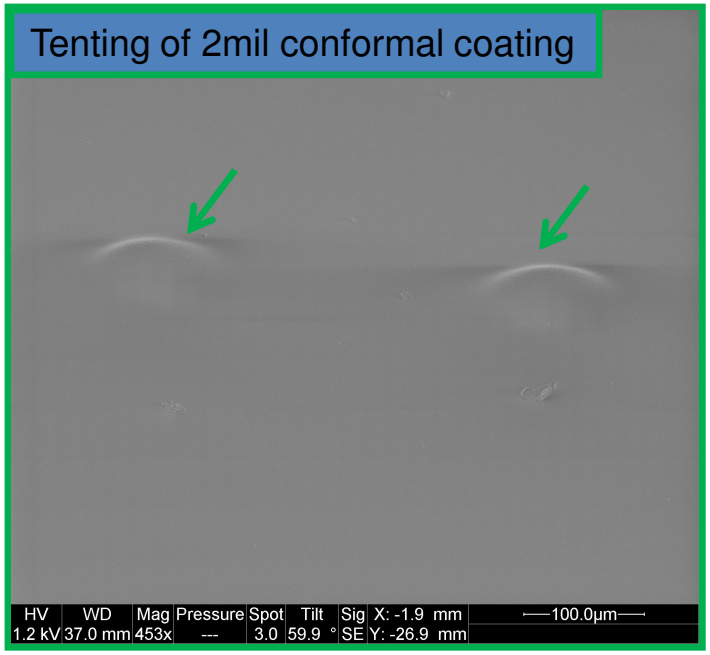
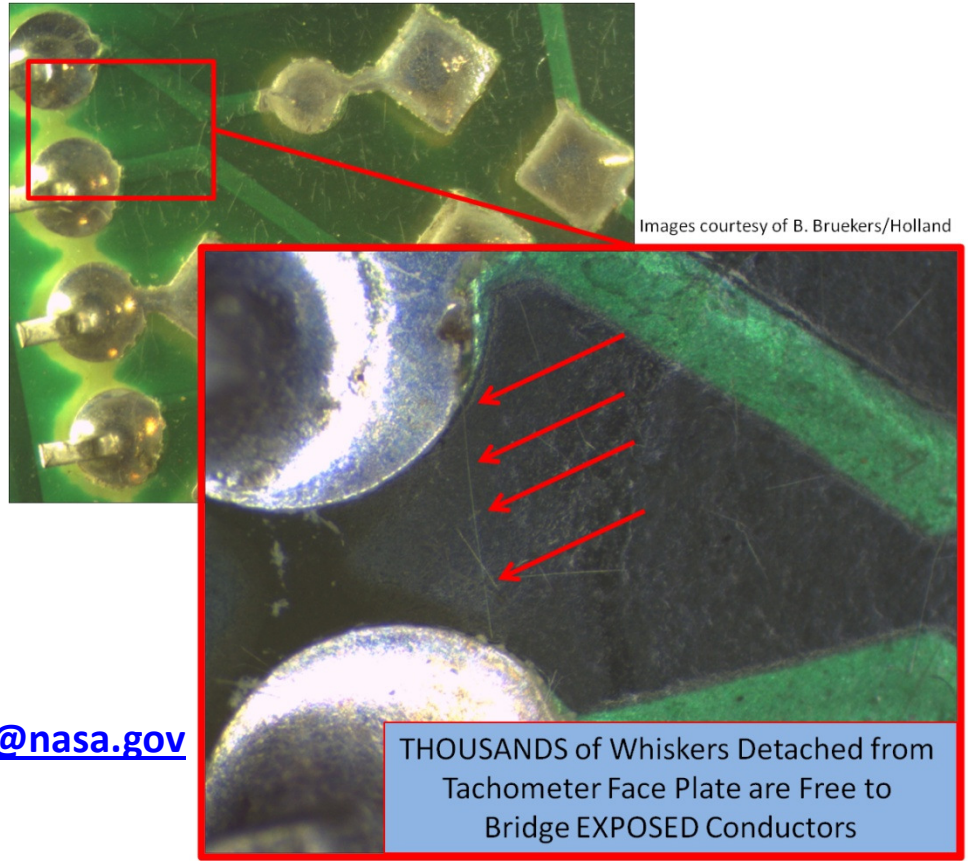
Long Term Investigation of Urethane Conformal Coating Against Tin Whisker Growth

http://nepp.nasa.gov/whisker/





Images courtesy of B. Bruekers/Holland

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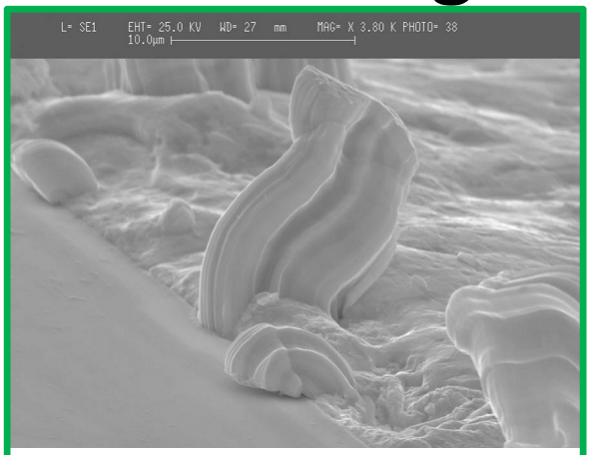
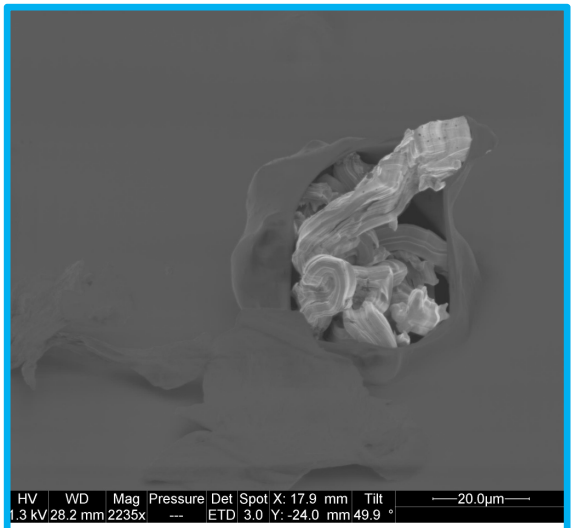
Background of This Study

- 1998 – Galaxy IV commercial satellite failed on-orbit due to a metal vapor arc initiated by tin whiskers growing from *supposedly* tin-lead surfaces
  - Surfaces were later confirmed as being pure tin, despite certificates of compliance stating otherwise
  - Interruption of pager services due to this failure lasted for days
- As a response to the Galaxy IV failure, NASA initiated a study to assess the effectiveness of a urethane conformal coating as a whisker mitigation
  - Polyurethane conformal coating (Uralane 5750) was chosen as a coating most common to space applications
  - Study initiated in 1998 with progress reports publicly published in 2000, 2001, and 2008 [10][11][12]
  - Current presentation is an 11-year update of the ongoing investigation

Mitigations Against Tin Whiskers



Whiskers growing from eutectic SnPb die attach attach solder



Whiskers penetrating thin (<0.1mil) conformal coating

- Mitigation is not elimination –

  it is reduction in severity

  - Whiskers may still form after application of a mitigation strategy
  - Effective mitigation strategies severely reduce risk of whisker formation and/or whisker-induced harm
- The most effective whisker mitigation strategies:
  - Application of tin (Sn) with lead (Pb)
    - Pb does 'something' to limit whisker growth
    - Typically 3%wt Pb or more is required
    - Past studies indicate that as low as 0.5%wt Pb may be adequate [1]
  - Placing physical barriers to prevent whisker bridging
    - Conformal Coating
    - Potting
    - Tape wrap

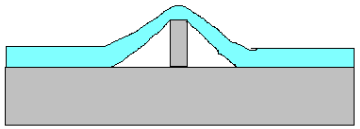
Subject of this talk

How can Conformal Coat Help

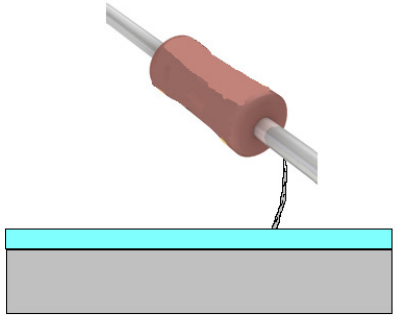
1. Will conformal coat inhibit nucleation of whiskers?

Subjects of this talk

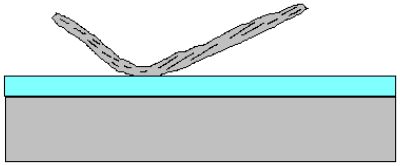
2. Will conformal coat inhibit outward escape of whiskers?



3. Will conformal coat inhibit inward penetration of whiskers?



4. Will conformal coat protect against loose (i.e. detached) whisker debris?



Research on Whiskers vs Conformal Coating (1/2)

	Boeing [2][3][4]	Schlumberger [5]	Lockheed Martin [6][7]	NPL [8]	Raytheon [9]
Acrylic	1 and 3mil thick. OK in ambient. Penetrated in 25°C/95%RH	--	1,2,3 mil thick. 5 years 50°C/50%RH – penetration and tenting of 1mil coating	5-20µm thick. OK after 150days in ambient	--
Silicone	1 and 3mil thick. OK in ambient. Penetrated in 25°C/95%RH	unknown thickness 120C storage and thermal cycles – whiskers penetrated coating of	--	14-588µm thick. OK after 150 days in ambient	Whiskers penetrated (unknown thickness or conditions)
Parylene C	0.4mil thick. OK in ambient. Penetrated in 25°C/95%RH	--	0.5mil thick. 5 years 50°C/50%RH – no tenting or penetration	--	--

Research on Whiskers vs Conformal Coating (2/2)

	Boeing [2][3][4]	NASA [10][11][12]	Lockheed Martin [6][7]	NPL [8]
Urethane (Polyurethane)	--	2mil thickness fully effective after 9 years of ambient	1,2,3 mil thick. 5 years 50°C/50%RH – penetration and tenting of 1mil coating	9-57µm thick. OK after 150 days in ambient
Urethane Acrylate	1 and 3mil thick. OK in ambient. Penetrated in 25°C/95%RH	--	--	13-79µm thick. OK after 150 days in ambient

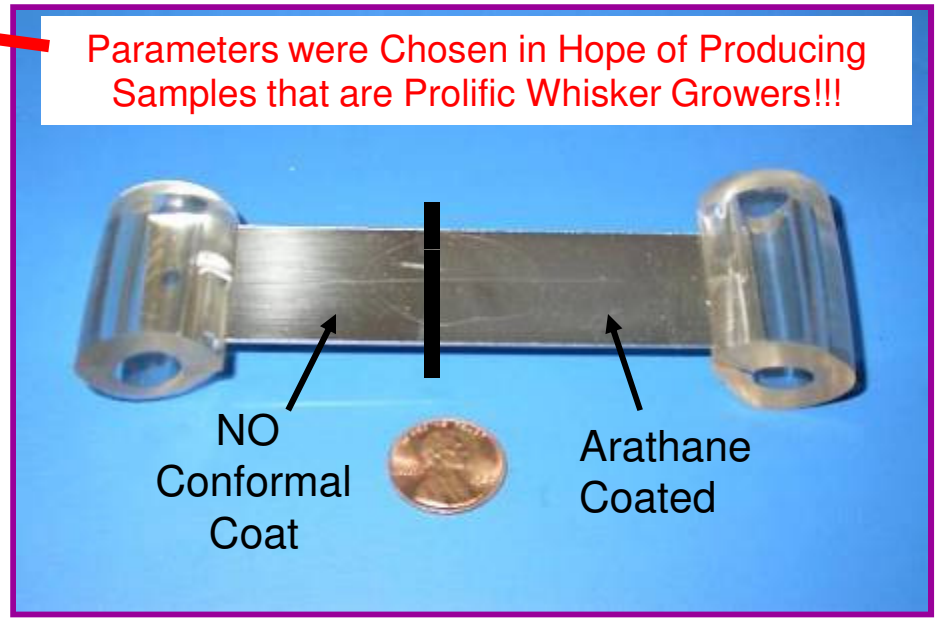
Today's presentation is an 11-year update to this study

NASA GSFC Conformal Coating Experiment

- Objective:
  - Evaluate the effectiveness of Uralane 5750 (now Arathane 5750) conformal coating as a whisker mitigation strategy
  - Arathane 5750 is a conformal coating commonly used in aerospace applications due to a variety of desirable properties
- Approach:
  1. To obtain samples that are prone to grow whiskers
  2. Apply conformal coat
  3. Store in ambient conditions
  4. Monitor for whisker nucleation and penetration through coating

Conformal Coat (Arathane 5750* Polyurethane) ~11 Years of Office Ambient Storage

- **Specimens: 14 total**
  - 1” x 4”x 1/16” Brass 260
  - Tin-Plated 200 microinches
  - A few intentional scratches created after plating in an attempt to induce localized whisker growth
- **Conformal Coating:**
  - Arathane 5750 on ½ of sample
  - Nominal Thickness = 2 mils
  - Locally THIN Regions also examined
- **Storage Conditions:**
  - Office Ambient ~ 11 years



** Arathane™ 5750 was previously known as Uralane™ 5750*

Control Areas – No Conformal Coat
11-Years of Office Ambient Storage

- Control Areas Grew Whiskers Abundantly within the First Year.
- 11 years after plating, control areas grew substantial number of whiskers (~50 whiskers/mm^2)
- Some whiskers exceeding 1mm in length on uncoated regions

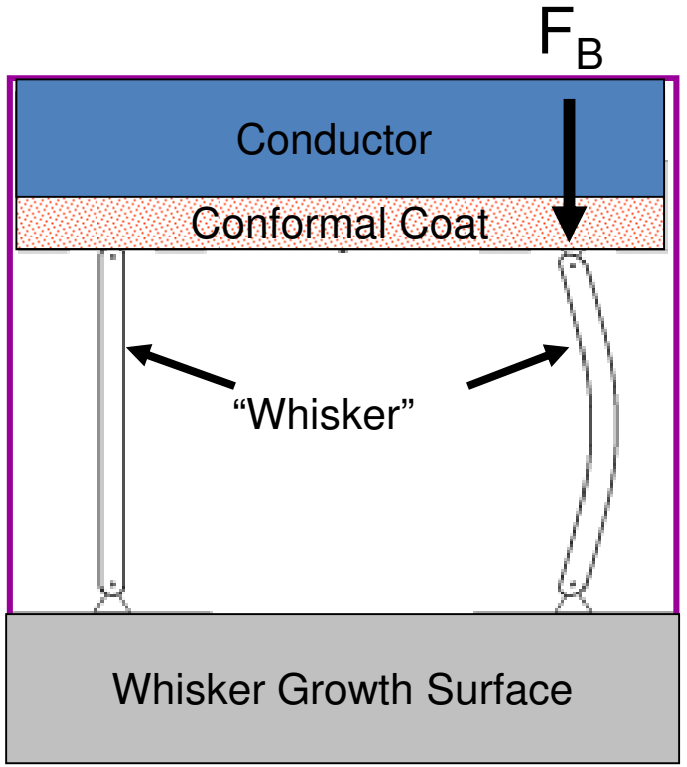
Arathane 5750 – 2 Mils Thick
11-Years of Office Ambient Storage

- Whiskers nucleated under the conformal coating within the first year
- HOWEVER, 11 years after coating, no whiskers found to penetrate nominal 2mil thickness of conformal coating
- SEM and optical inspection reveal 'tenting' of conformal coat caused by whiskers forming beneath the coating and lifting it up
- Following slides explain how conformal coating may prevent outward whisker growth

Euler Buckling
Axial Force Required to Buckle a Metal Whisker

$$F_B = \frac{\pi^2 EI}{(KL)^2} \approx \left(\frac{\pi^3 \cdot E}{32}\right)\left(\frac{d^4}{L^2}\right)$$

E = Young's Modulus of whisker material,
I = Area Moment of Inertia,
(e.g. I = π d^4 / 64 for circular cross section)
L = Length of whisker,
K = Column Effective Length Factor
K = 0.5 for whisker fixed at both ends
K = 0.7 for fixed at one end, pinned at other

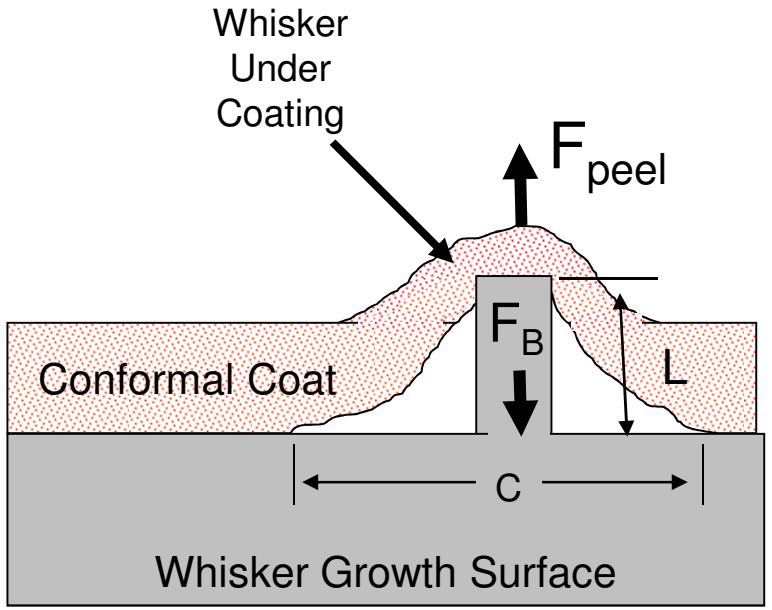


Whiskers Lift and Peel Conformal Coat Until Whisker Buckles OR Coating Fails (F_{peel} vs. F_{Buckle})

- As whisker first emerges it is short and stiff thus $F_B > F_{peel}$ and whisker begins to lift the coating forming a "circus tent" with height L = length of whisker;

- "Tent" joins the surface at a circle of circumference C ~ 2πQL,
  - Q describes the details of tent-like shape

- To peel conformal coating up and away from the surface, one needs to apply a force (F_{peel}) proportional to the circumference:
  - $F_{peel} = \Phi * C = 2\ pi\ Q\ \Phi\ L$
    Φ = peel strength of material which describes the adhesion of the coating to the tin, and the effect of the separation angle. It also depends on the rate at which the coating is peeled away.

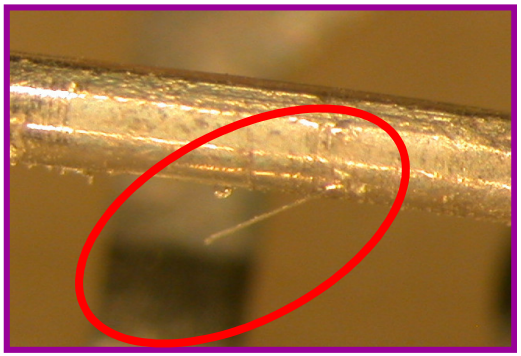


Arathane 5750 has better self-cohesion than adhesion to a tin surface

Will Whiskers Buckle Before Puncturing the Coating on a Distant Surface?

- The displacement of the conformal coat due to a whisker pushing against the coating is:

$$D = \left(\frac{1-\nu^2}{E_{coat}}\right)\left(\frac{F_B}{d}\right) \approx \left(\frac{\pi^3}{32}\right)\left(1-\nu^2\right)\left(\frac{E_W}{E_{coat}}\right)\left(\frac{d^3}{L^2}\right)$$



Where

D = Displacement of conformal coat

ν = Poisson's ratio

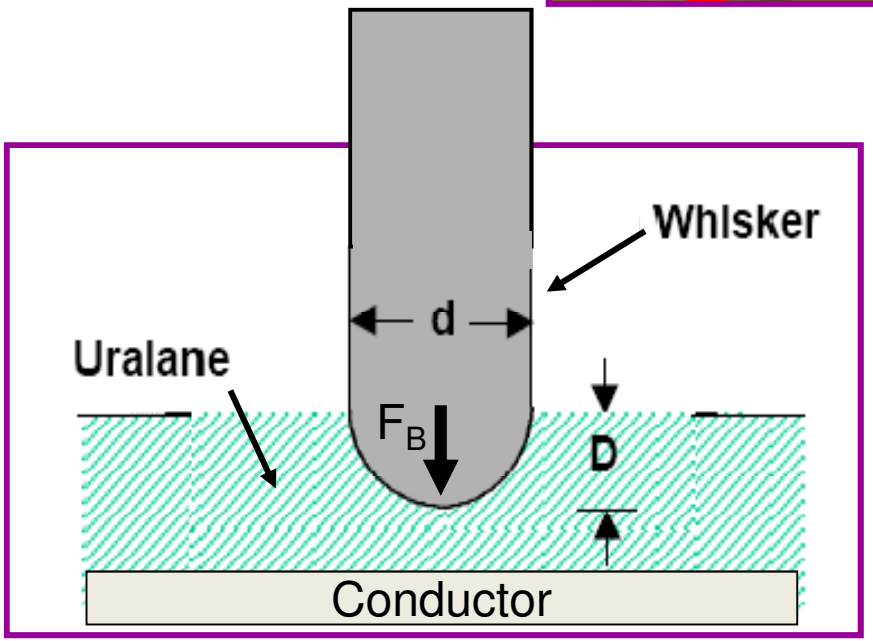
E_{coat} = Young's Modulus of coating

E_W = Young's Modulus of Whisker

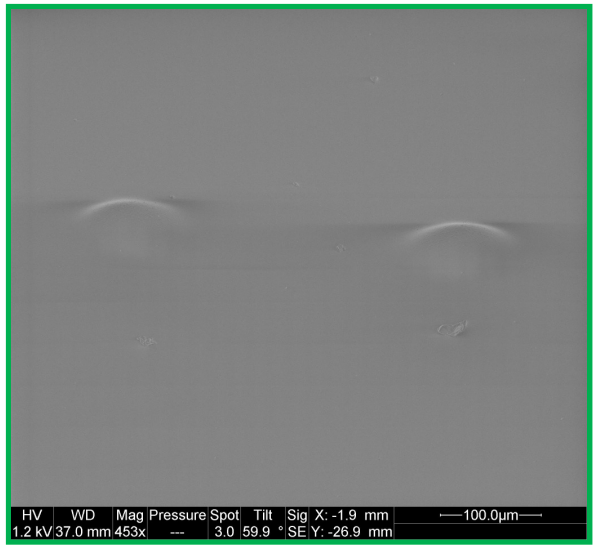
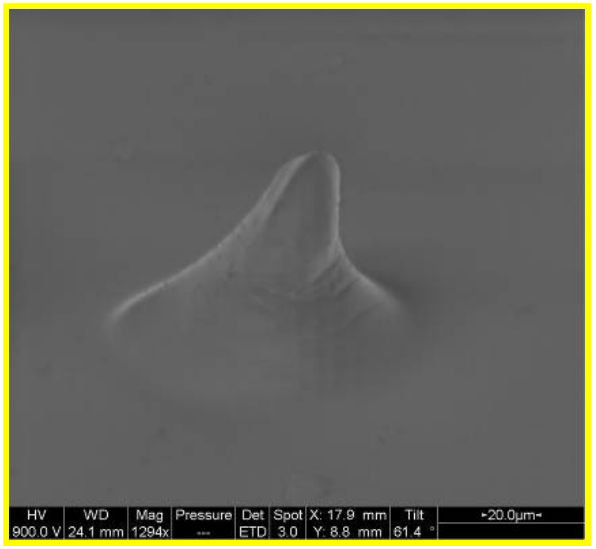
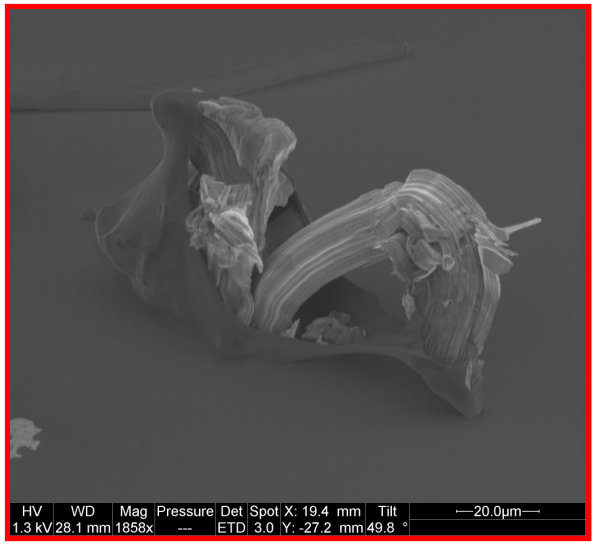
d = "Diameter" of whisker

L = Length of whisker

F_B = Euler Buckling Strength of the whisker

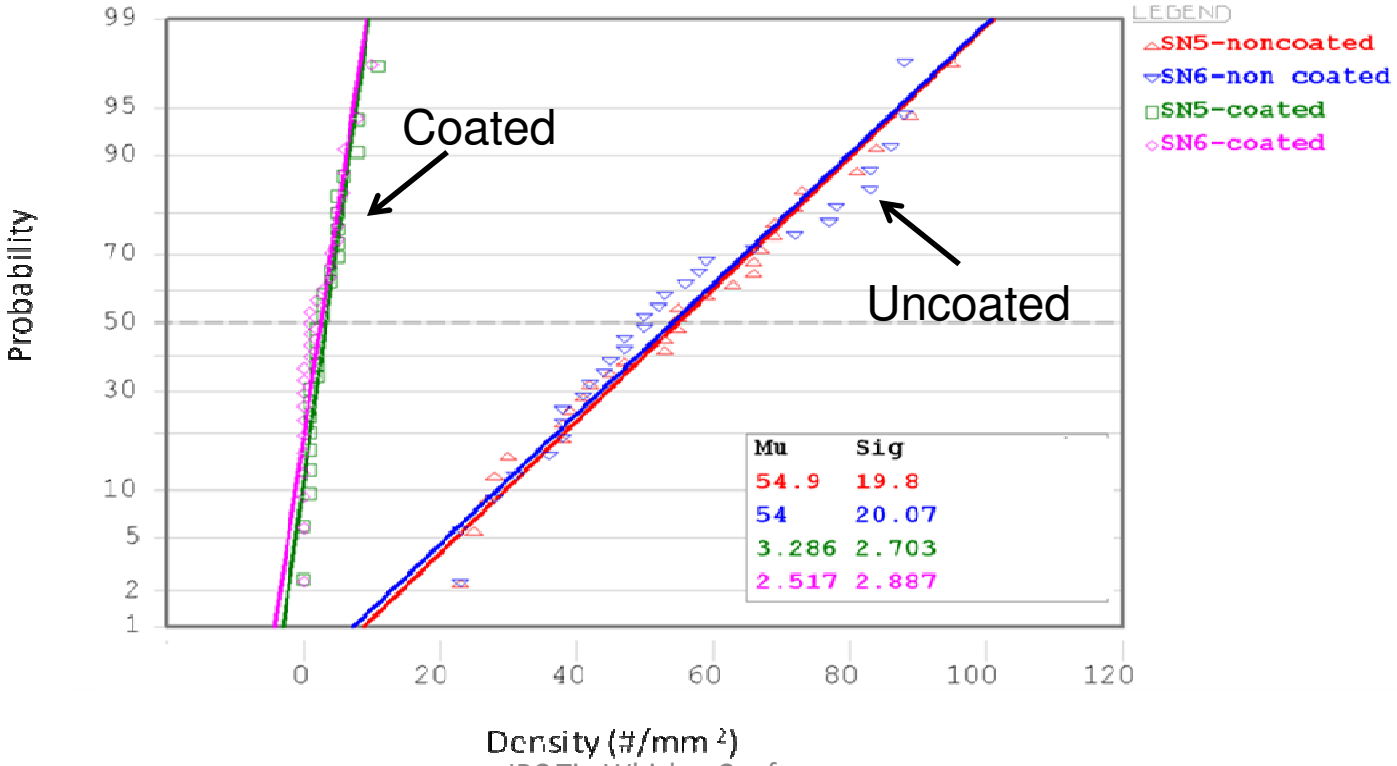


Arathane 5750 Conformal Coat - 11-Years of Office Ambient Storage

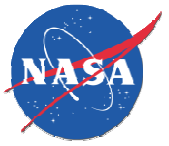
2 Mils Arathane = Very Effective	~0.5 Mils Arathane = Less Effective	~0.1 Mils Arathane = Not Effective
		
Whiskers Completely Entrapped Under the Coating → Euler Buckling	Whisker "Lifting" Coating into Shape of Circus Tent, But Not Yet Penetrating	Whiskers Breaking Through "Thin" Coating

Comparing Whisker Densities (#/area) Coated vs Uncoated

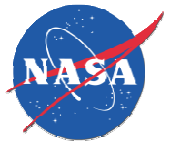
- Two samples were examined using SEM both on coated and uncoated regions to compute number of whiskers per area
  - 30 areas each 0.64mm^2 on uncoated regions
  - 30 areas each 0.9mm^2 on coated regions
- 'Tenting' was counted on coated side as sign of whisker nucleation
  - SEM does not 'see' into conformal coating, thus only whiskers that are lifting the coating are counted



Effects of Conformal Coating



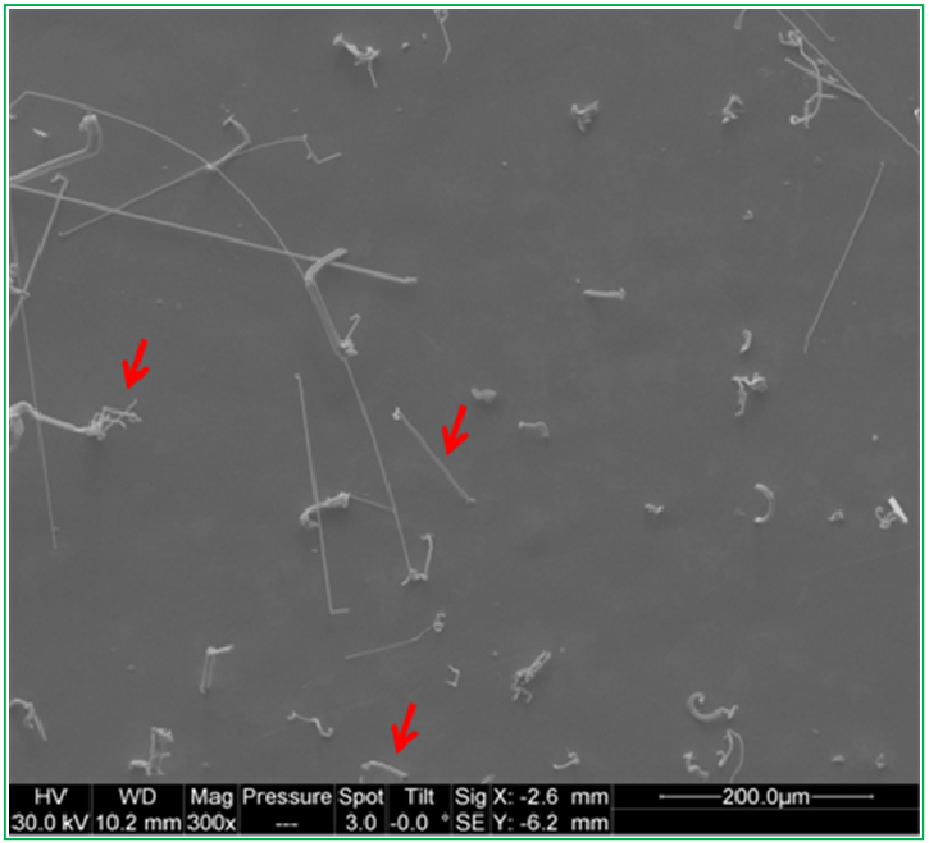
- Conclusion 1: *No whiskers have penetrated 2 mils of Arathane 5750 after 11 years*
  - Despite samples being capable of forming approximately 50 whiskers/mm^2 on coated areas greater than 600mm^2
- Conclusion 2: *Whiskers are able to penetrate when Arathane 5750 coating is thinner (~0.1mil or less)*
  - Conformal coating processes can leave "weak zones"
    - Shadowing effects may prevent complete coverage when applying coating
    - Coating may flow/thin prior to completion of cure
  - Thinner coatings are more prone to whisker puncture
- Conclusion 3: *Even "Poor" Coatings Can Offer Some Protection*
  - Long whiskers bend easily (Euler Buckling) and are less likely to re-penetrate even thin conformal coat applied on a distant conductor.
  - Conformal coat protects against a conductive bridge from detached whiskers lying across a pair of coated conductors



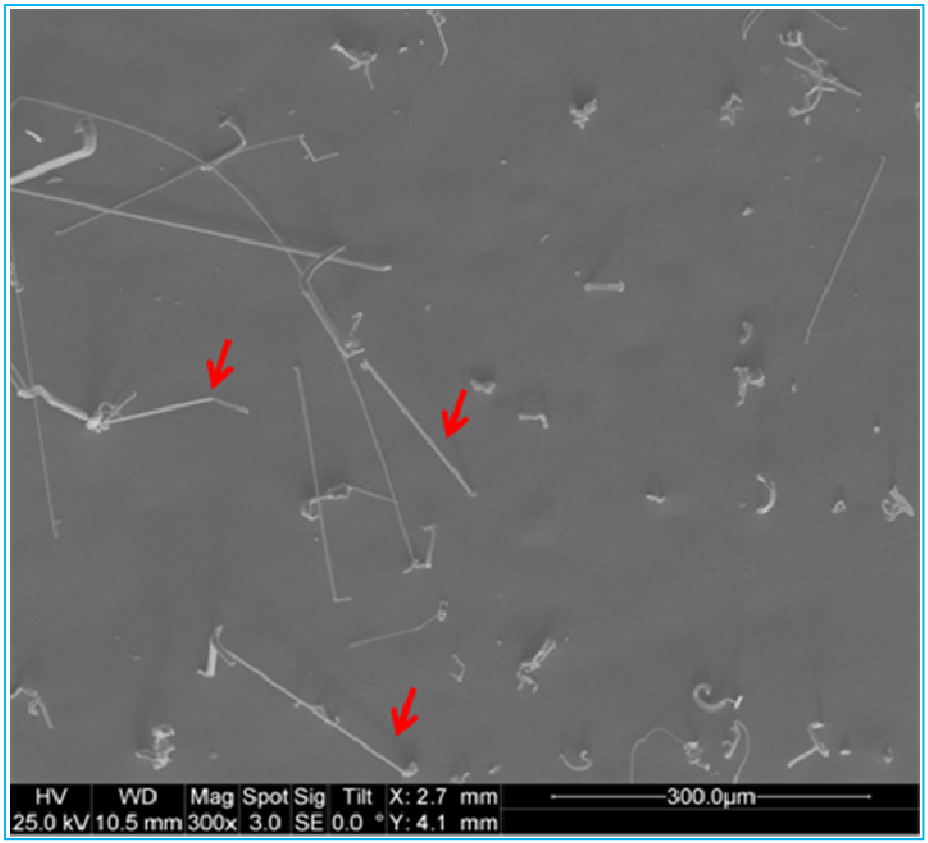
Additional observations of whisker growth behavior and distributions (#/area, length, thickness)

Continuous Whisker Growth

Whisker growth continues even a decade after initiation



9 years

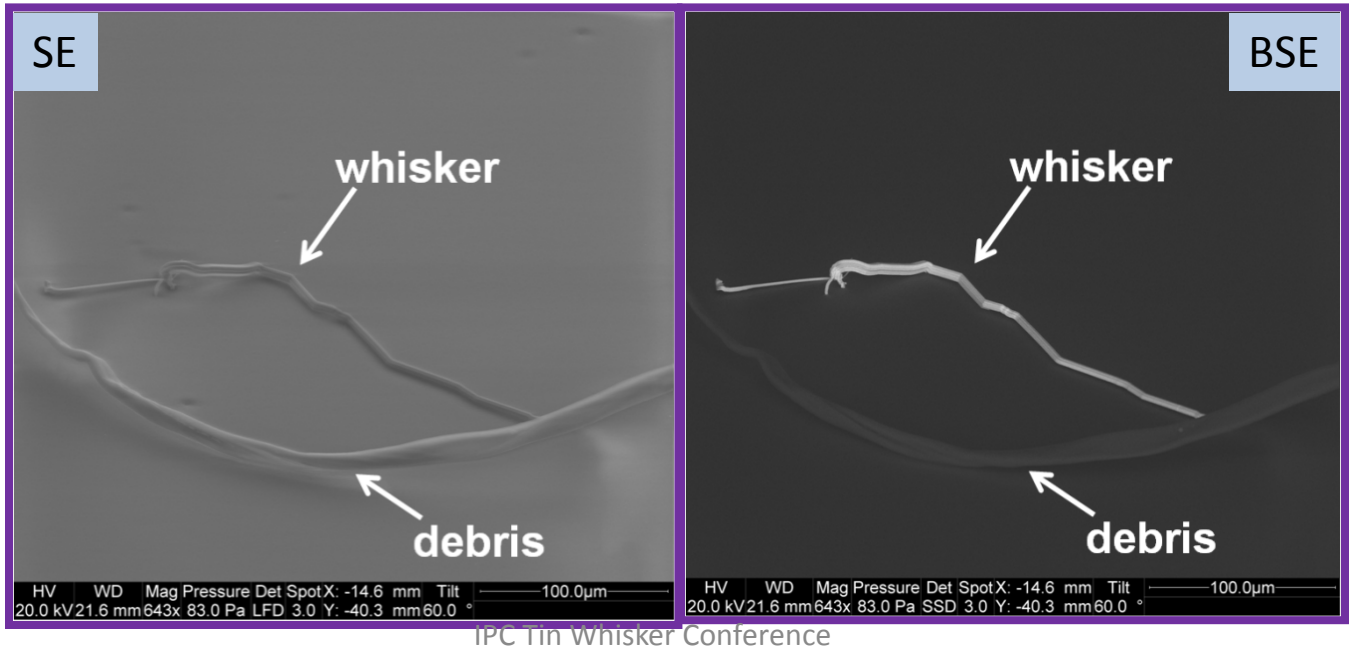


11 years

SEM Observation Methods

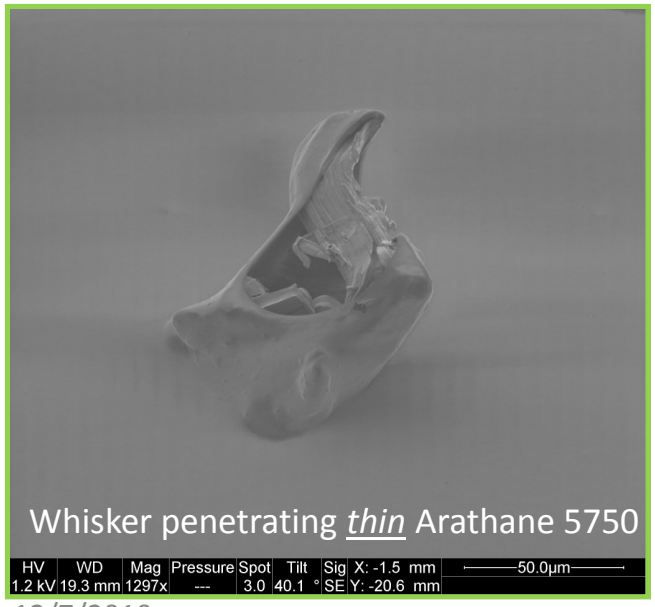
Tips and Tricks

- Use of Secondary Electron (SE) and Backscattered Electron (BSE) detectors
  - SE provides higher image resolution and gives topographical view
  - BSE relates image contrast to atomic number of elements viewed. This allowed easy distinction between metallic whiskers and carbon dust fibers
- Use of low voltages (1-2kV) for imaging of highly non-conductive areas with conformal coating
- Use of stage tilting to improve signal accumulation at SE detector for better imaging at low voltages

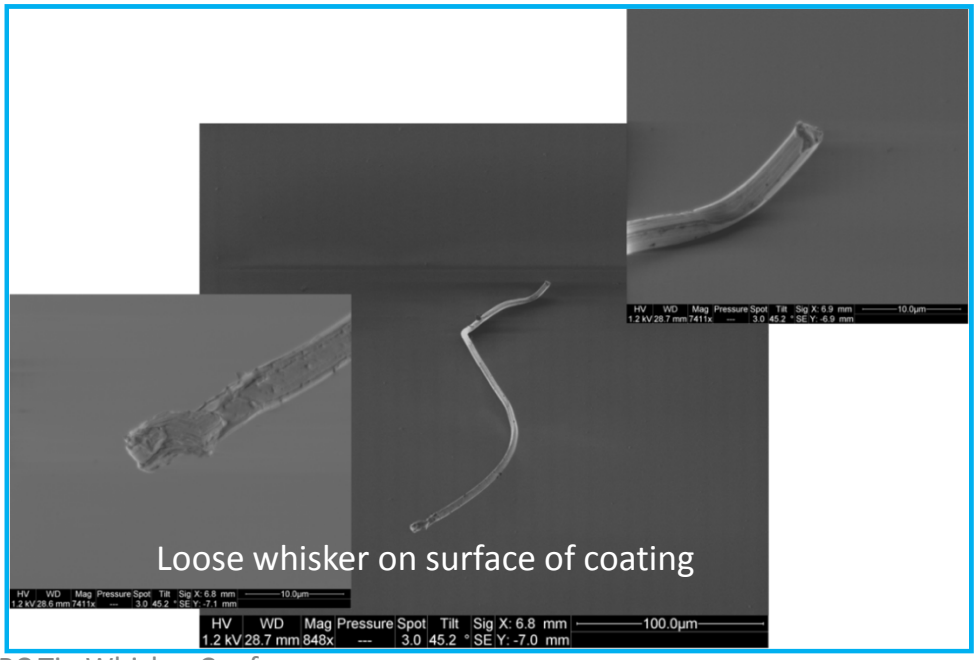


Distinguishing Penetrating and Loose Whiskers on Conformal Coating

- Whiskers identified on the surface of conformal coating may be
  - Penetrating the coating by growing from the substrate below the coating
  - Dislodged whiskers from the control areas of the sample that settled <u>on top</u> of the coating
    - Lesson learned: Prevent this by keeping control and coated areas isolated from each other
- Know how the coating should be behaving if a whisker is growing
  - Does the coating stretch out and form a 'tent' with whisker as center pole? (true for Urethanes)
  - Does coating allow the whisker to go through it without providing much resistance? (true for acrylics)



Whisker penetrating *<u>thin</u>* Arathane 5750



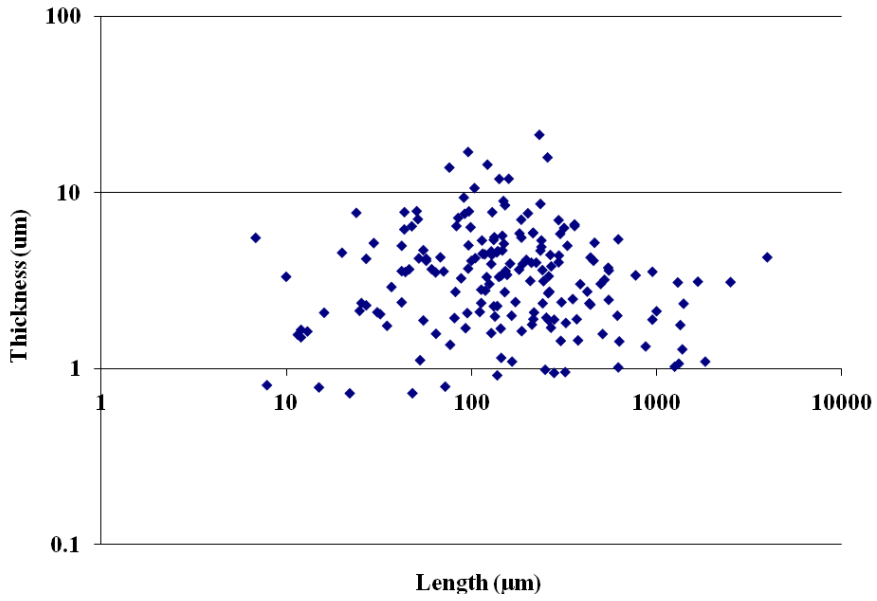
Loose whisker on surface of coating

Tin Whisker Growth Statistics

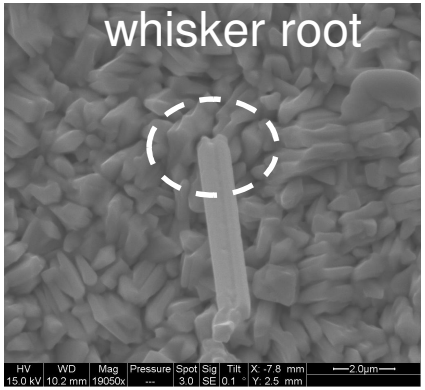
- Whisker density was measured on randomly located 30 uncoated areas ~0.64mm^2 each
- Whisker lengths and thicknesses were measured for 187 whiskers randomly picked from whiskers growing on areas used for density measurements
  - **<u>Lognormal</u> distribution fits both length and thickness [13]**

Whisker growth metric (units)	Distribution type	μ	σ	Median
Density (#/mm^2)	Normal (Gaussian)	54	20	50
Length (μm)	Lognormal	5.01	1.15	150
Thickness (μm)	Lognormal	1.17	0.67	3.38

Note: μ=ln(median); σ=(ln(1+variance/mean^2)$^{1/2}$

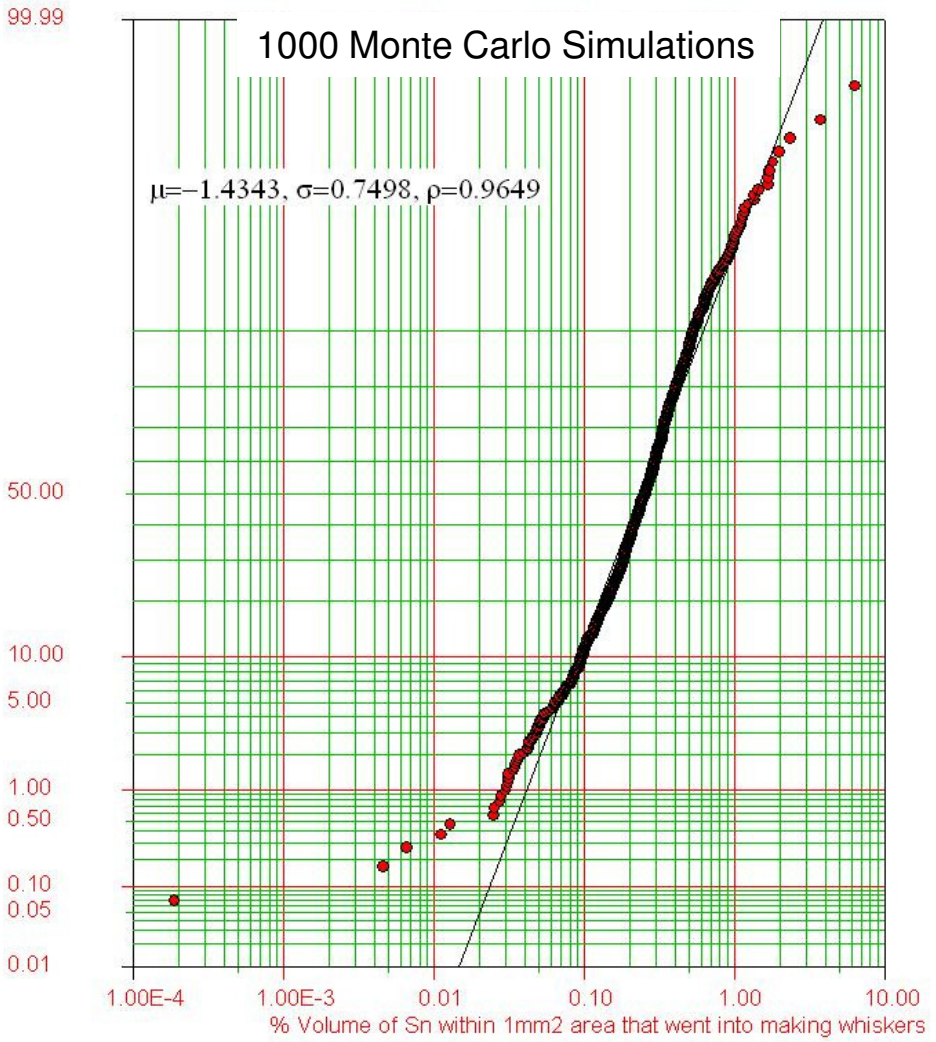


- Graph represents lack of correlation between whisker length and thickness
  - Meaning that whiskers of any thickness can grow to any length
  - Thus, thick whiskers can grow dangerously long (Euler Buckling of whisker $\propto$ thickness^4)



How Much Sn is Consumed in Growing a Dense Population of Whiskers?

- Local depletion of tin surrounding a whisker root is rarely observed
- Long-range diffusion of tin supplies the material to form a whisker
- Monte Carlo simulation based on measured distributions was used to calculate tin consumption. Parameters used:
  - Whisker density (#/area)
  - Whisker lengths
  - Whisker thicknesses
  - Tin coating thickness ~6.5µm
  - Assumed area 1mm^2
- Results of simulation:
  - Median tin consumption is ~0.24% of the available Sn in the film
  - This agrees with lack of visual depletion of Sn

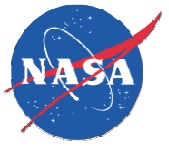


Conclusions

- *No whiskers have penetrated 2 mils of Arathane 5750 after 11 years*
  - 'Tenting' was observed in areas of 2mil thick coating, where whiskers are pushing the coating up
  - Areas with coating significantly thinner (~0.1mil) showed whisker penetrations through the coating
  - Control non-coated areas grew ample whiskers (~50 whiskers/mm^2)
- After a decade, existing whiskers continue to grow and new whiskers nucleate
  - These observations are contrary to popular belief that whisker growth terminates a few years after initiation
- Growth statistics indicate no correlation between whisker thickness and whisker length, both of which fit lognormal distributions
  - Median whisker thickness was 3.4µm
  - Median whisker length was 150µm
- Volume of tin consumed in whiskers is only a fraction of a percent of tin available in the surrounding area of whisker growth

References

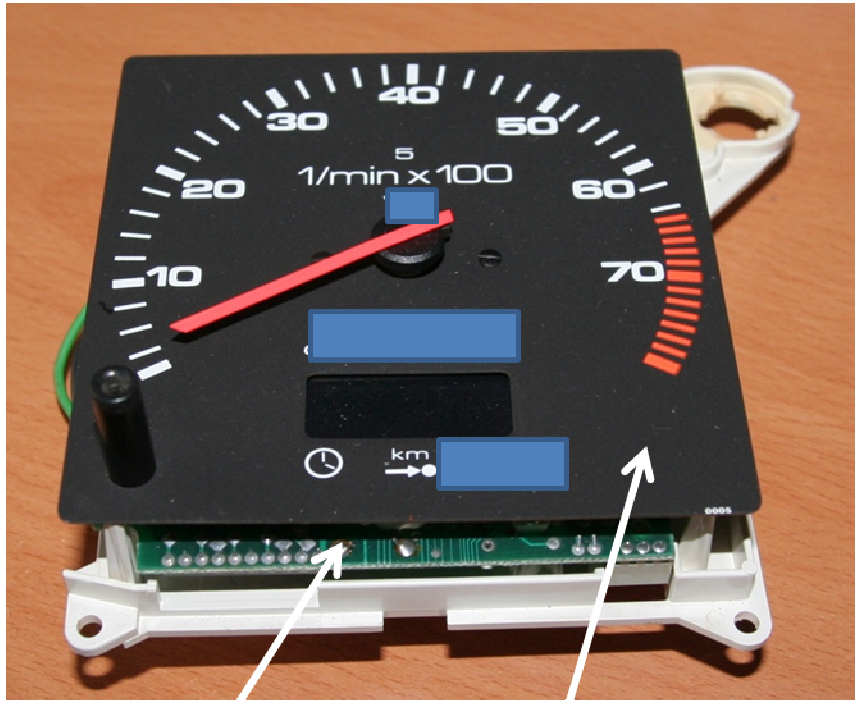
1. P.L. Key, "Surface Morphology of Whisker Crystals of Tin, Zinc and Cadmium," IEEE Electronic Components Conference, pp. 155-157, May, 1970 or 1977
2. T. Woodrow and E. Ledbury, "Evaluation of Conformal Coatings as a Tin Whisker Mitigation Strategy", IPC/JEDEC 8th International Conference on Pb-Free Electronic Components and Assemblies, San Jose, CA, April 18-20, 2005
3. T. Woodrow and E. Ledbury, "Evaluation of Conformal Coatings as a Tin Whisker Mitigation Strategy, Part 2", SMTAI, Sept. 2006
4. T. Woodrow and E. Ledbury, "Evaluation of Conformal Coatings as a Tin Whisker Mitigation Strategy, Part 3", Symposium on Reprocessing Tin Whisker Mitigation, and Assembly Rework, University of Maryland, November 11-126 2008
5. N. Asrar, “Tin Whiskers Formation on an Electronic Product: A Case Study”, Journal of Failure Analysis and Prevention, Volume 7, Number 3, pp. 179-182, 2007
6. V. Kumar and L. Woody, “Effect of Conformal Coating on Tin Whisker Growth”, Proceedings of the IPC Apex Conference, Paper S31-01, 2007
7. W. Fox, L. Woody, “Conformal Coatings for Tin Whisker Risk Management”– 5 yr update, 2009. Available http://www.circuitmart.com/pdf/conformal_coatings_tin_whisker_management.pdf
8. M. Wickham, C. Hunt, “NPL Report MAT 36: Evaluation of the Ability of Conformal Coatings to Inhibit Tin Whiskering”, September 2009
9. R. Ogden, “Tin Whisker Observations”, Circuit Assembly, pp.26–29, November 2009
10. J.S. Kadesch and H. Leidecker, “Effects of Arathane Conformal Coating on Tin Whisker Growth”, Proceedings of IMAPS Nordic, The 37th IMAPS Nordic Annual Conference, pp. 108-116, September 10-13, 2000
11. J.S. Kadesch, and J. Brusse, “The Continuing Dangers of Tin Whiskers and Attempts to Control them with Conformal Coat”, NASA's EEE Links Newsletter, July 2001
12. J. Brusse, H. Leidecker, L. Panashchenko, “Metal Whiskers: A Discussion for CALCE Symposium”, Symposium on Part Reprocessing, Tin Whisker Mitigation and Assembly Rework, November 12, 2008
13. L. Panashchenko “Evaluation of Environmental Tests for Tin Whisker Assessment”, MS Thesis, University of MD, 2009. Available: http://hdl.handle.net/1903/10021



Back-Up

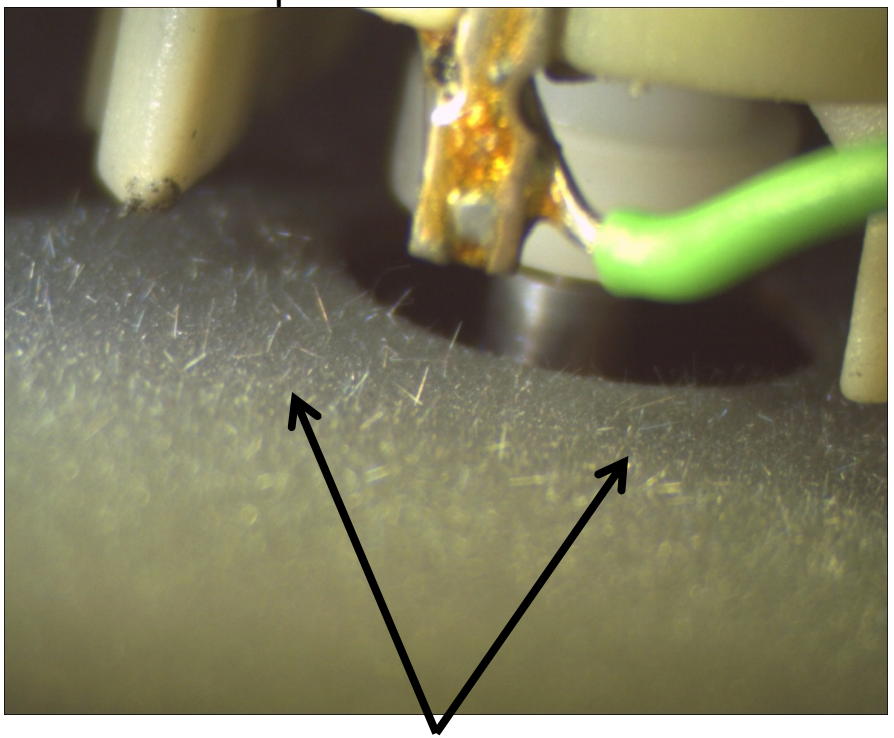
Metal Whiskers on Tachometer
One of Several Recent Observations

- Title slide of this presentation showed a PWB covered with whiskers
  - This image is courtesy of B.Bruekers (Holland)
  - Image taken of a small PCB inside a vintage 1980's car tachometer
  - Whiskers are growing from a zinc-plated iron face plate



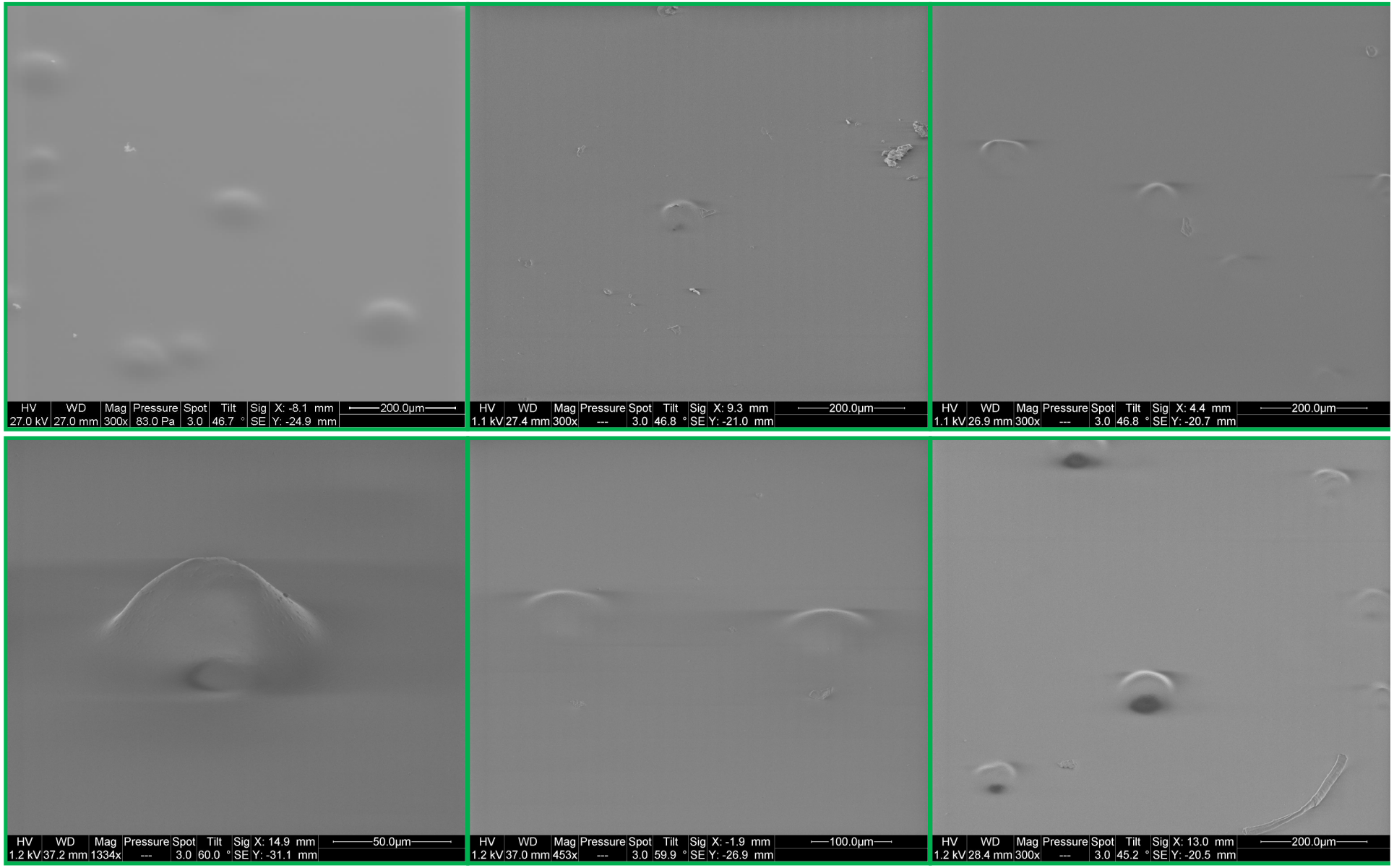
Printed Wiring Board

Face Plate

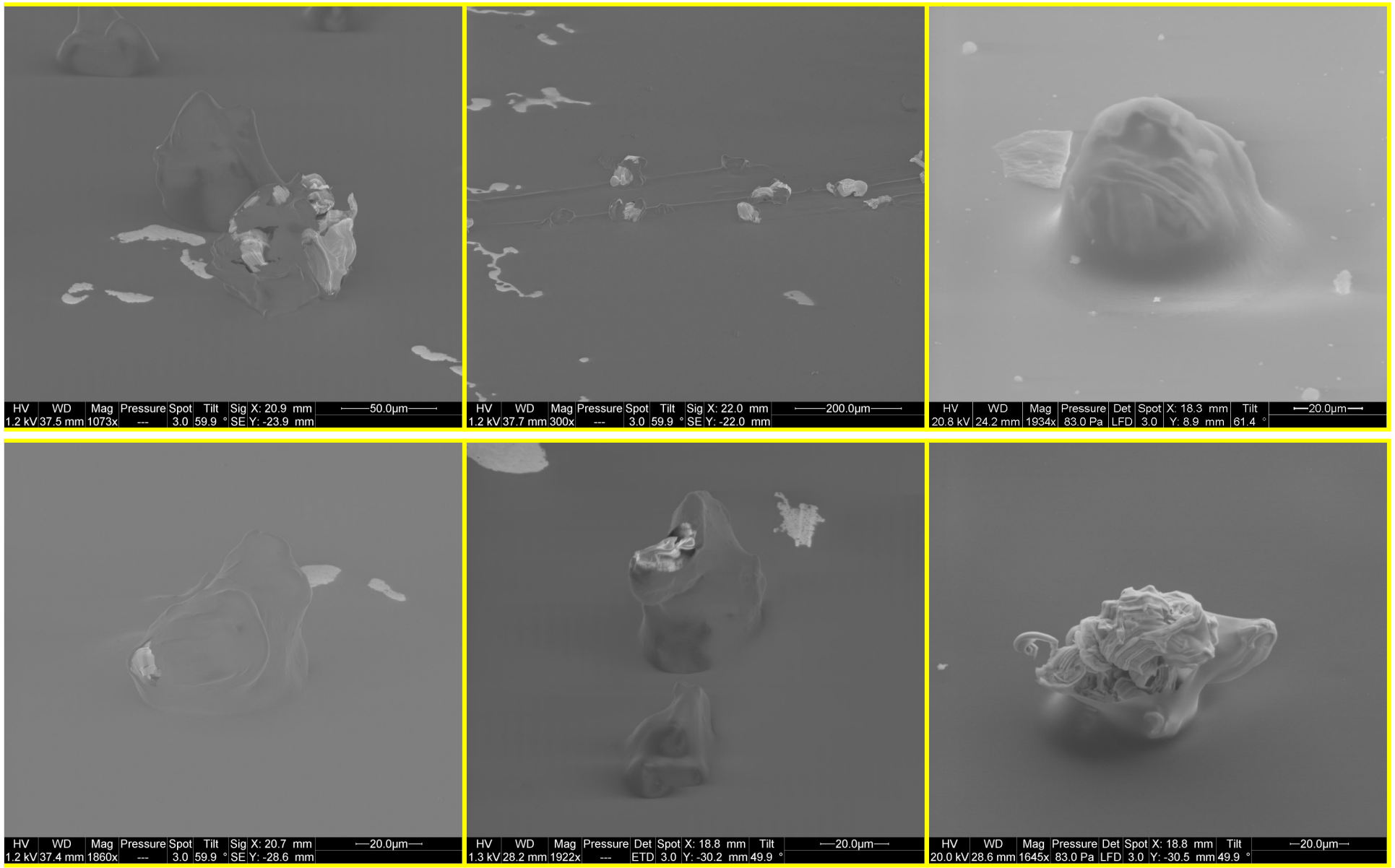


Rear of Face Plate is *Infested w/ Zinc Whiskers*

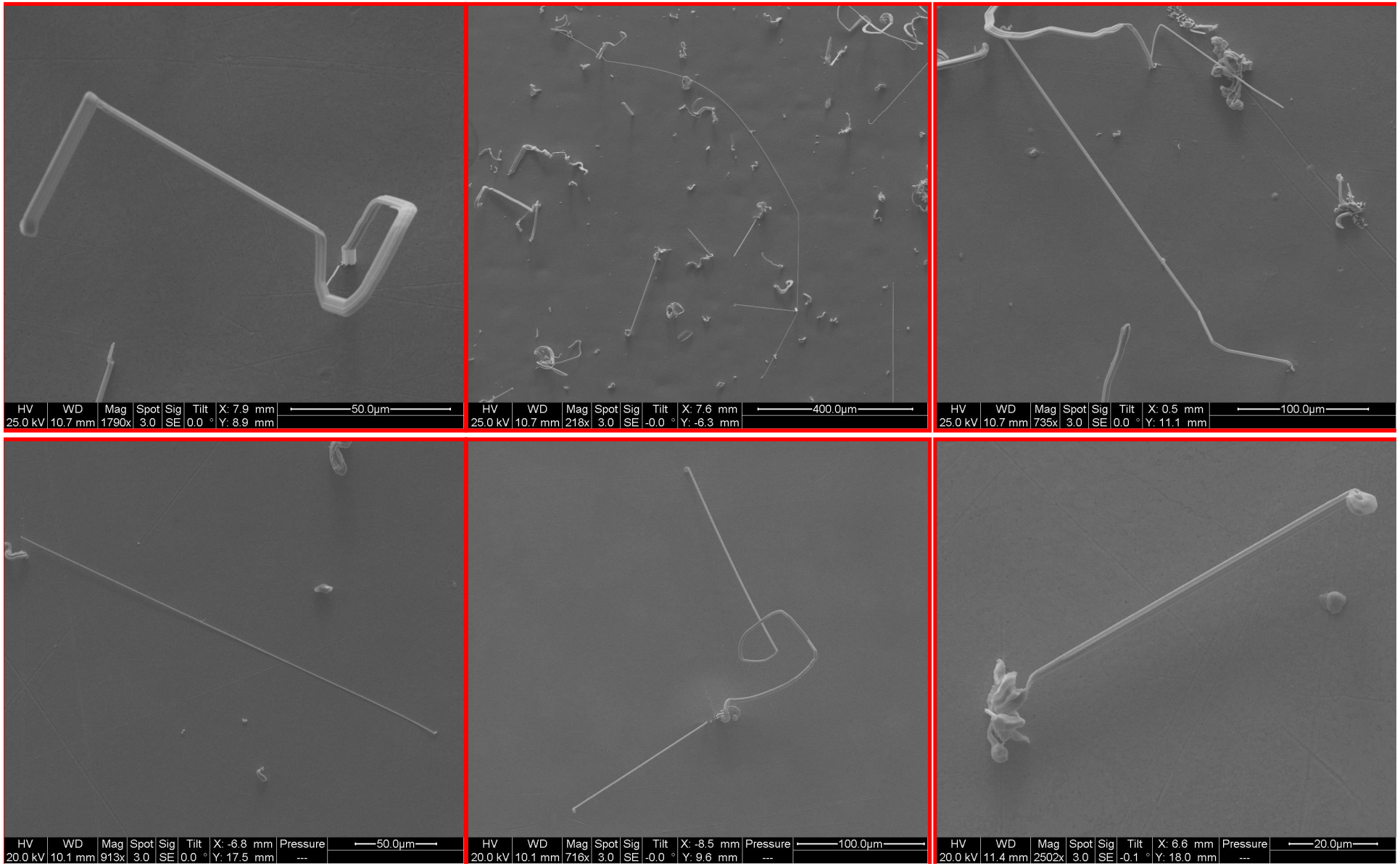
SEM images of Whiskers Tenting
Nominal 2mil Arathane5750



SEM images of Whiskers Tenting and Breaking
Thin Arathane5750

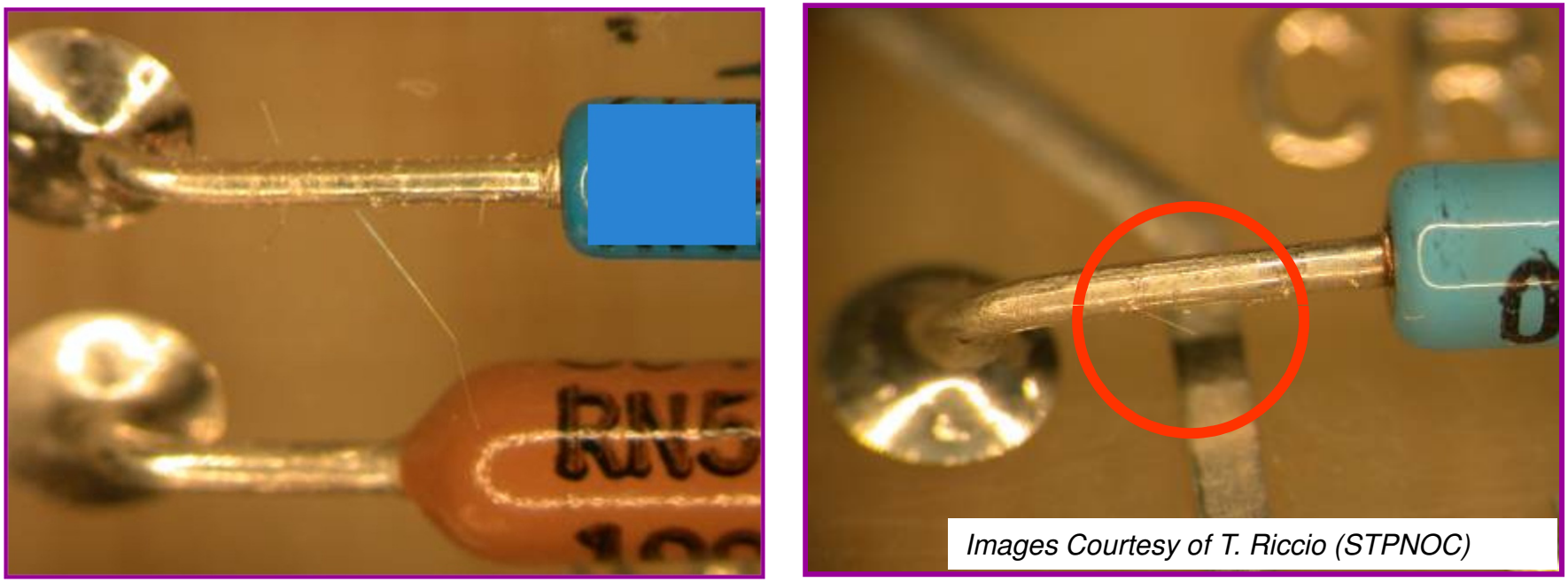


SEM images of Whiskers Growing on **Uncoated** areas of the samples



Whisker bridging to an uncoated trace

Tin Whiskers on Tin-Plated Axial Leaded Diodes



- Diode Leads were NOT Hot Solder Dipped prior to assembly; thus leaving large surface area of pure tin coating prone to whisker growth
- PWB and components were NOT Conformal Coated; thus leaving adjacent conductors exposed to bridging by whisker growth

Thank Goodness for Euler Buckling and Conformal Coat on this PWB!!!

Photo Credit: M&P Failure Analysis Laboratory
The Boeing Company Logistics Depot