Creep Corrosion in Electronics
A Panel Discussion

Today's Event: Wednesday, May 01, 2024

Time: 1:00 PM EST/12:00 PM Central

Panelists:
Sean Clancy, Ph.D.
Randy Schueller, Ph.D.
Christopher Genthe
Paul Leone

Outline

Randy Schueller

- What is creep corrosion? What drives it? Why do we care?

Paul Leone

- Where does it occur and why still so common? How does one rate the severity of the exposure environment? What types of components are most at risk of failure?

Chris Genthe

- What are good test methods and ways of determining risk of field failure?

Sean Clancy

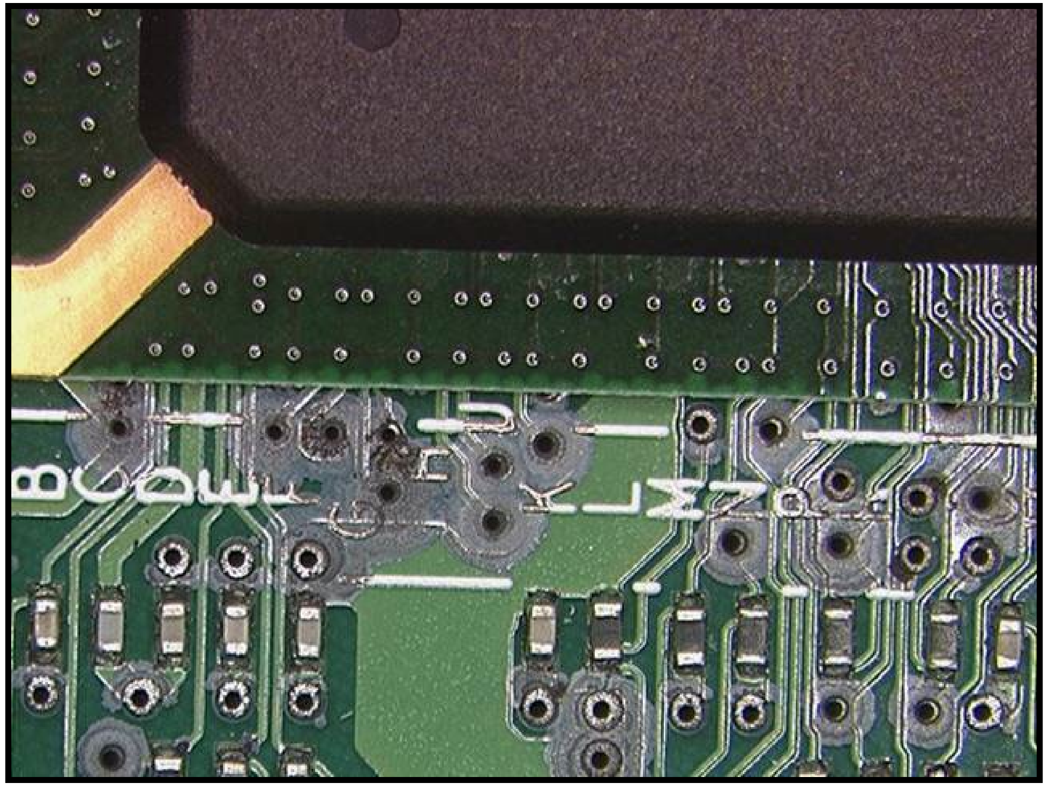
- What are mitigation strategies? What are good component design changes?

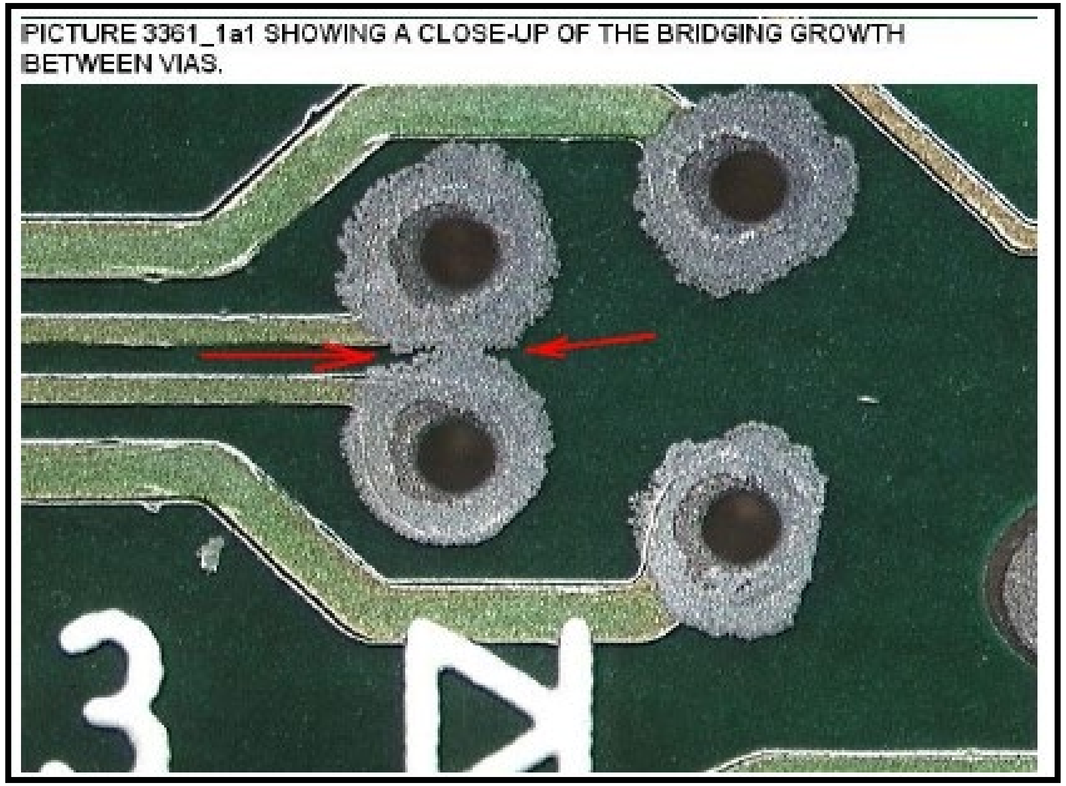
What is Creep Corrosion?

Creep Corrosion Origins

- Creep corrosion first became noteworthy with the lead-free solder transition.
- Immersion silver was introduced as a surface finish on PCBs. MFG and Temp/Humidity/Bias did not reveal any failure concerns.
- However, once released into the field, failures began to rapidly occur in certain high sulfur environments (and there are more of these than you might think)
- Replacement computers failed just as quickly.

Typical Creeping Corrosion Bridging





- Corrosion product is semi-conductive (resistance of about 1 MOhm).
- Resistance decreases as humidity increases.
- Traces sensitive to leakage current trigger the system failure.
- Visual inspection required to identify failures (most are CNDs).

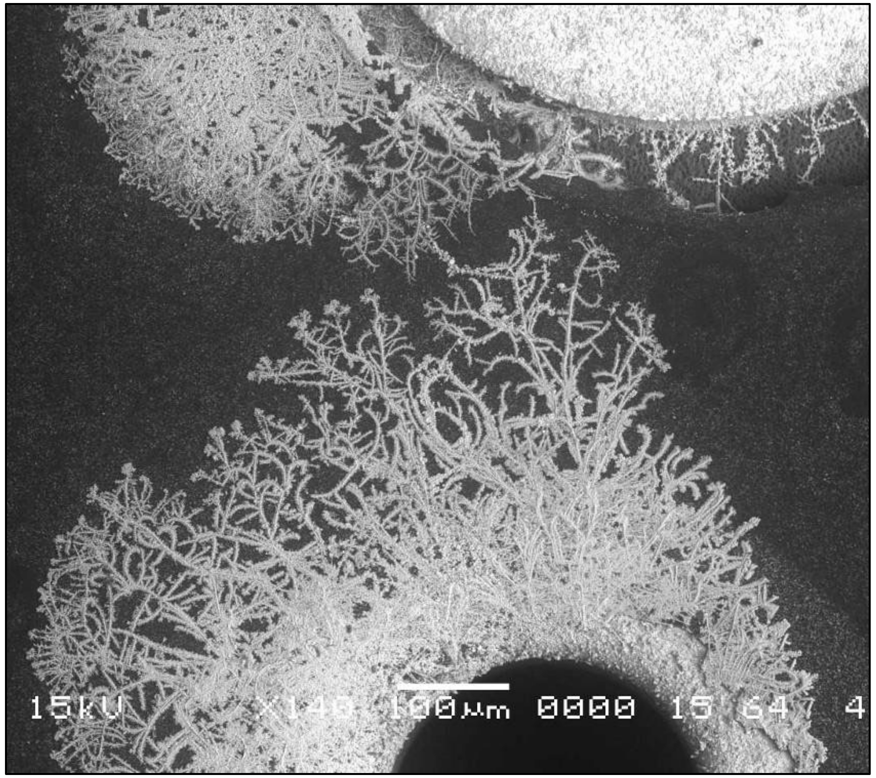
Creep Corrosion vs. ECM

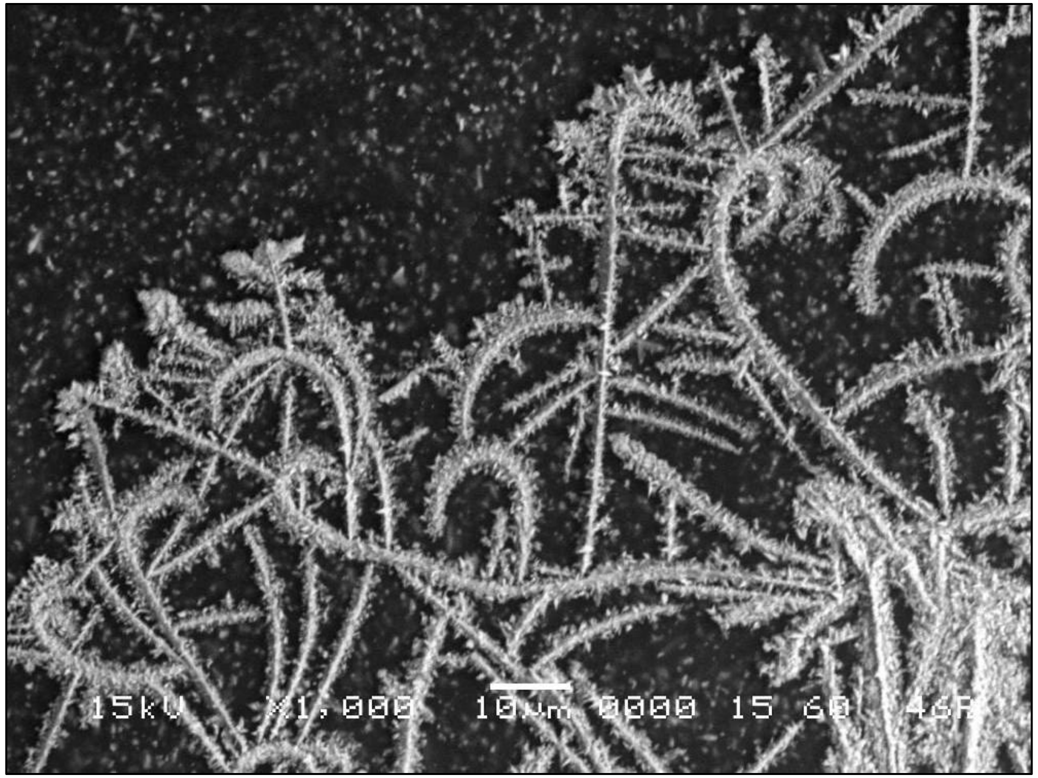
- How is creep corrosion different from electrochemical migration?

A: They both require contaminants and moisture.

- However, ECM requires an electric field which drives migration of metals (which often form dendrites).
- Creep corrosion tends to occur in all directions equally. The corrosion product is a chemical compound (typically copper sulfide). Can occur without the electronics even being powered.

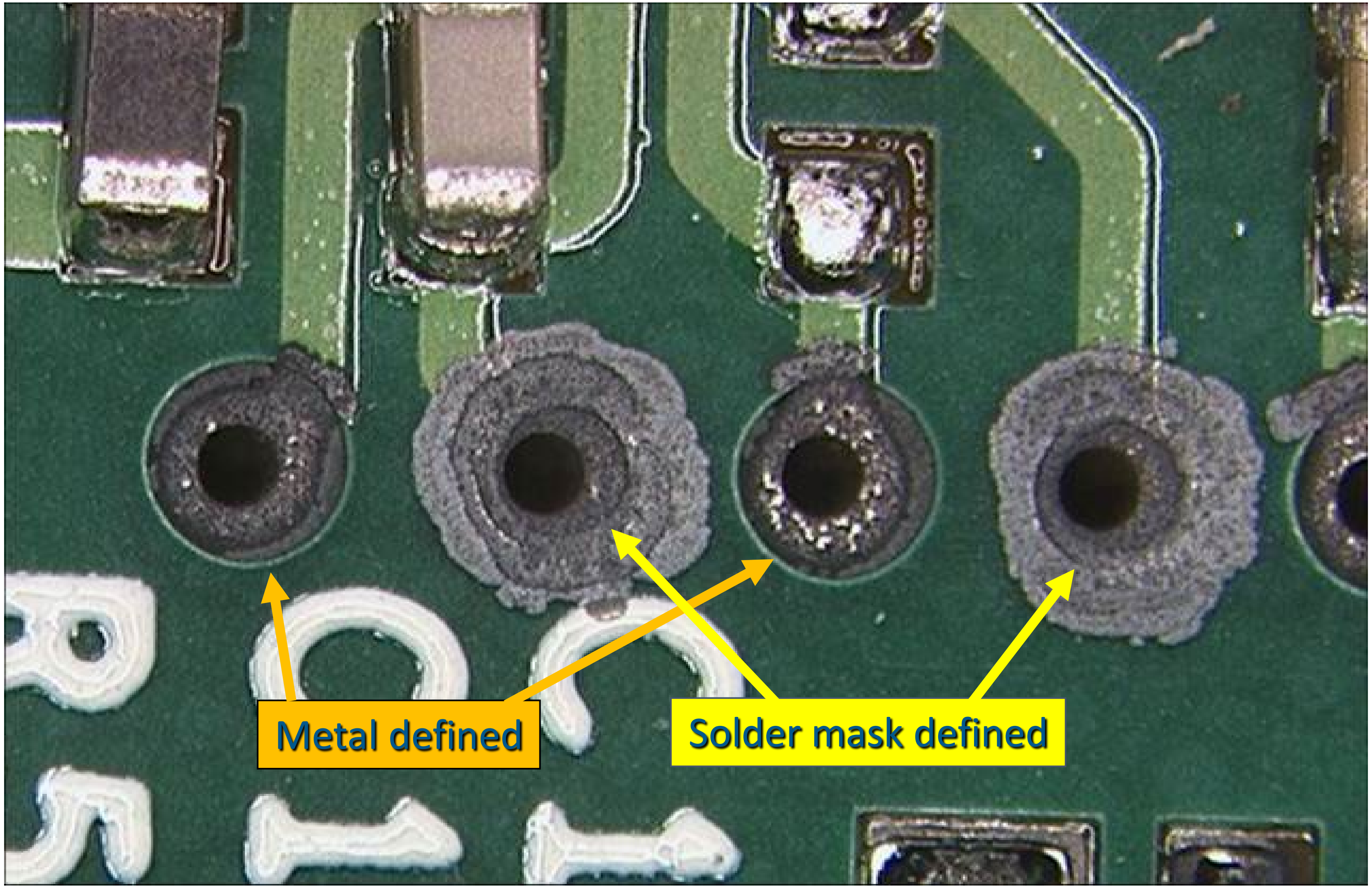
Growth of Corrosion Product





- Not electrochemical migration – voltage not required.
- Believed to form in condensed moisture.
- Implies a high humidity environment with elevated sulfur levels.

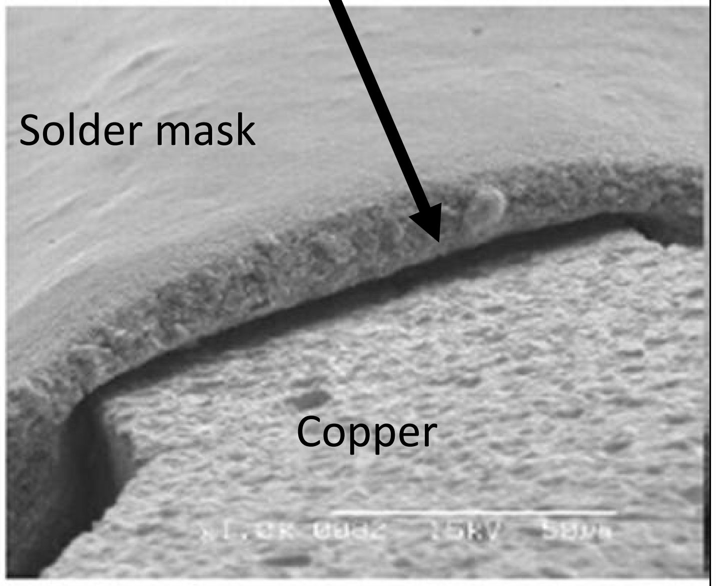
SMD Features are Most Susceptible to Creep

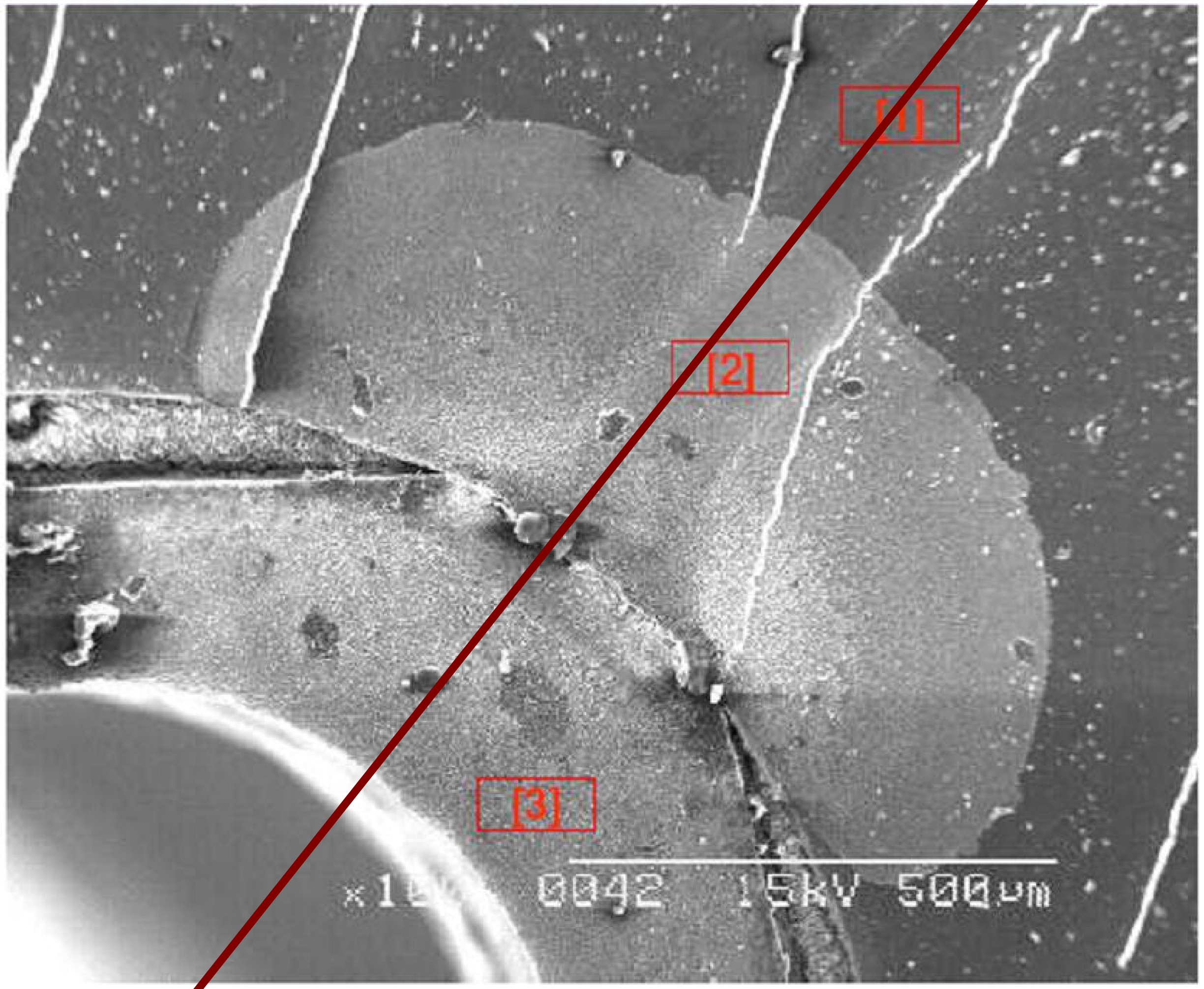


Creep Corrosion on Solder Mask

Cross-Section Location

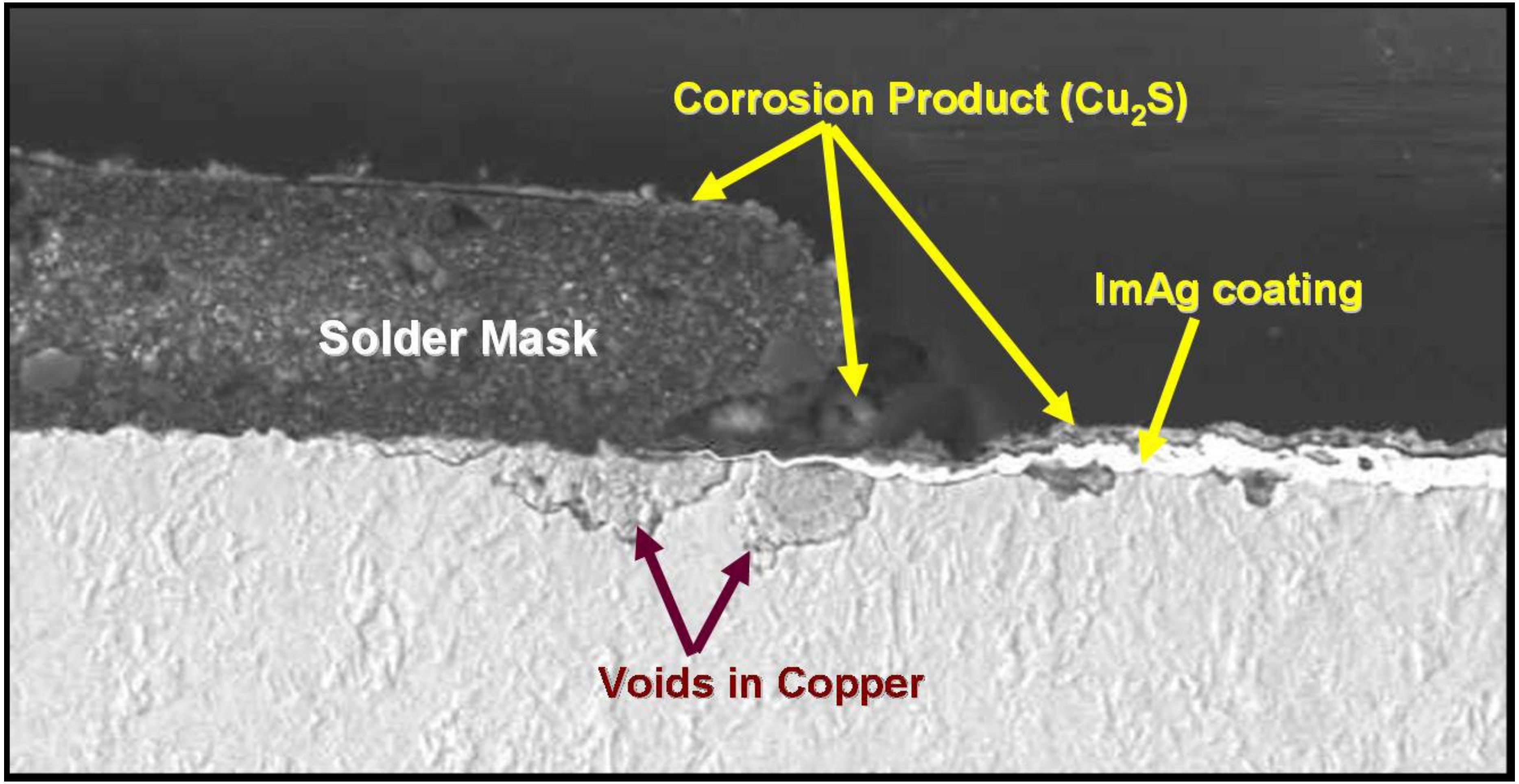
Solder mask crevice is the source of most corrosion.



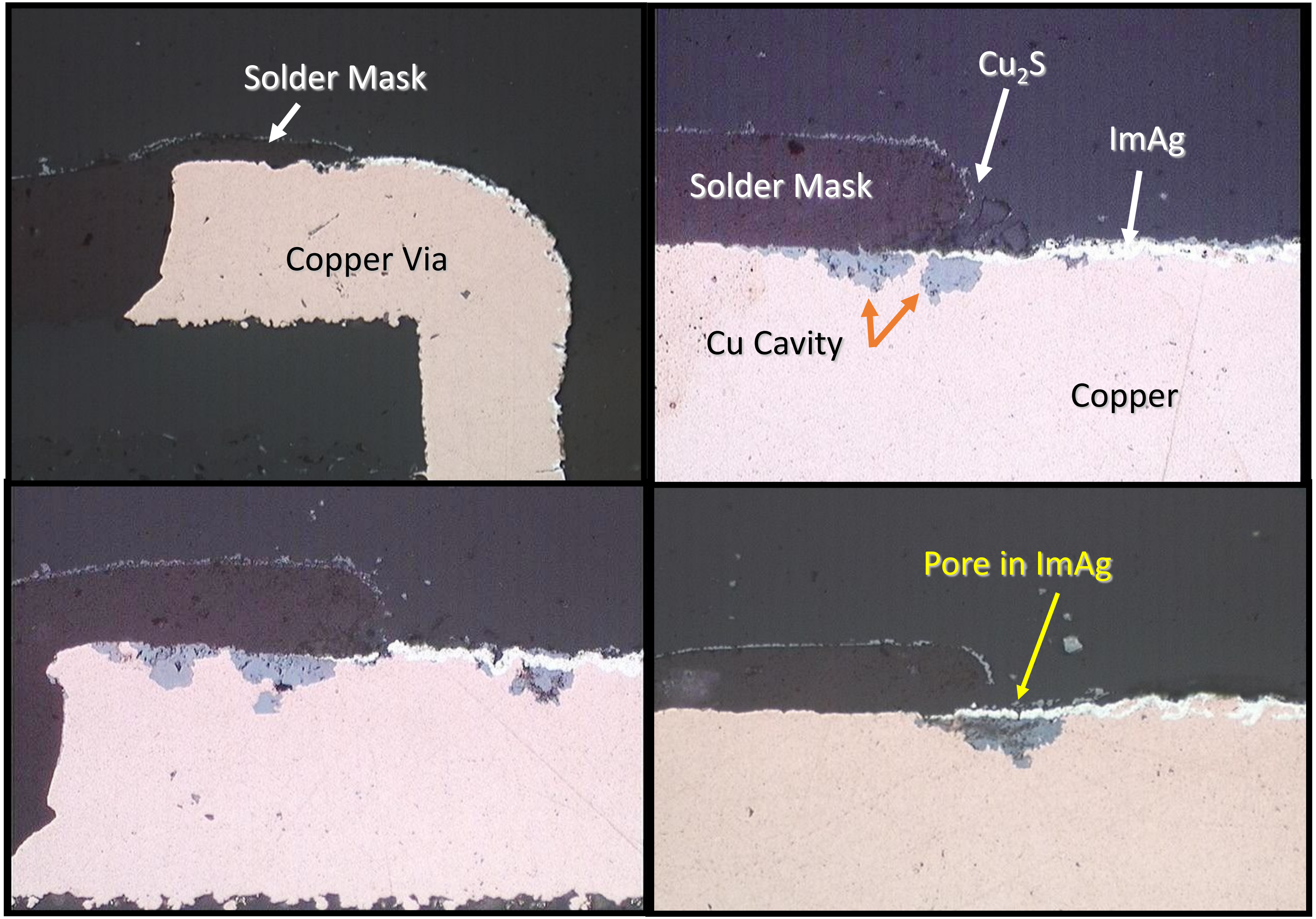


Creep Corrosion Mechanism

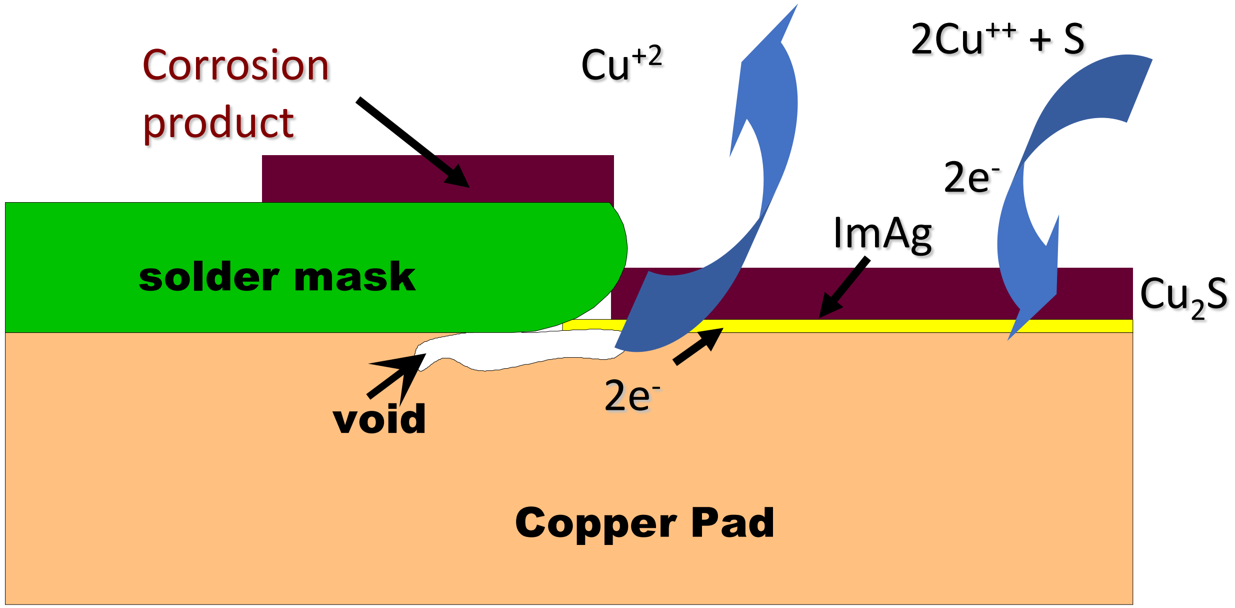
- Cross-section image of solder mask defined edge.
- Copper is attacked to form Cu_2S.



Failure Mechanism (Cross-Section Examples)



Exposed Cu at Solder Mask Interface Allows Galvanic Corrosion to Take Place

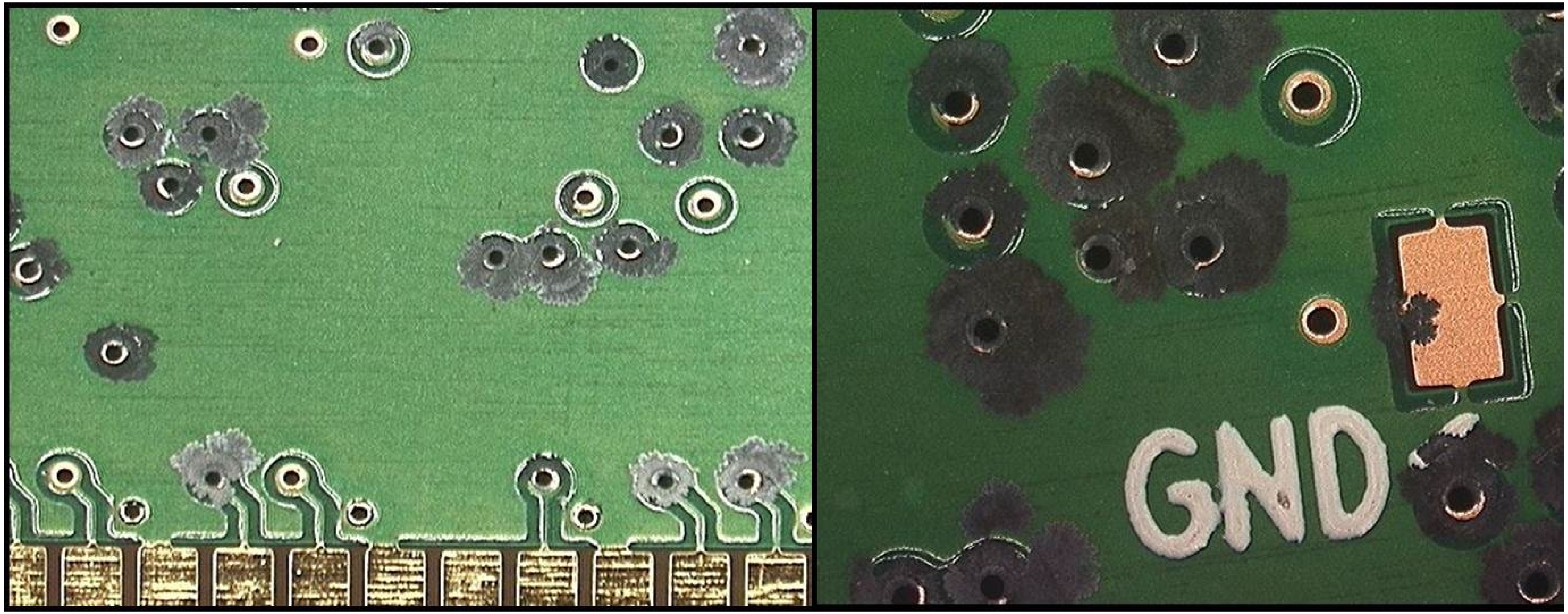


- A thin pool of moisture will form on a surface at RH >50% (film thickness depends on hydroscopic properties of the material).
- Pool absorbs active sulfur.
- This electrolyte enables transfer of Cu^{++} into solution where it reacts with S and deposits as Cu_2S (non-soluble in water).

Condensation

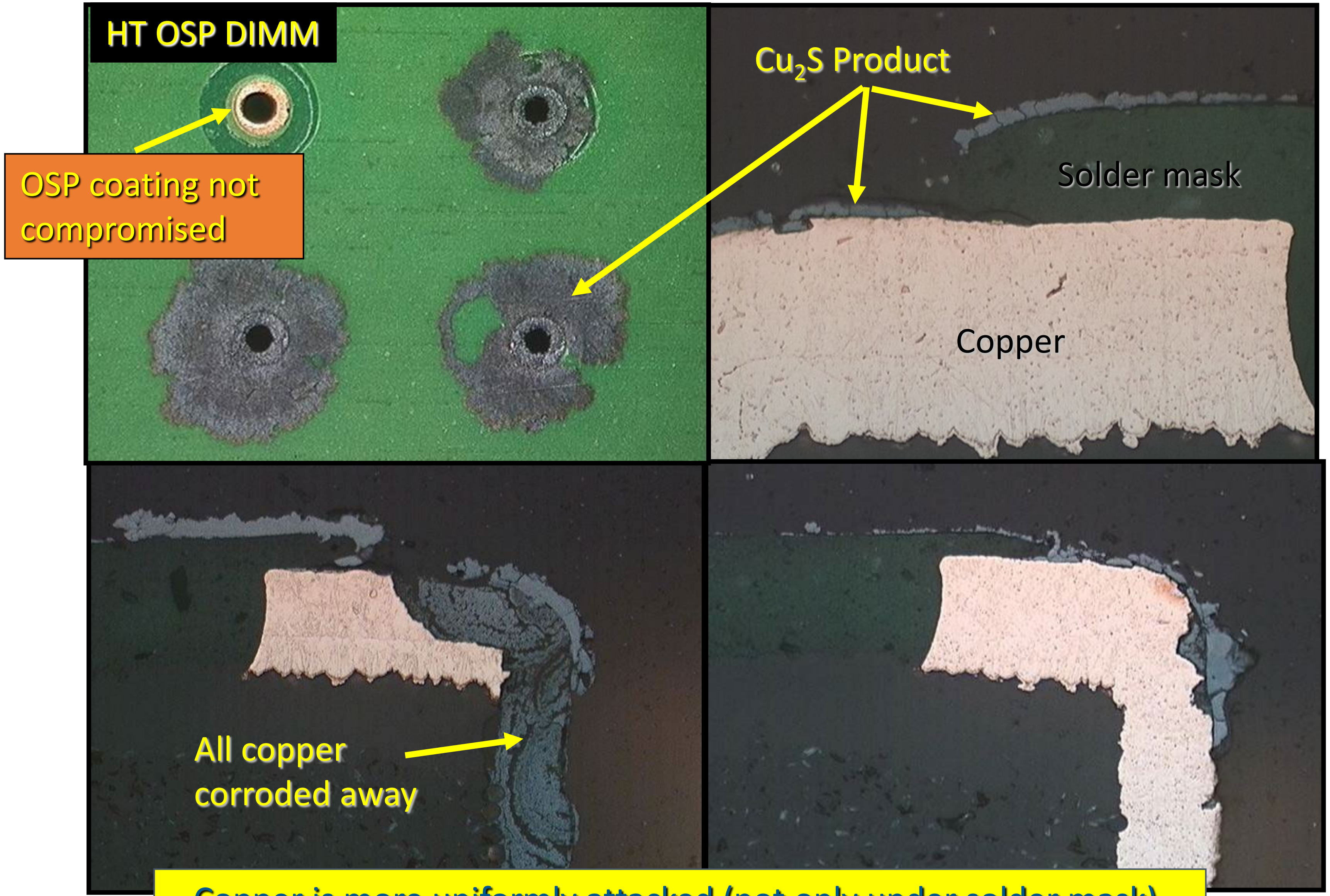
- What is condensation?
  - When surface moisture becomes visible?
  - The amount of adsorbed moisture at 100%RH?
- Film thickness can range (metals)
  - Minimum (10 monolayers of moisture)
  - Dew (~1,000 monolayers of moisture)
  - Raindrops (~10,000 monolayers of moisture)
- When does condensation occur?
  - At 100%RH
  - When the surface temperature is below the dew point
  - Presence of **cracks** and delaminations
  - Surface is Hygroscopic
- Impact of condensation
  - Sulfur compounds brought to surface with moisture
  - Weak acid is formed on the surface (breaks down CuO_2).
  - Copper sulfide creep is sensitive to condensation.

DIMM Corrosion (OSP)



- In severe environments even OSP surface finish can creep corrode (galvanic reaction not required).
- This example was from an ink stripping area in a paper mill (high sulfur and high humidity)

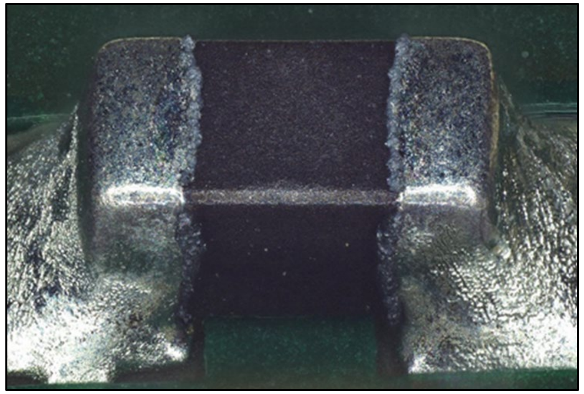
Cross-Section of Vias (OSP Finish)



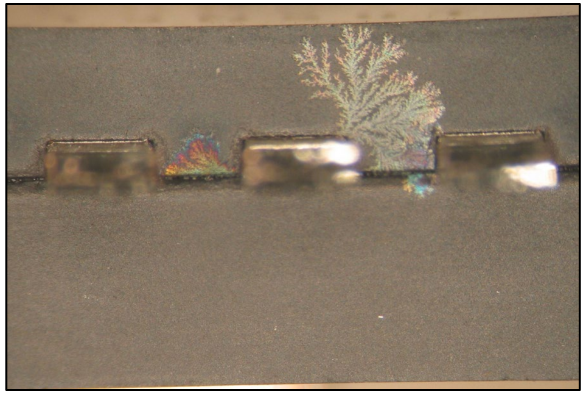
Copper is more uniformly attacked (not only under solder mask).

Where Does Creep Corrosion Occur?

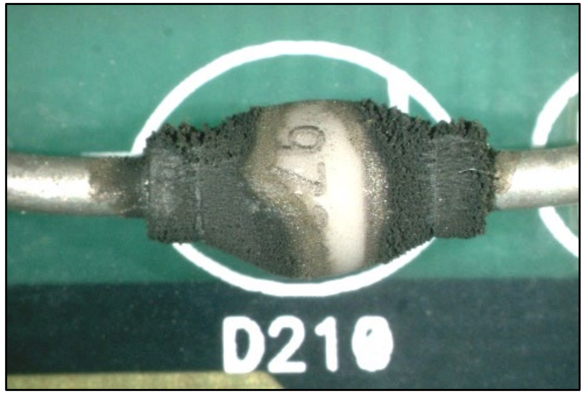
Impacts of Industrial Environments – Components



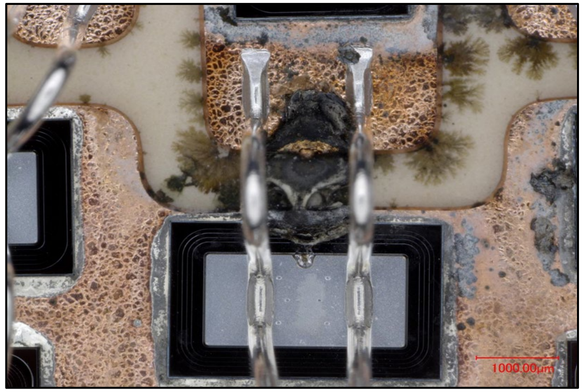
Tire and Rubber



Pulp and Paper

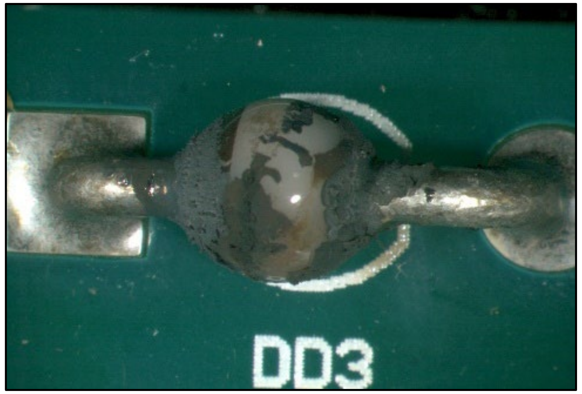


Oil and Gas

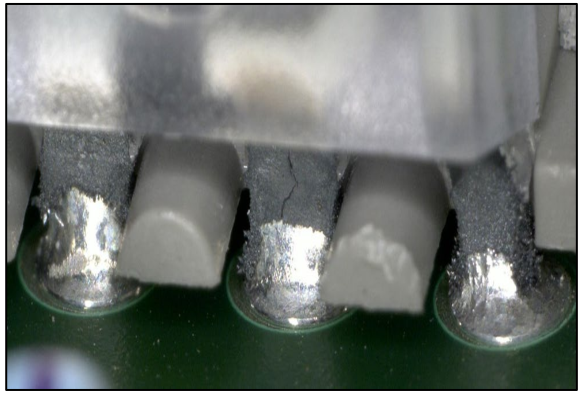


Food and Beverage

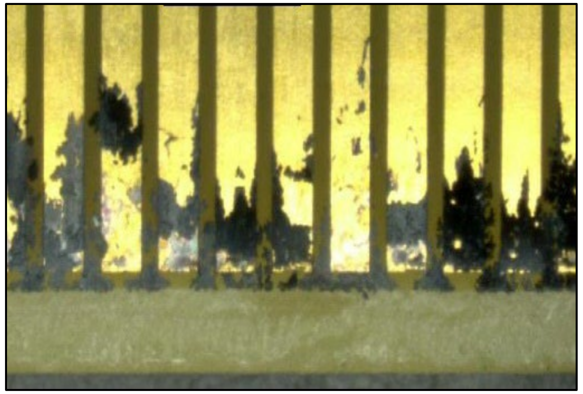
Application environments can negatively impact the life of industrial electronics



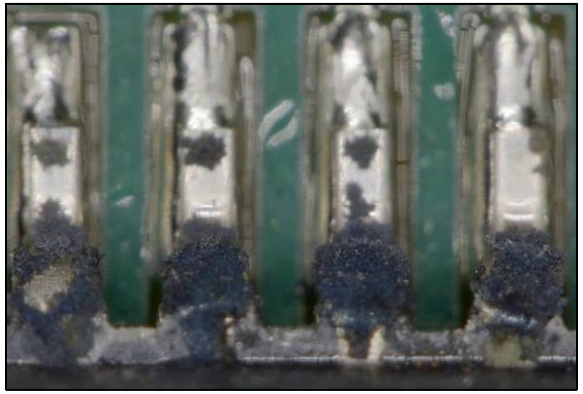
Water and Wastewater



Mining, Materials, Cement



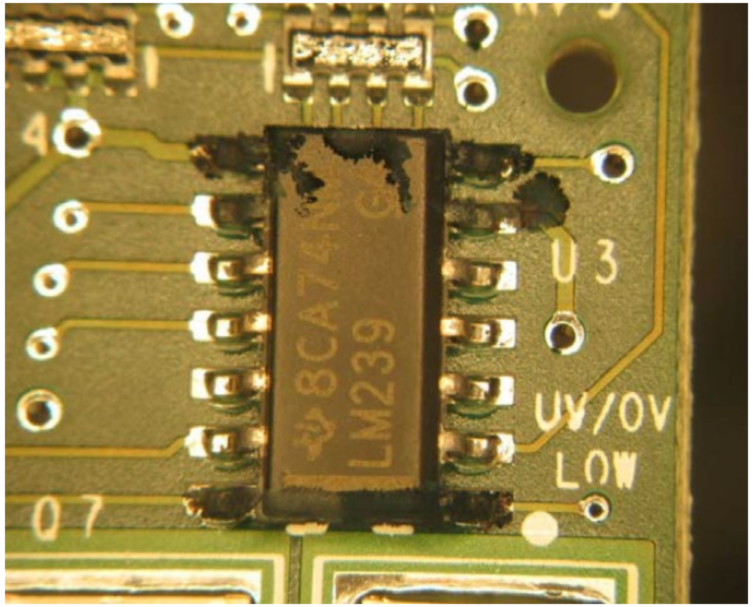
Entertainment



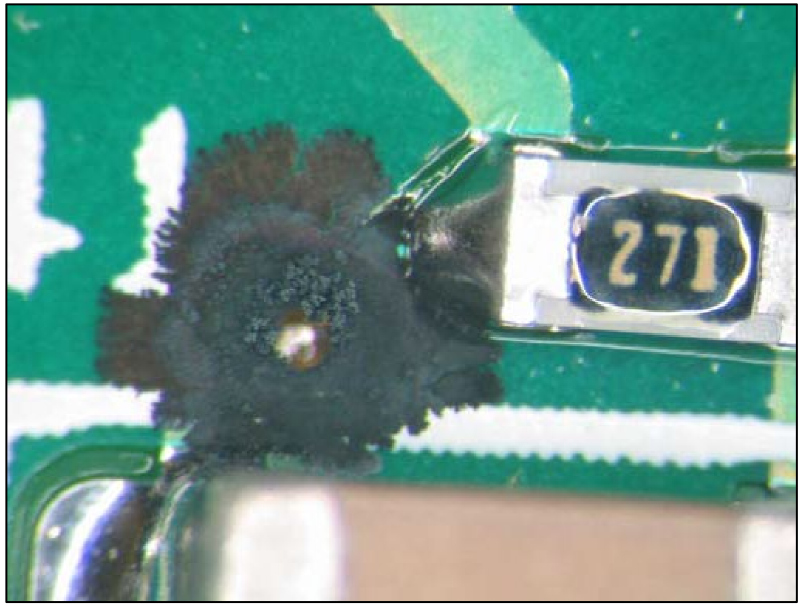
Transportation

Courtesy of Rockwell Automation

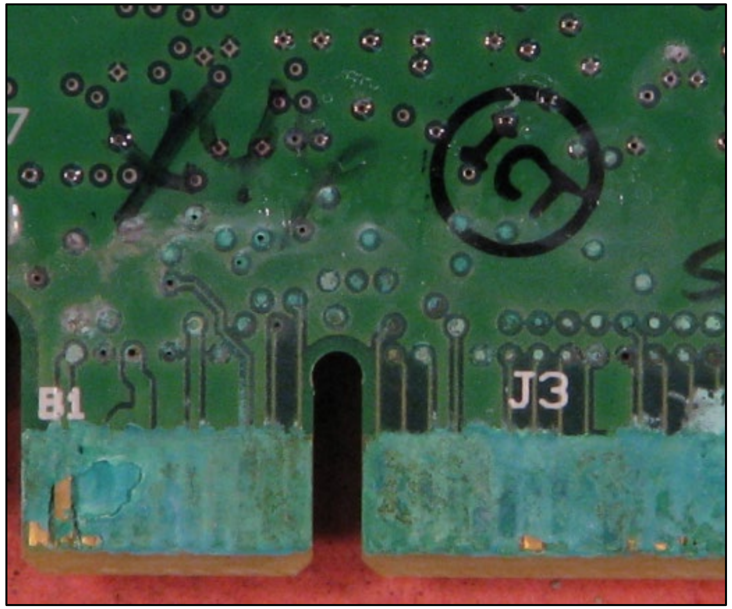
Impacts of Industrial Environments – Products



Creep corrosion (pulp & paper)

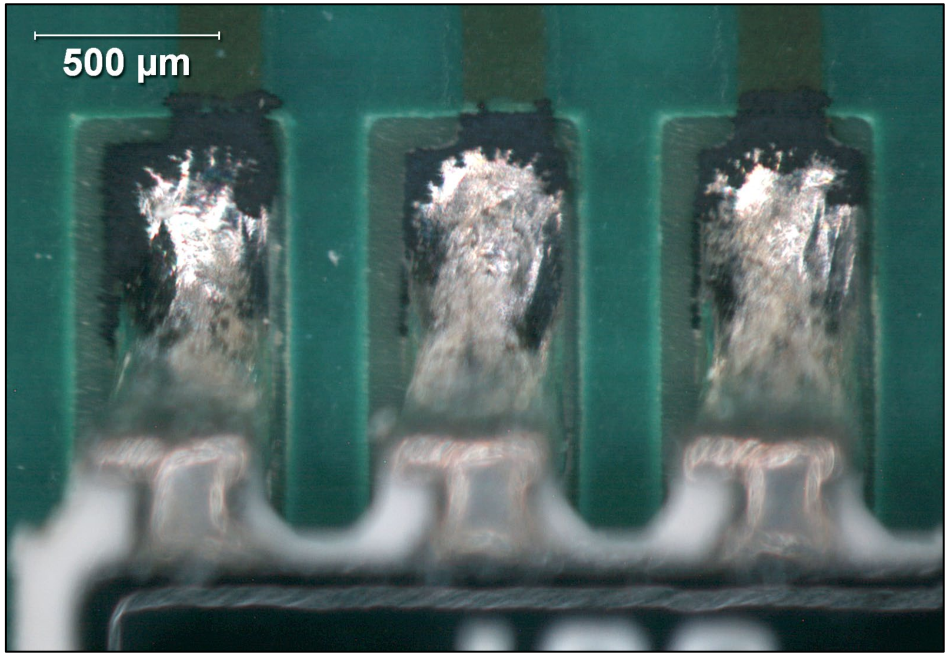


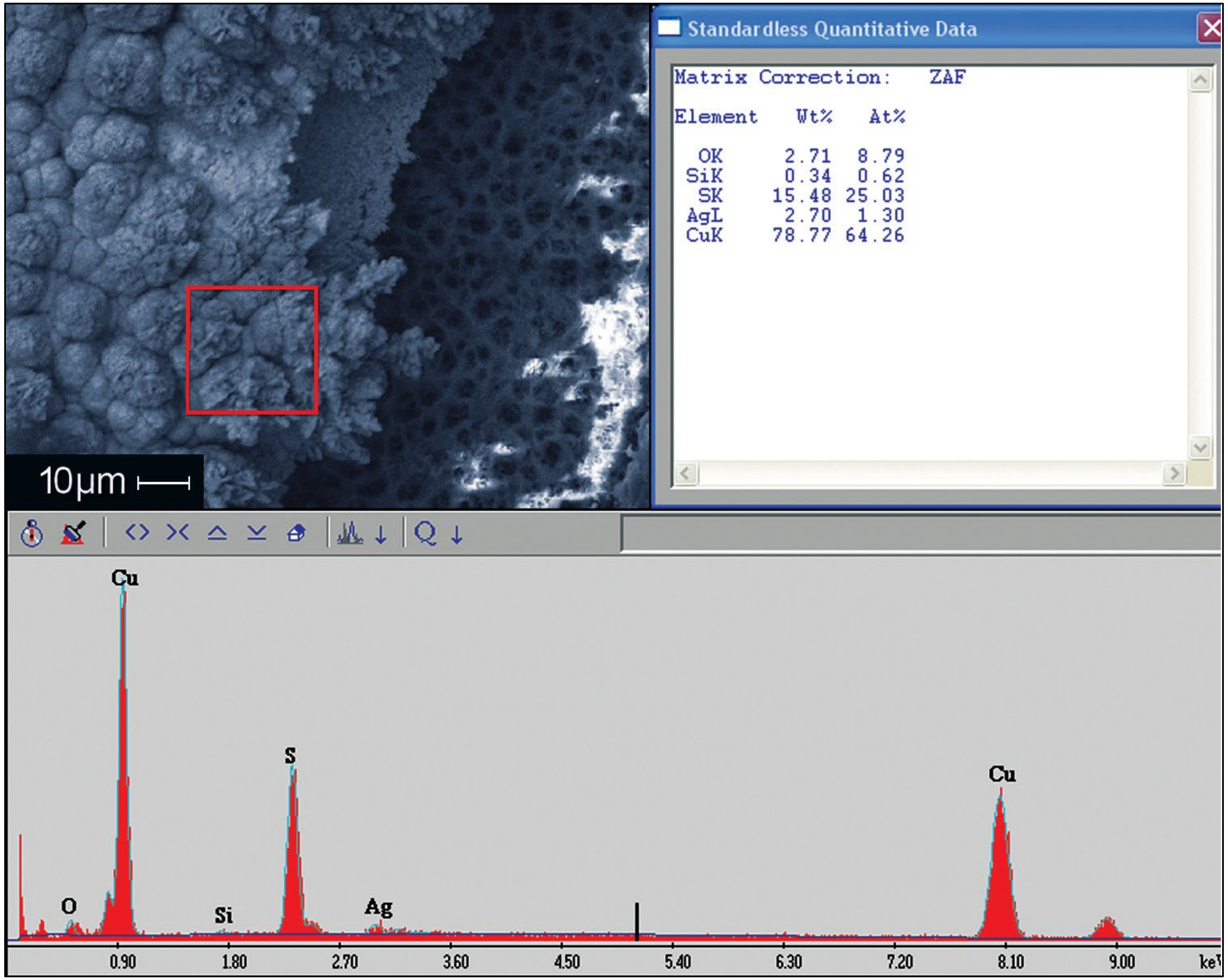
Creep corrosion (sewage treatment)



$CuCl_2$ corrosion on *copper edge connector from moisture* containment

Impacts of Industrial Environments





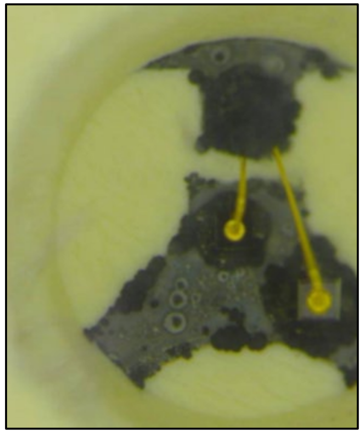
Creep corrosion observed on a telecom PCBA deployed to Southeast Asia.

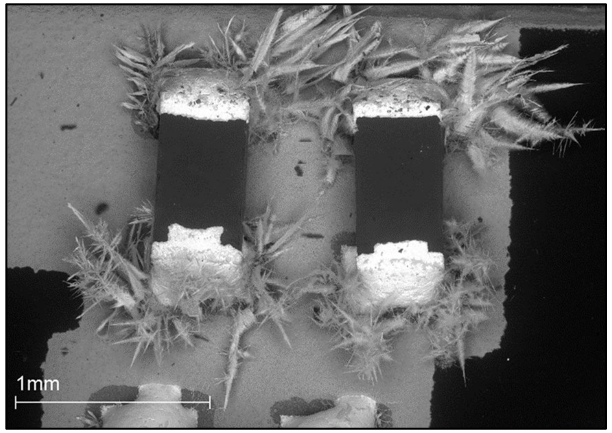
Similar failures experienced with industrial controllers in Western Europe within six months of installation.

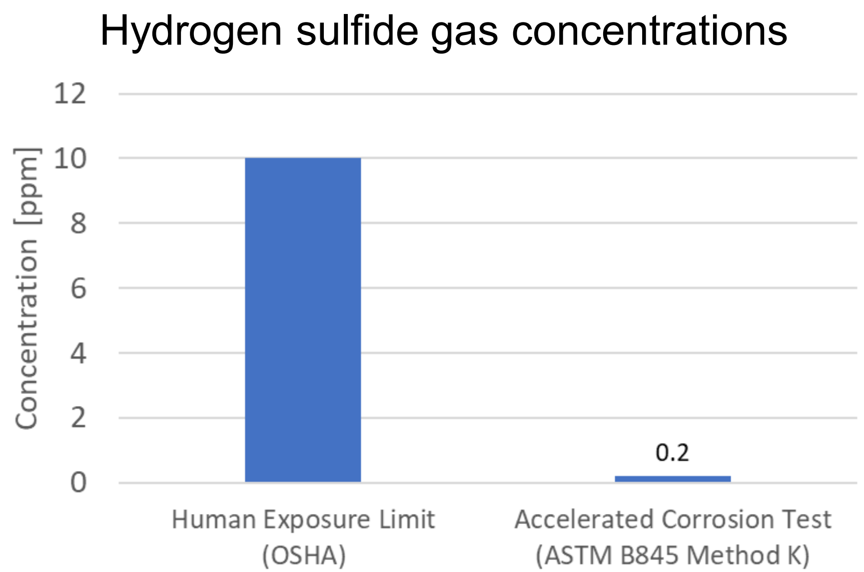
- *Courtesy of S. Clancy from ACI Technologies*

Impacts of Environment

- Electronic components can experience corrosion in certain environments
  - Construction methods and the materials used are factors
- Low levels of contaminates can cause significant corrosion issues on electronic assemblies: typically, copper (Cu) or silver (Ag)
  - Cu or Ag doesn’t necessarily have to be directly exposed
  - Contaminants can diffuse through adhesives, coatings, and other polymeric encapsulates
- Environmental contaminant concentrations are typically **well below established human exposure limits**
  - Users of industrial electronics don’t identify the contaminants as a concern
  - Contaminant concentrations can exist in magnitudes as low as a few parts per billion (ppb)



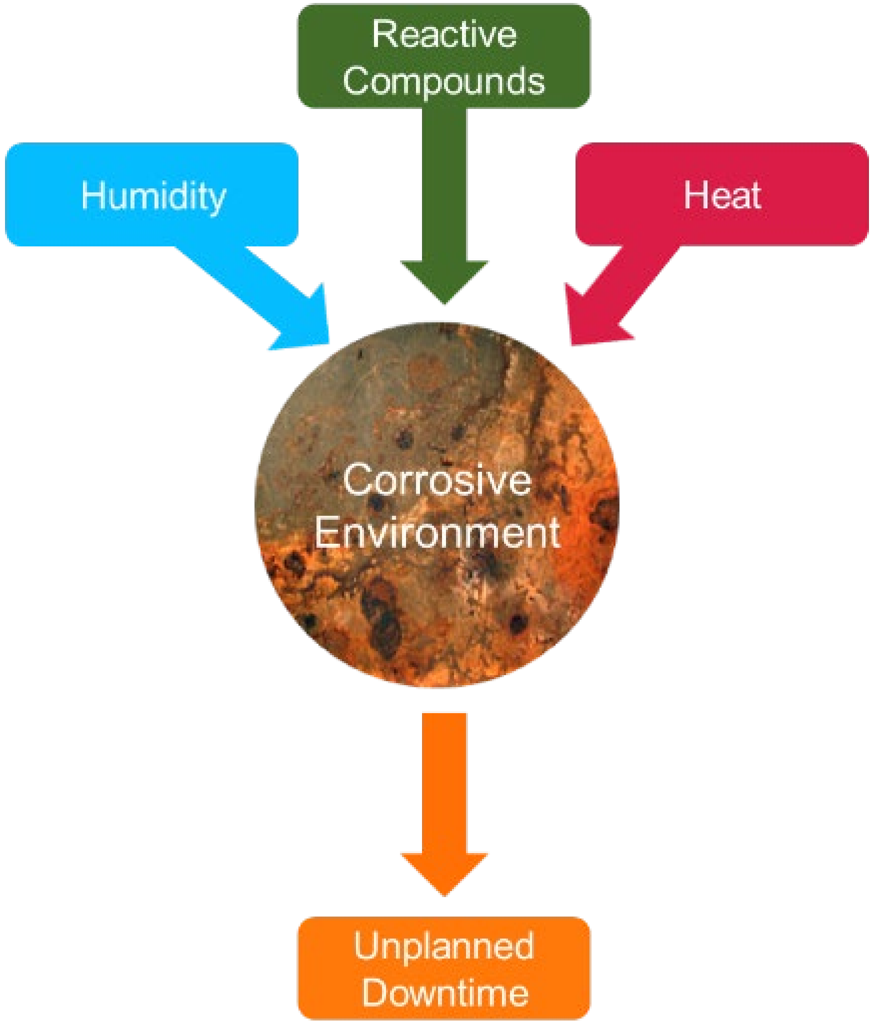




H_2S gas concentration: limits for humans and levels for a harsh accelerated corrosion test used for electronics.
(10ppm is 8-hour personal exposure limit per OSHA)

Impacts of Environment

- Air flow
  - Increasing air flow typically increases corrosion rate
- Humidity
  - Can alter which metals become most impacted by corrosion
  - Increasing humidity typically increases copper corrosion rate
  - Cyclical humidity may increase corrosion rate
- Temperature
  - Increasing temperature typically increases corrosion rate
  - Temperature cycling may induce localized condensation that can further increase corrosion rate
- Environments – Macro vs Micro
  - Each area (process, room, etc.) may have different environmental factors
  - Environmental conditions in a specific area may not match micro-environment inside a product
  - A single product may have multiple micro-environments



- *Courtesy of Rockwell Automation*

Classification of the Environment

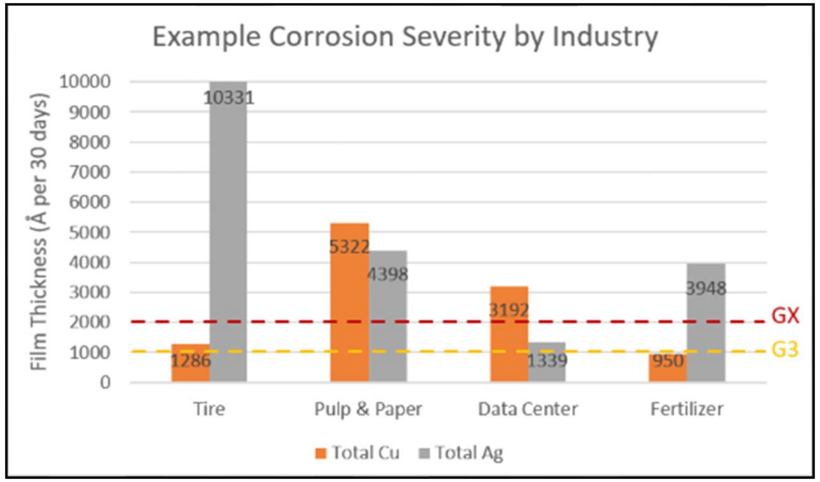
Atmospheric Corrosion Severity, Also Called "Reactivity"

Use a standard that considers: Reactivity of copper and silver, impact of multiple reactive compounds, temperature and humidity. ANSI/ISA 71.04-2013 is a good choice.

- Corrosion classification coupons – Low cost, short time for results
- Each coupon contains a strip of copper and silver along with a temperature and relative humidity logger.
- Place coupons around facility, inside and outside of enclosures.
- Coupons are placed in the environment for 30 days then removed and sent back to coupon vendor for analysis.
- **Coupon vendor provides reports detailing corrosion rate observed, trend plots of temperature and humidity, and classification per ANSI/ISA 71.04-2013, Airborne Contaminants – Gases.**

Severity Level	G1 Mild	G2 Moderate	G3 Harsh	GX Severe
Copper Reactivity Level (Å per 30 days)	<300	<1000	<2000	≥2000*
Silver Reactivity Level (Å per 30 days)	<200	<1000	<2000	≥2000*

*No upper limit for GX



Courtesy of Rockwell Automation

How Do You Test for Risk of Creep Corrosion?

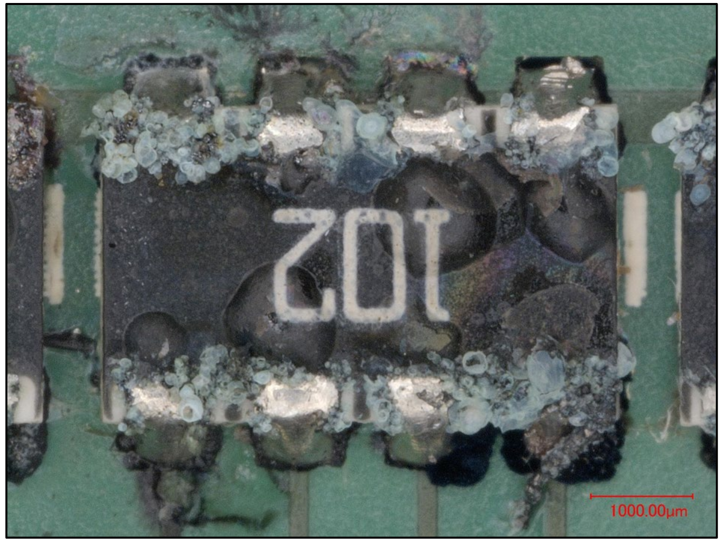
Application Environment vs. Accelerated Testing

- Know the application environment
  - Coupon exposure
  - Air sampling

- Does the test method reproduce the application corrosion mechanism
  - There are many ways to get to a specific corrosion rate, but not necessarily the correct mechanism

- Standard mixed flowing gas testing does a good job of recreating the creep mechanism
  - If the test is not creating all corrosion mechanisms found in application, multiple accelerated tests may be necessary

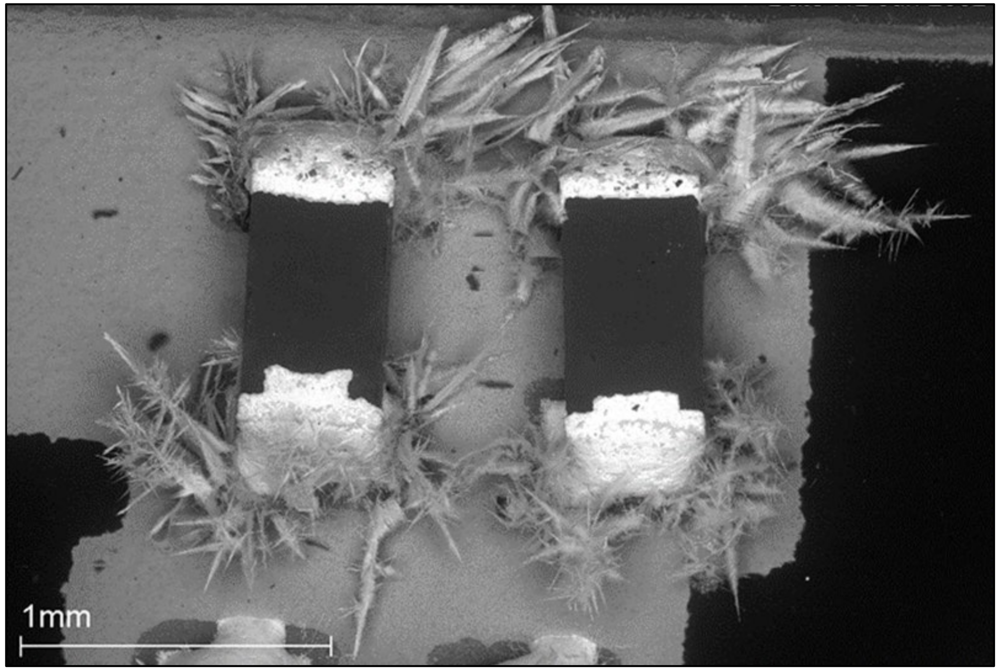
- Acceleration factors are determined by corelating time to failure in field to time to failure in test
  - Every corrosion induced failure mode may have a different acceleration factor



- *Courtesy of Rockwell Automation*

Accelerated Testing – Why Test?

- Validate failure analysis results
- Reproduce corrosion mechanisms found in the field
- Selection and evaluation of components
  - Validation of new designs
  - For specific environments
- Obtain reference information
- Determine material acceptance requirements, performance/quality control parameters
- Develop/evaluate corrosion control and monitoring programs
- Determine most economical means of control
- Determine future research areas
  - Material selection
  - Control methods
  - Environment development
- Benchmarking
  - Lot to lot (over time)
  - Vendor to vendor
- Determine probable service life



Many times, more than one test is needed to determine adequate corrosion performance

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Test Methods for Electronics – Examples

- ASTM B845 Mixed Flowing Gas (MFG) Tests for Electrical Contacts
  - Thirteen test environments defined, mild to very harsh
- ISO/IEC 60068-2-60 Flowing Mixed Gas Corrosion test
  - Four environments defined, mild to harsh
- EIA-364-65 Mixed Flowing Gas Test Procedure for Electrical Connectors, Contacts, and Sockets
  - Six environments defined, mild to harsh
- ASTM B 809: Standard Test Method for Porosity in Metallic Coatings by Humid Sulfur Vapor (“Flowers of Sulfur”)
  - To determine plating porosity for silver, copper, or copper alloy substrates
- EIA-977 Electronic Passive Components Exposure to Atmospheric Sulfur
  - 60 °C and 105 °C FoS tests
- …and there are others
- ….and there are many modifications to exiting defined test environments

ASTM G85 Annex 4, Modified Salt Fog, SO_2, Salt Fog, Cyclic

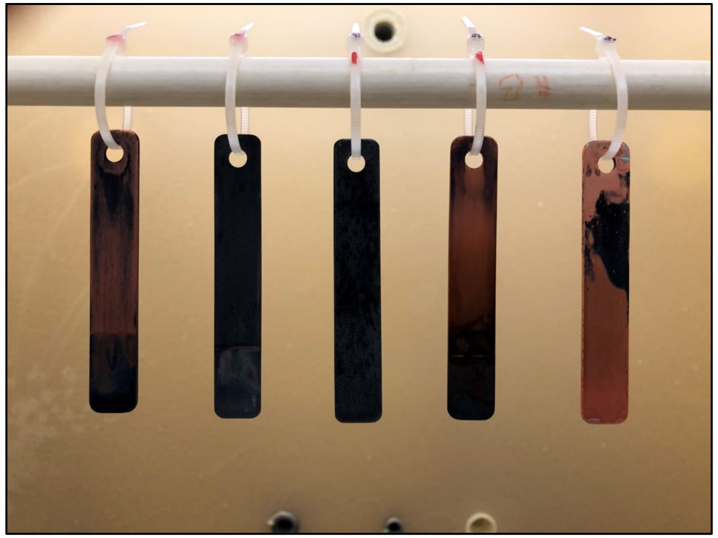
- Most test specifications define an environment
  - For most, how you use it is up to you
    - Duration
    - Corrosion rates
    - What does “passing” mean

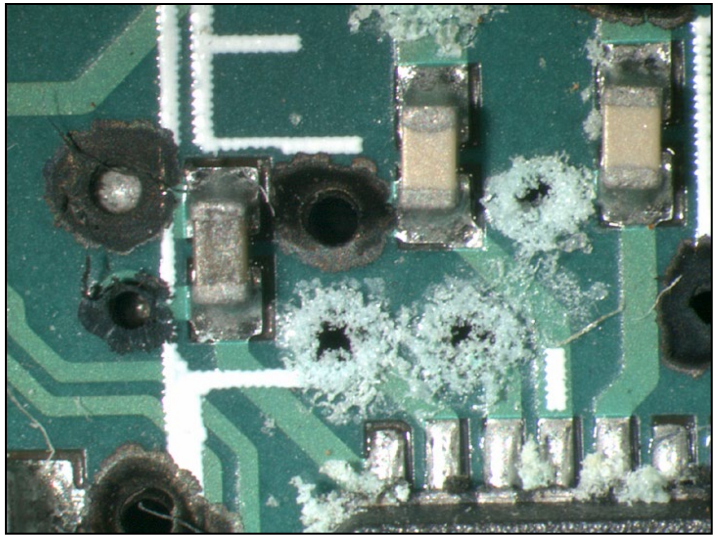
Courtesy of Rockwell Automation

Mixed Flowing Gas Testing

- Specifically defined gas concentrations, temperatures, and humidity levels
  - Synergistic effect between gases
  - Test designed to generate different types of corrosion mechanisms in varied application environments

- Test design rationale – Specific ionic compounds, or combination of compounds, will attack specific material systems
  - Sulfur compounds
    - Copper, silver, nickel
  - Chlorine compounds
    - Tin, stainless steel, steel, copper, lead........
  - NOx
    - Good oxidizing agent
  - Humidity
    - Needed for ion exchange
  - Heat
    - Increase rates





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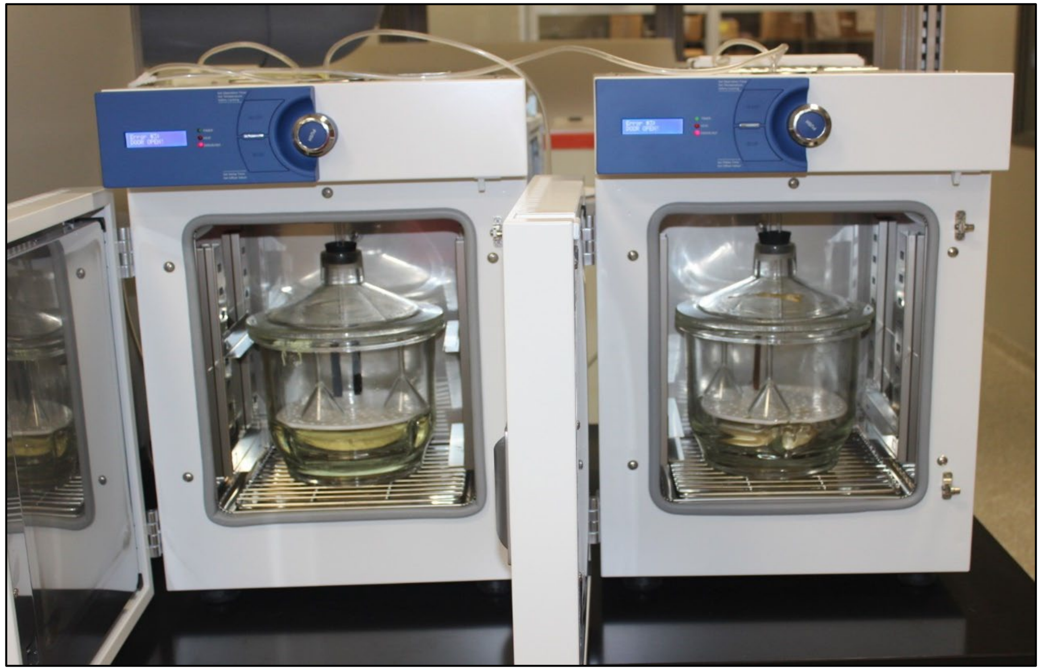
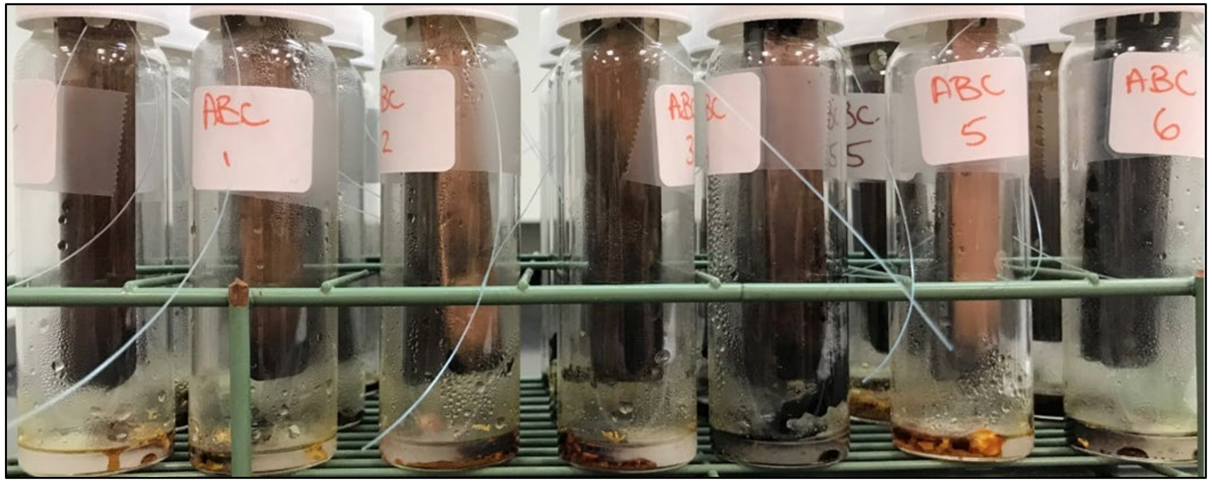
Flowers of Sulfur (FoS) Testing

- Elemental sulfur exposure
- Certain mechanism can be induced or accelerated
  - Vary temperature
  - Vary humidity
  - Add other contaminants
  - Vary duration





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Accelerated FoS Variant Testing – One Example

Found it is relatively easy to go a little too far with aggressiveness of environment

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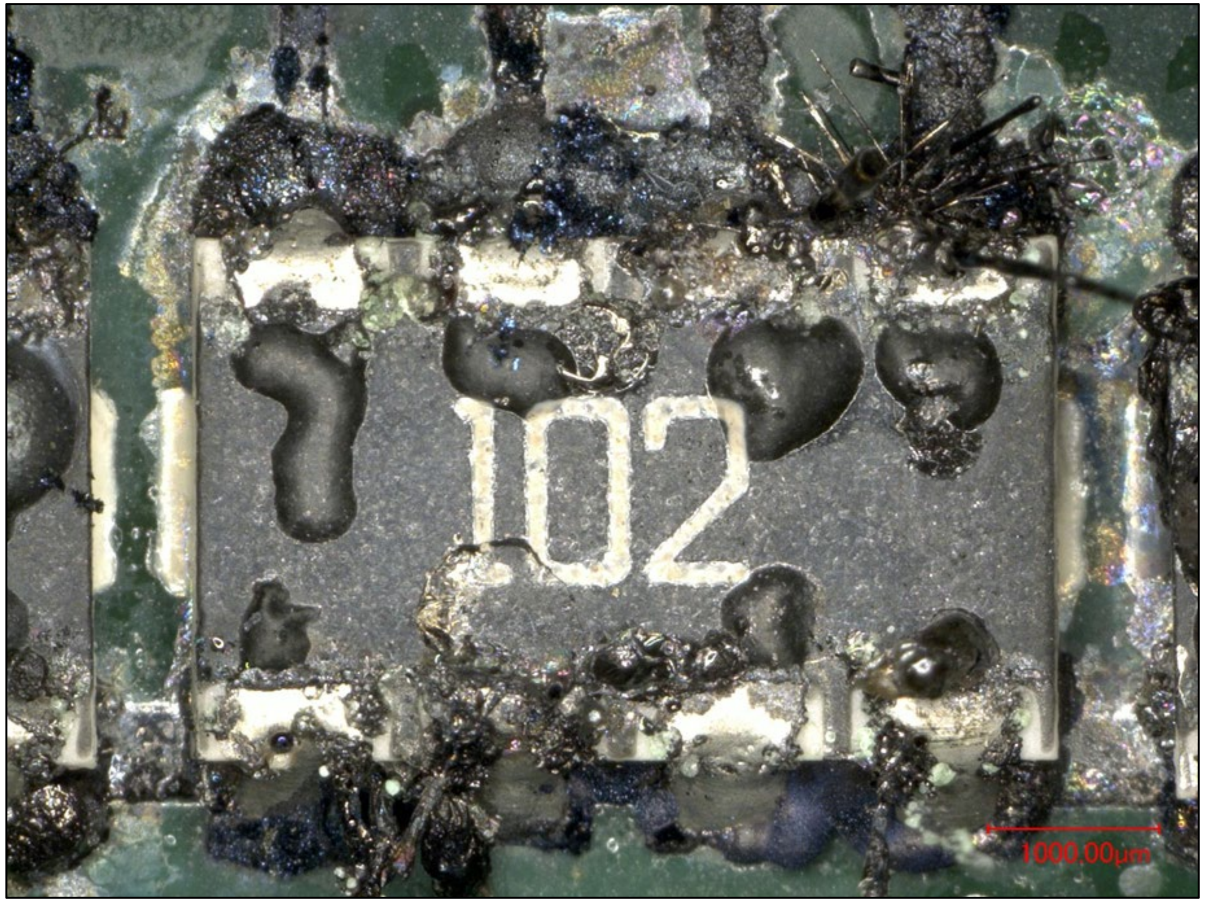
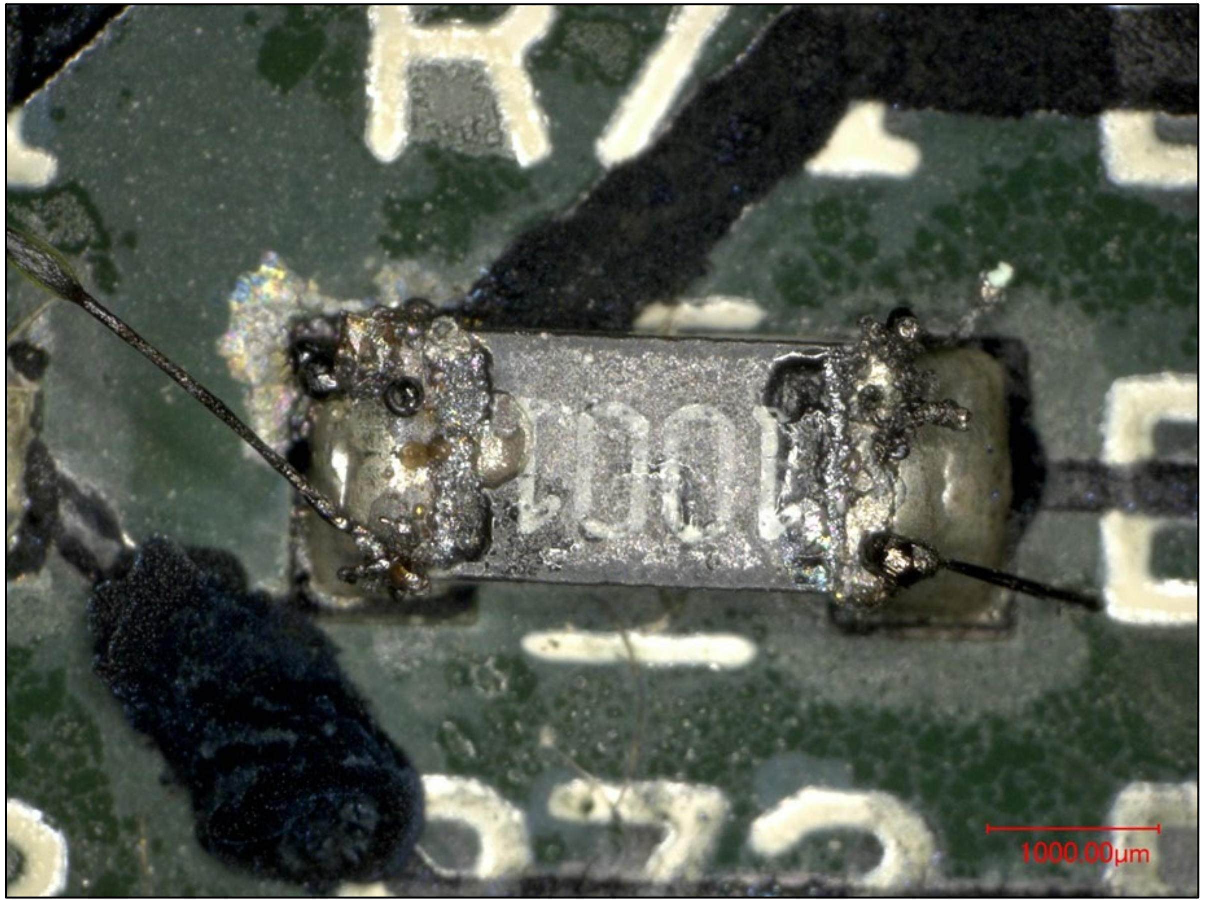
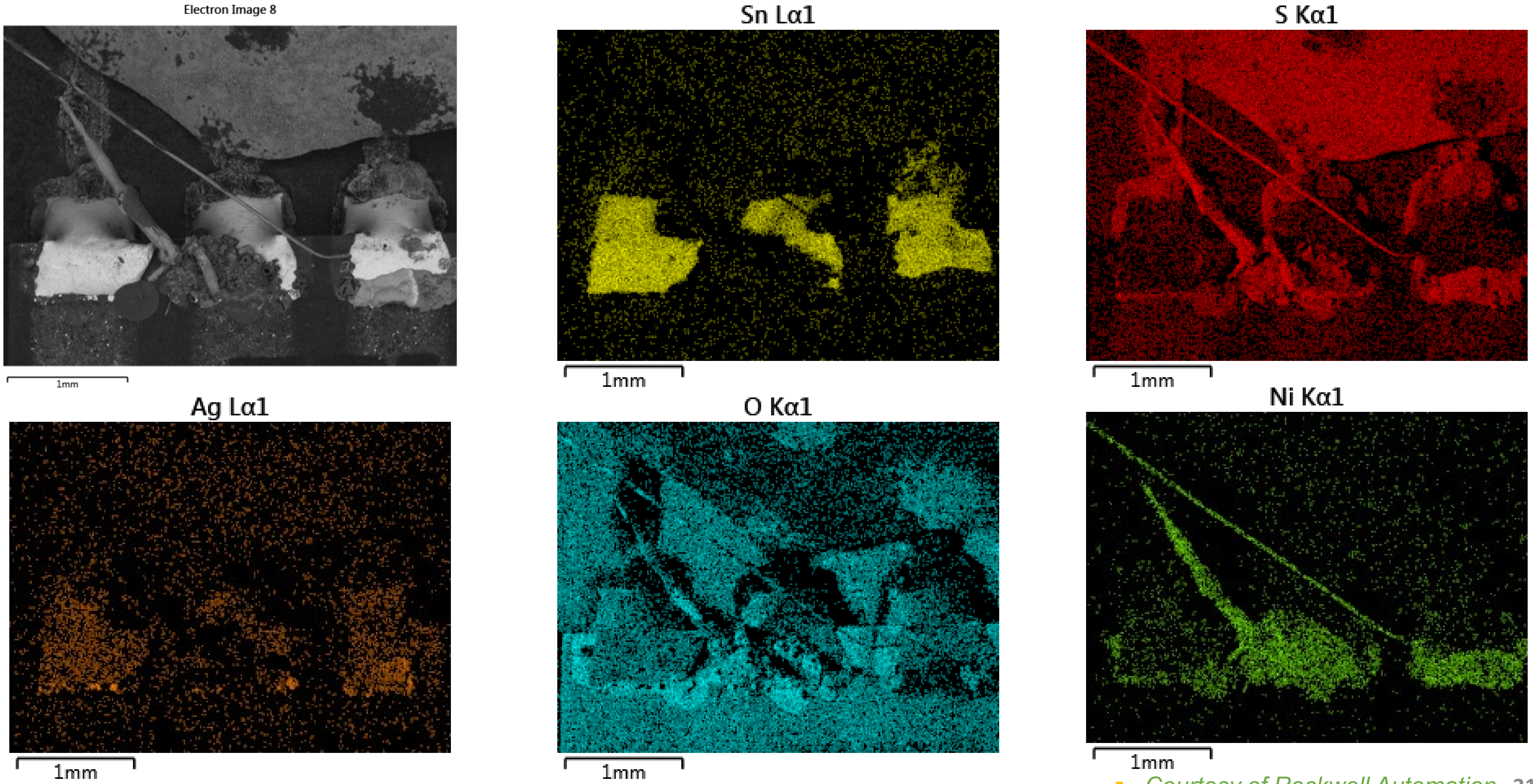
Accelerated FoS Variant Testing – Another Example

Inducing unwanted corrosion mechanisms





Whiskers?



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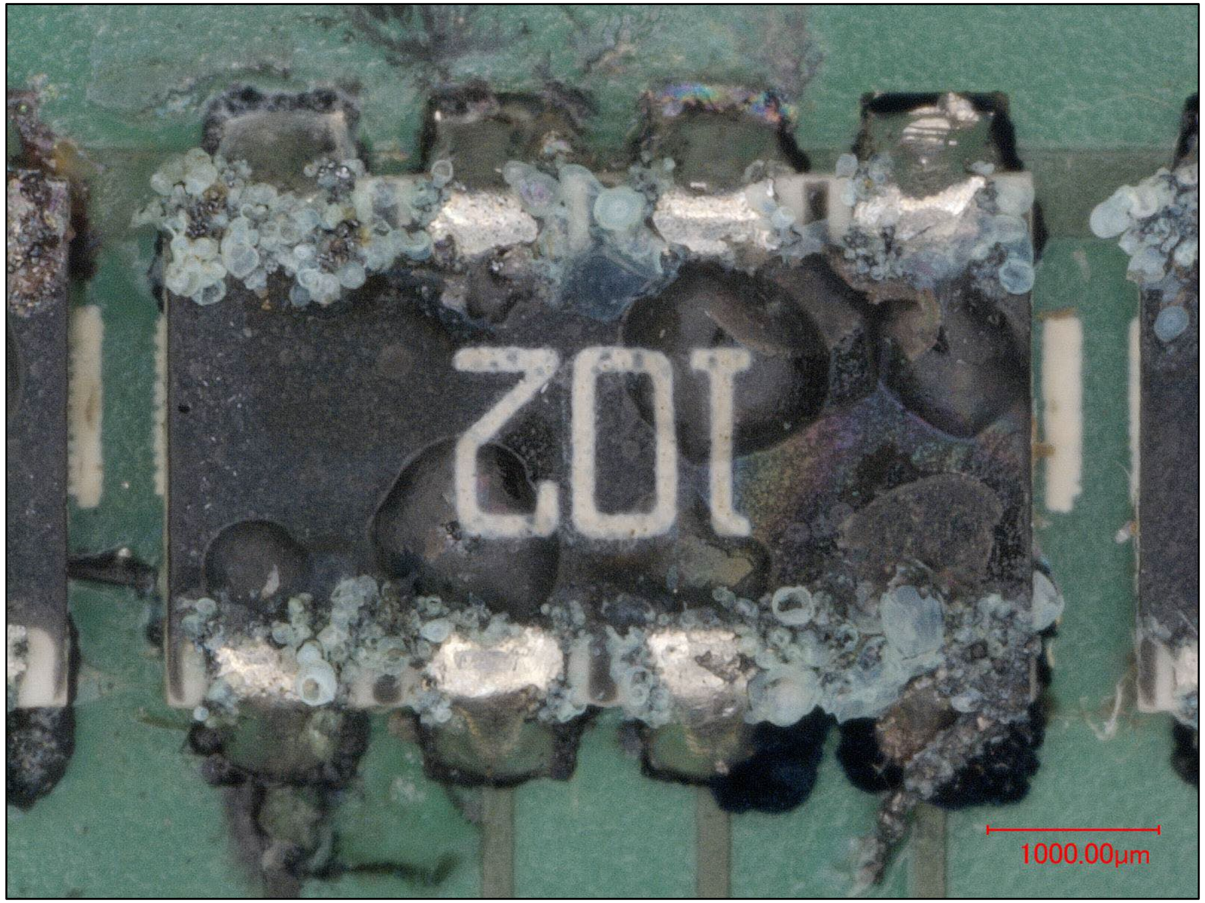
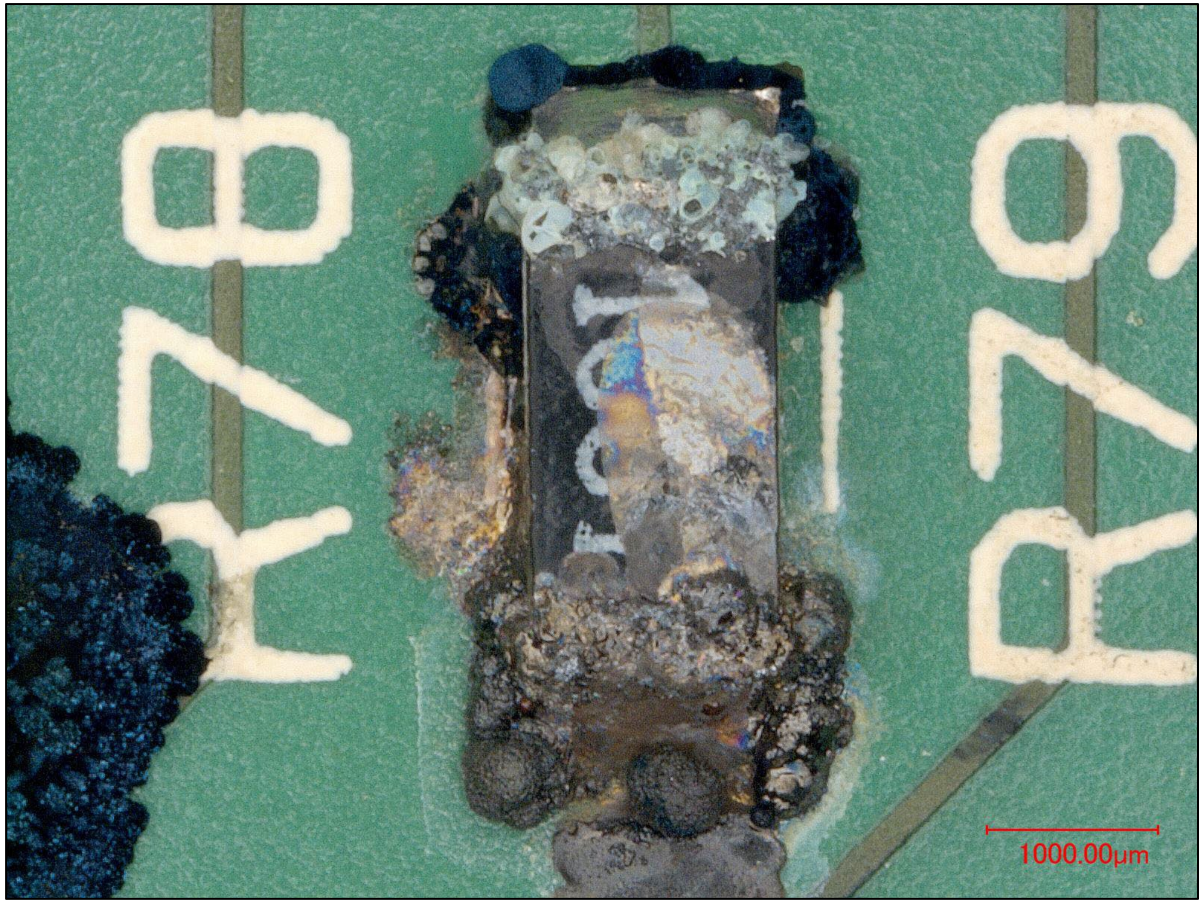
Back Off the Temperature

Slowed the nickel sulfide whisker growth, ended up with more nickel oxide/hydroxide growth





Corrosive Gas Accelerated Test Examples

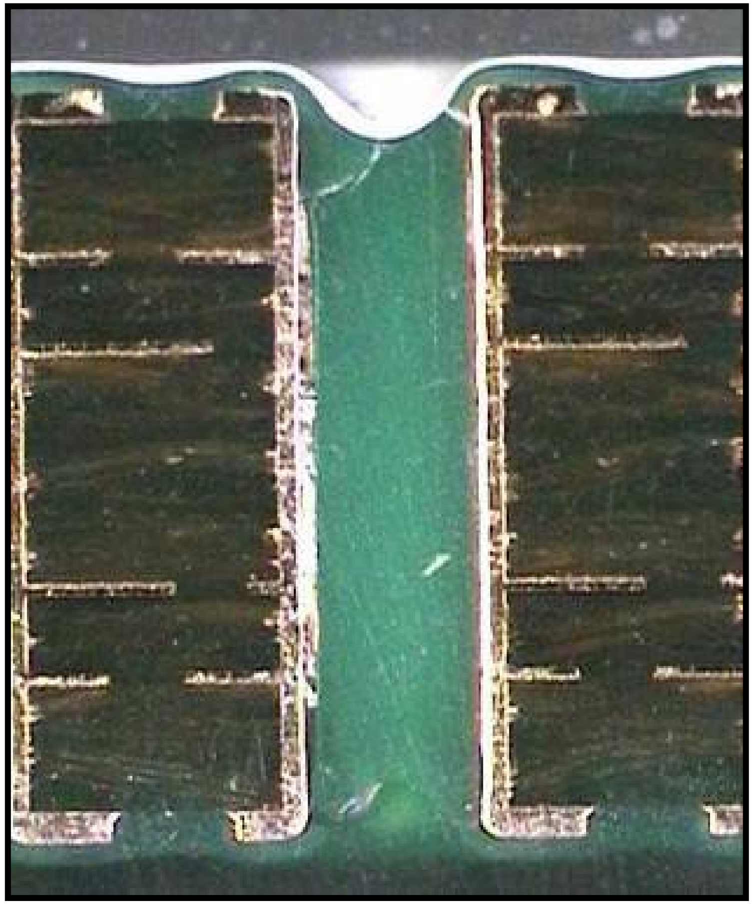
- Some corrosion mitigation techniques have excelled in extremely corrosive environments, such as:
  - Flowers-of-Sulfur simulates sulfurous atmospheres from air pollution, due to coal power plants, the oil & gas industry, clay or paper processing, etc.
  - Mixed Flowing Gases simulates and amplifies the types of gases that may be found in an industrial environment
  - Sulfur-Based Clay Test also simulates sulfurous atmospheres from air pollution

- Flowers-of-Sulfur (FoS)
  - 530 to 1500 ppb Sulfur
  - 60 to 71 °C
- Mixed Flowing Gases (MFG)
  - Duration: 10 days
  - Temperature: 50 °C
  - Relative Humidity: 75% RH
  - Hydrogen Sulfide: 200 ppb
  - Sulfur Dioxide: 200 ppb
  - Nitrogen Dioxide: 200 ppb
  - Chlorine: 50 ppb
- Sulfur-Based Clay Test
  - Chavant J-525 Industrial Hard Styling Clay
  - Add water to wet clay and heat in microwave
  - Place warm, wet clay in sealed container with samples

How Do you Reduce the Risk of Creep Corrosion?

Modify Design of PCB – Surface Finish Selection, etc.

- Eliminate use of ImAg on Cu
  - Ag on Ni
  - OSP
  - LF HASL
- Cover exposed silver with solder paste (overprint pads)
- Plug vias with solder mask (or move them far apart)
- Use non-solder mask defined (NSMD) test points (and move apart)
- Minimize copper exposure with improved solder mask adhesion and/or increased thickness



Solder Mask Via Plug

Eliminate Sulfur Exposure

- Eliminate sulfur exposure
  - Air filters
  - Enclosures
  - Remote use of hardware
  - Eliminate airflow over PCBs
  - Conformal coatings

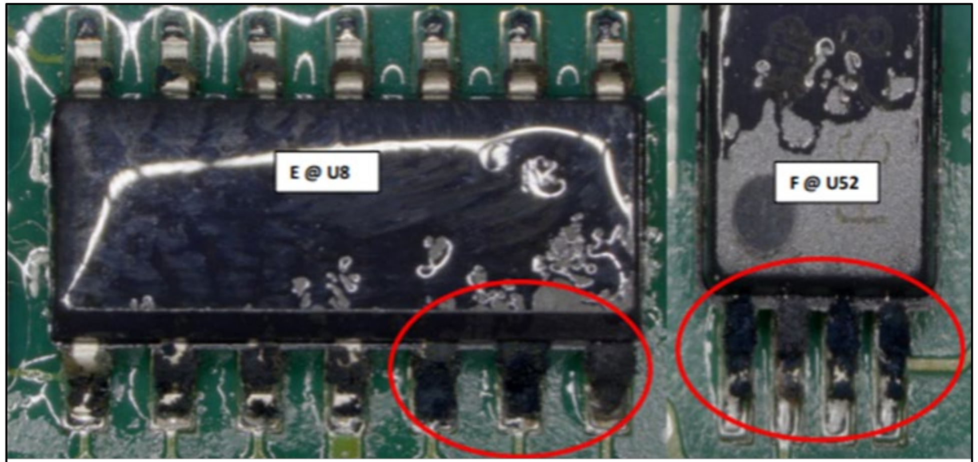
Conformal Coating Selection

Coating Type	**Properties**	**Comments**
Epoxy	Good adhesion Excellent chemical resistance Acceptable moisture barrier	Difficult to rework Needs compliant buffer Not widely used
Urethane	Good adhesion High chemical resistance Acceptable moisture barrier	Difficult to rework Widely used Low cost
Acrylic	Acceptable adhesion **Poor chemical resistance** High moisture resistance	Easy to rework Widely used Moderate cost
Silicone	Poor adhesion **Low chemical resistance** Excellent moisture resistance	Possibility of rework Moderate usage High cost
Parylene	Excellent adhesion Excellent chemical resistance Excellent moisture resistance	Challenging to rework large areas Batch Process Higher Cost

Solutions for Problematic Environments

There are many methods for solving corrosion issues, and some work better than others for specific environments

- Utilize a layered approach to corrosion prevention
  - Specify components with construction materials more robust to corrosive environments
  - Apply a coating to provide an additional layer of protection
- Different classes of coatings each have their pros / cons
  - Coating performance varies even within a specific material type
- Complete coating coverage of suspect areas is key for optimal performance
  - Consider the geometry of the area
  - Items that need to be coated and the methodology required for complete coverage

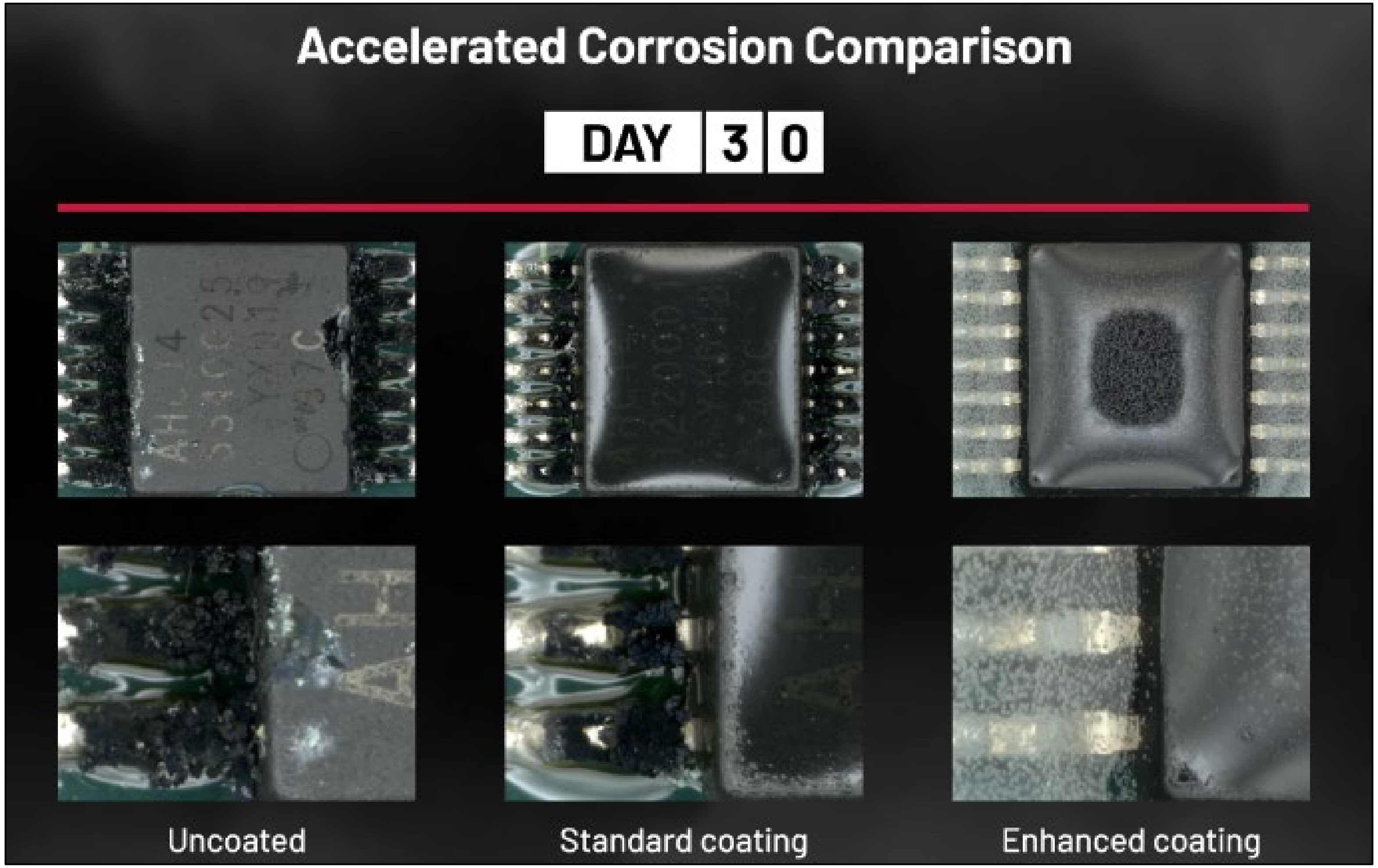


SMT with thin coating on lead and areas of missing coating

Courtesy of Rockwell Automation

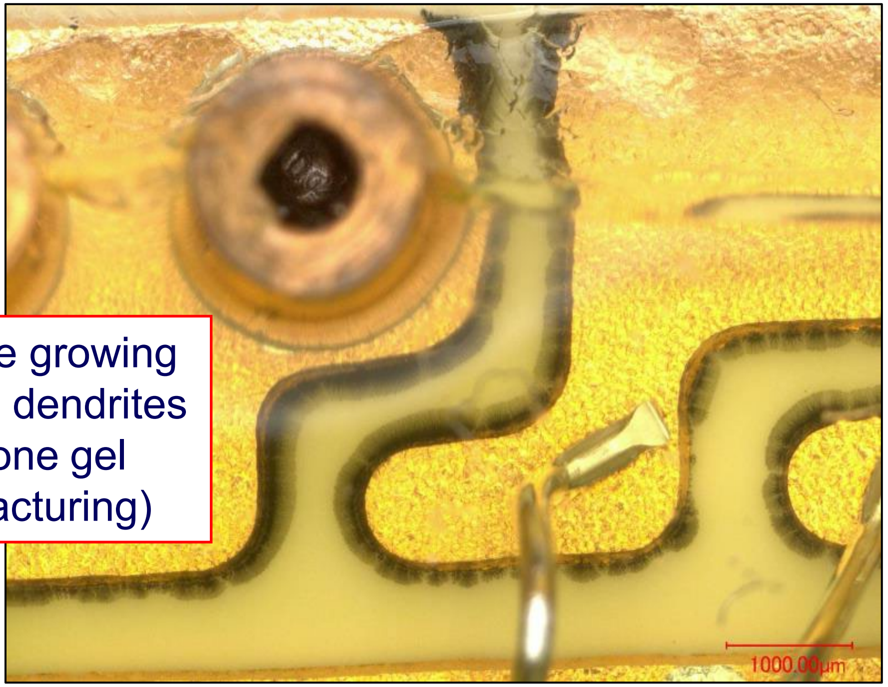
Solutions for Problematic Environments

If coating is going to be used for protection, complete coating coverage is key

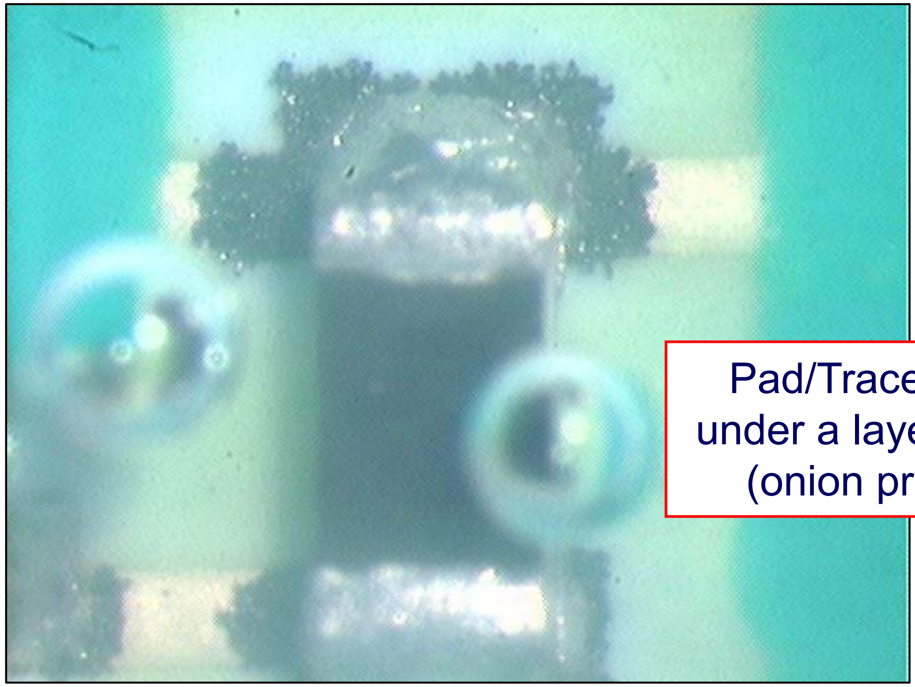


Solutions for Problematic Environments

- Contaminants that cause corrosion may not be similar from industry to industry
- Different contaminate chemistries can produce different reactions and have different permeability through coatings

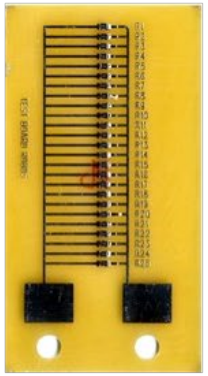


Power module growing copper sulfide dendrites under silicone gel (Tire manufacturing)



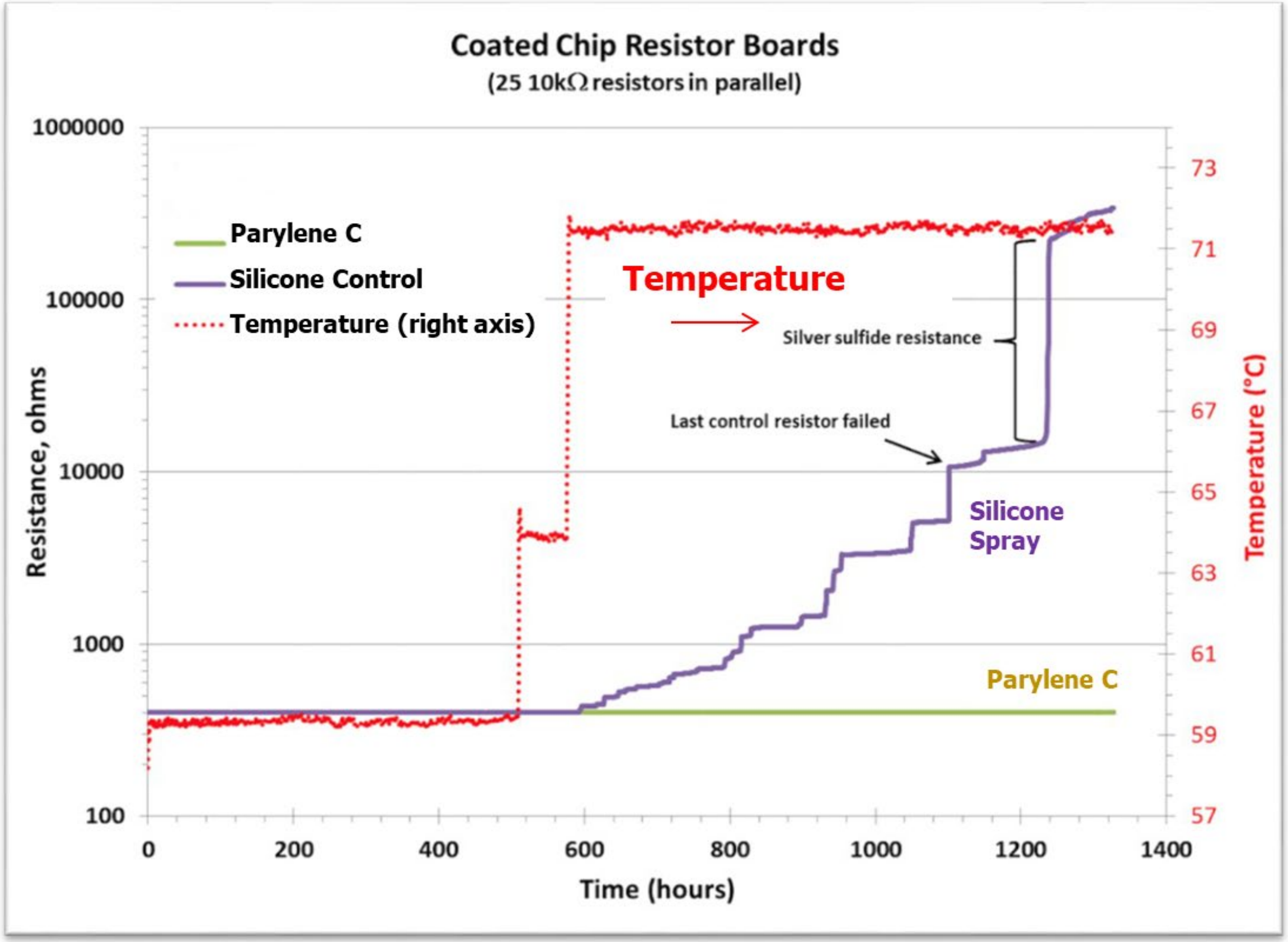
Pad/Trace corroding under a layer of silicone (onion processing)

Conformal Coatings – FoS – Silicone vs. Parylene



Coating Applied

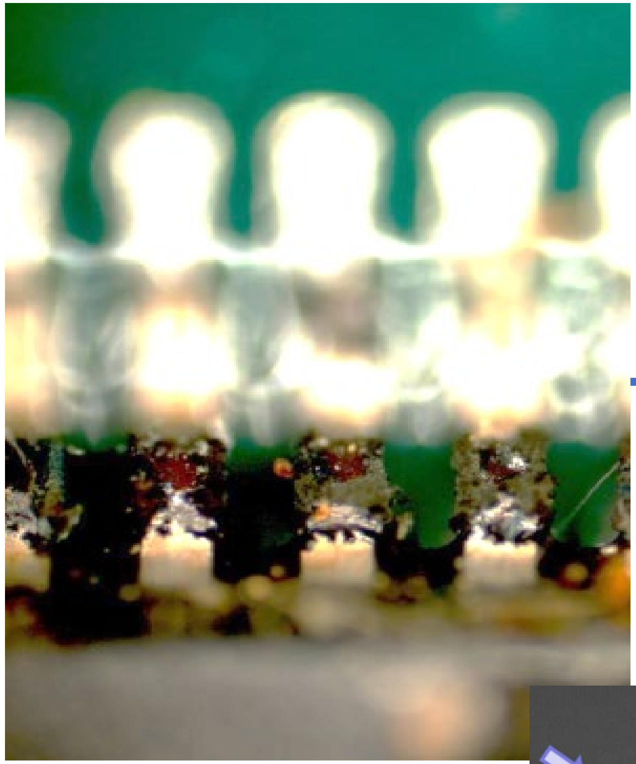
Sulfur Environment
530 to 1500 ppb
60 to 71 ˚C



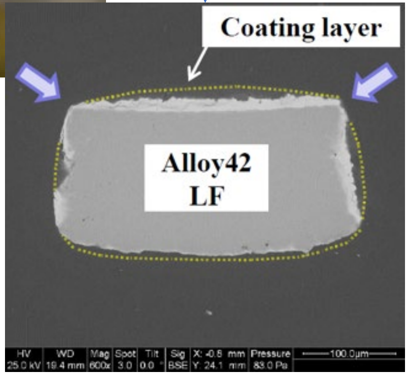
▪ *Performed by Battelle with HZO Samples*

Conformal Coatings – MFG – Silicone vs. Parylene

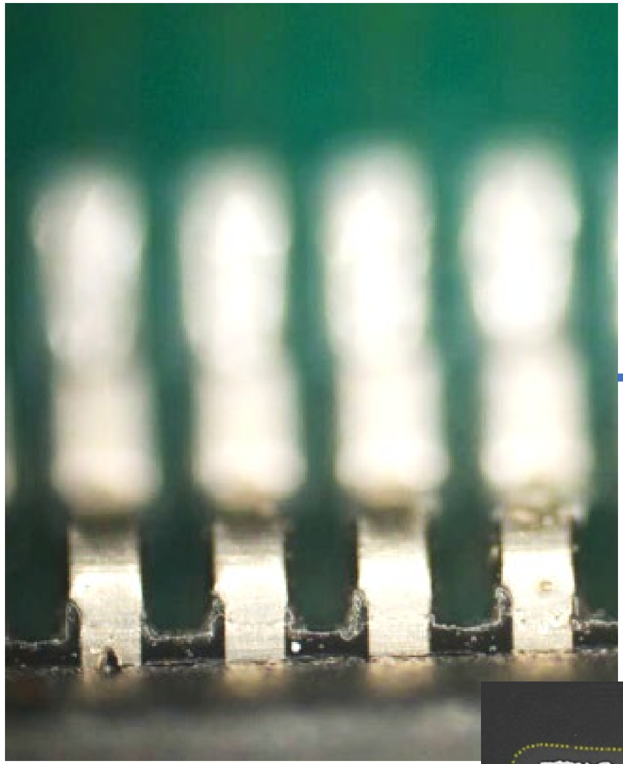
Silicone Spray Coating



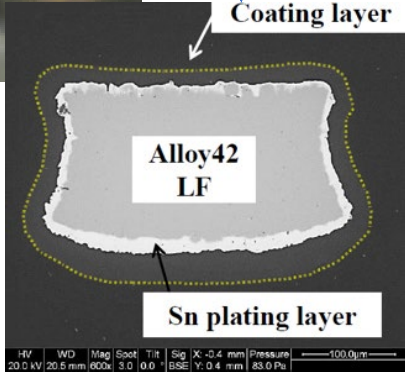
Copper Creep Corrosion on Exposed Surfaces



Parylene C CVD Coated



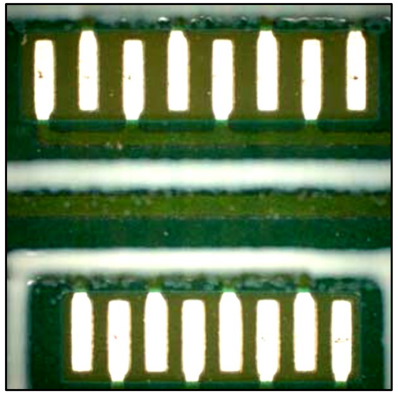
No Corrosion



- *Performed by CALCE, University of Maryland with HZO Samples*

Conformal Coatings – MFG

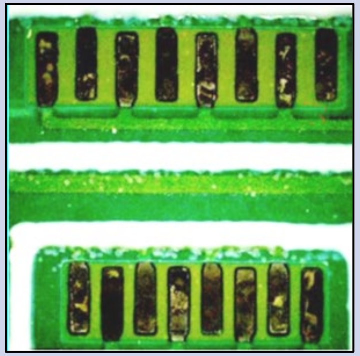
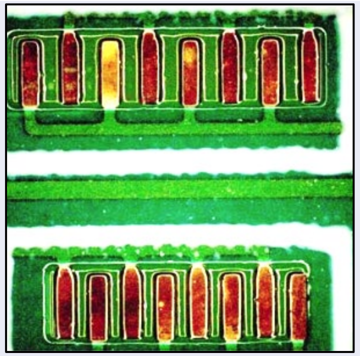
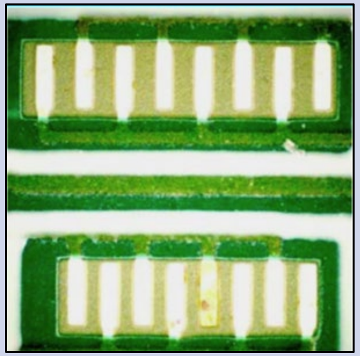
Before MFG



Test Conditions

- Duration: 10 days
- Temperature: 50 °C
- Relative Humidity: 75% RH
- Hydrogen Sulfide: 200 ppb
- Sulfur Dioxide: 200 ppb
- Nitrogen Dioxide: 200 ppb
- Chlorine: 50 ppb

After MFG

Type of Coating	Image	Comments
None		Complete surface corrosion
Acrylic		Complete surface corrosion & edge corrosion
Parylene C		Minor surface corrosion

- *Performed by CALCE, University of Maryland with HZO Samples*

IPC Standards to Consider

- Conformal Coatings and Potting Materials
  - IPC-CC-830 – Qualification and Performance of Electrical Insulating Compound for Printed Wiring Assemblies
  - IPC-HDBK-830 – Guidelines for Design, Selection, and Application of Conformal Coatings
  - IPC-HDBK-850 – Guidelines for Design, Selection and Application of Potting Materials and Encapsulation Processes Used for Electronics Printed Circuit Board Assembly
- Solder Masks
  - IPC-HDBK-840 – Solder Mask Handbook
  - IPC-SM-840 – Qualification and Performance Specification of Permanent Solder Mask and Flexible Cover Materials
- Surface Finishes
  - IPC-4552 – Specification for Electroless Nickel/Immersion Gold (ENIG) Plating for Printed Circuit Boards
  - IPC-4553 – Specification for Immersion Silver Plating for Printed Boards
  - IPC-4554 – Specification for Immersion Tin Plating for Printed Circuit Boards
  - IPC-4556 – Specification for Electroless Nickel/Electroless Palladium/Immersion Gold (ENEPIG) Plating for Printed Circuit Boards

Thank you!