprenticeship.
- Uncapped ends: In standards, require caps to be shipped with connectors. Verify and inform (NREL experiment). Training, certification, informative outreach.
- Improper sizing of connector:cable: Certify cable/connector combinations (few present uses). Training, certification, informative outreach.
- Improper mechanical fastening to system: Training, certification, informative outreach. DETRIMENTAL mechanical perturbation identified in separate experiments (NREL).
- Live disconnection: Training, certification, informative outreach.
- Incomplete connection: ???

Fielded Connectors: Common Degradation Modes and Scorched Metal Pins

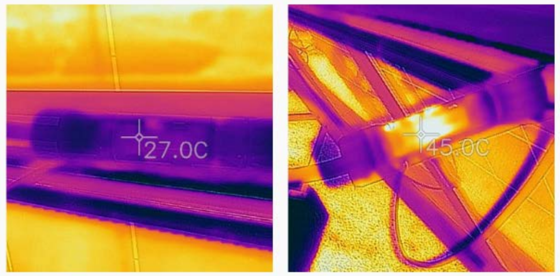
- Degradation modes from PVQAT: **incompatible makes**, **uncapped ends**, **improper assembly** …incomplete connection, improper sizing, and improper mechanical fastening.

- Examples today: incomplete connection, incompatible makes, **scorched plug & socket**.
  - -**Scorched metal pins:** majority of field samples (not accelerated), unexpected, may result from: design, manufacturing, uncapped ends, vibration/bending, CTE/abrasion, live disconnection, ...
  - -Other modes *may exist*, e.g., corrosion or fracture of polymers.

- Takeways from forensics:
  - -Use 4-wire R-I sweep to quantify, diagnose degraded connectors (vs. low current, 2-wire).
  - -Mass transport with intermediate ε phase Sn:Cu alloy; surface scale formation (maritime);
  - -Secondary damage to polymers (body & bushing).

BoS Reliability Projects and the PVQAT TG10

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



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

- Monthly PVQAT TG10 web group meetings covering 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.

Next meeting: 2024/5/21 RE: Failure analysis of cable connectors

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:

-Dr. Michael Kempe and Bill Sekulic of NREL.

-Numerous collaborators for field specimens (confidential).

-PVQAT TG10 (~200 recent followers).

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CPS 38524/ Agreement 38524 DOE SETO.

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NREL STM campus, Dennis Schroeder

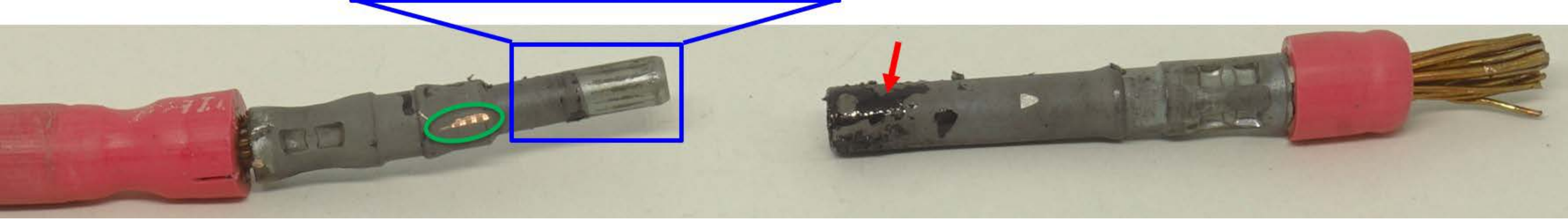
Additional comments & questions: David.Miller@nrel.gov

Additional slides
(reference/supplementary information)

Morphology Provides Clues for Scorched Pins

- Scorched pins observed on majority of field connectors, this project.
- Residual likeness of convolute spring often observed on metal pin.
- Causes: design, manufacture (plating), contamination, vibration, ?~~thermal misfit (localized abrasion & wear)~~?

A field-degraded connector: residual from convolute spring (inset); plastic from the connector body (red); artifact of milling (green)

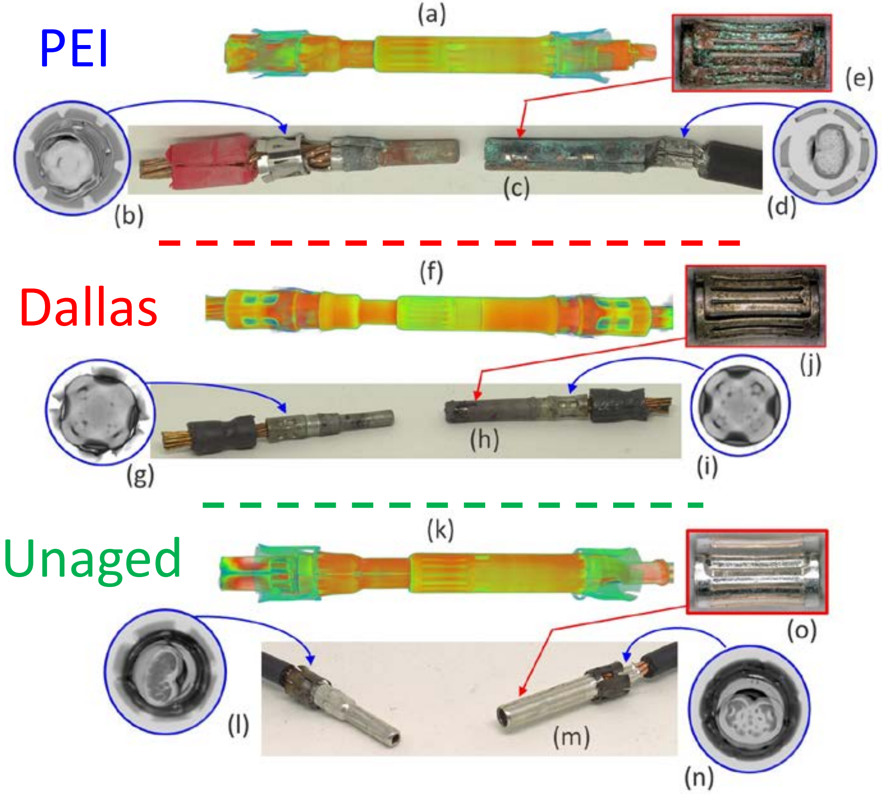


Diagnosing the R-I Specimens Using the Examination Protocol From This Study

•Incompatible plug & socket compromise mechanical seal of PEI connector.

•Blue-green appearance ⇔ ocean side corrosion.

•Mixed gas test (H_2S, NO_2, Cl_2, and SO_2, IEC 62852); fixed gas method (H_2O and SO_2, ISO 22479); and stress corrosion test (humid ammonia-air mixture, UL6703) presently assess corrosion.

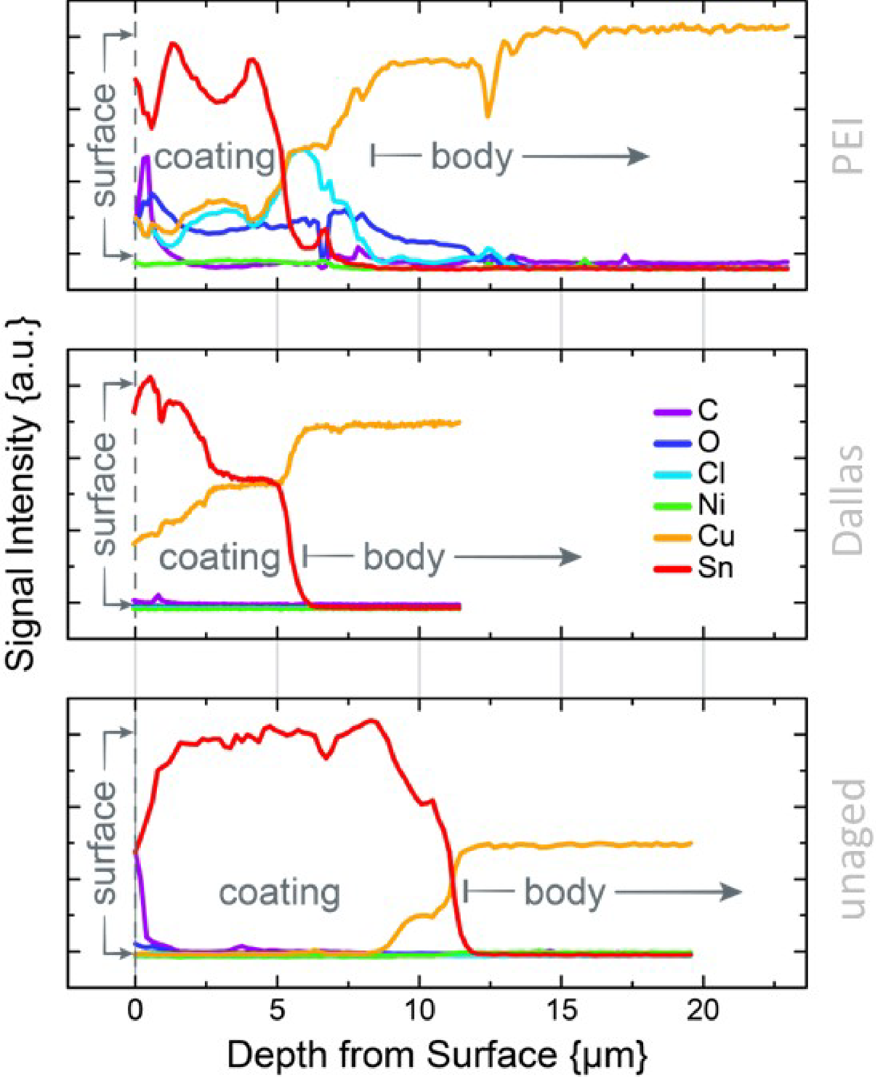


XCT and external appearance of plug, socket, spring, and crimp after deconstruction.

•Dallas specimen scorched at metal pins and spring, but not at crimps.

-Possibly: design, manufacture (plating), contamination, perturbation, thermal misfit (localized abrasion & wear), live disconnection.

•Barrel style pin (g & i, intended for 7 strand cable, USA); rolled pin (b) intended for higher strand count.



EDS Composition Analysis Readily Distinguishes Connector Metals

PEI (oceanside):
- Greatest concentration of Cl, O.
- 15-25 μm surface scale (corrosion).
- Ni may be artifact of incompatible plug & socket.

Dallas:
- Temperature → mass transport of Sn & Cu.
- Steady Sn/Cu alloy at $3 < h < 5$ μm.
  - -23.6±0.1 % at. Sn.
  - -Intermetallic ε phase Sn:Cu (23-24 %at.)

Unaged:
- ~10 μm outer Sn surface layer.
- Rapid Sn → Cu transition at $8 < h < 11$ μm.