Metal Whiskers:

Discussion for AAMI Cardiac Rhythm Management Device Committee

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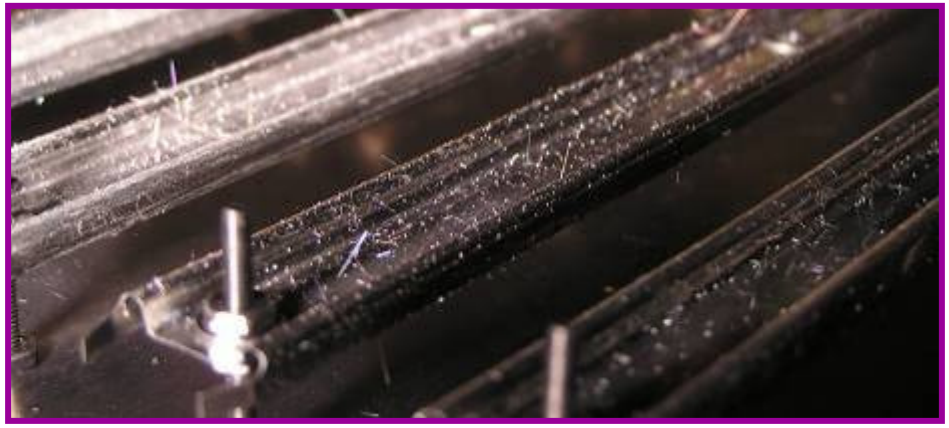
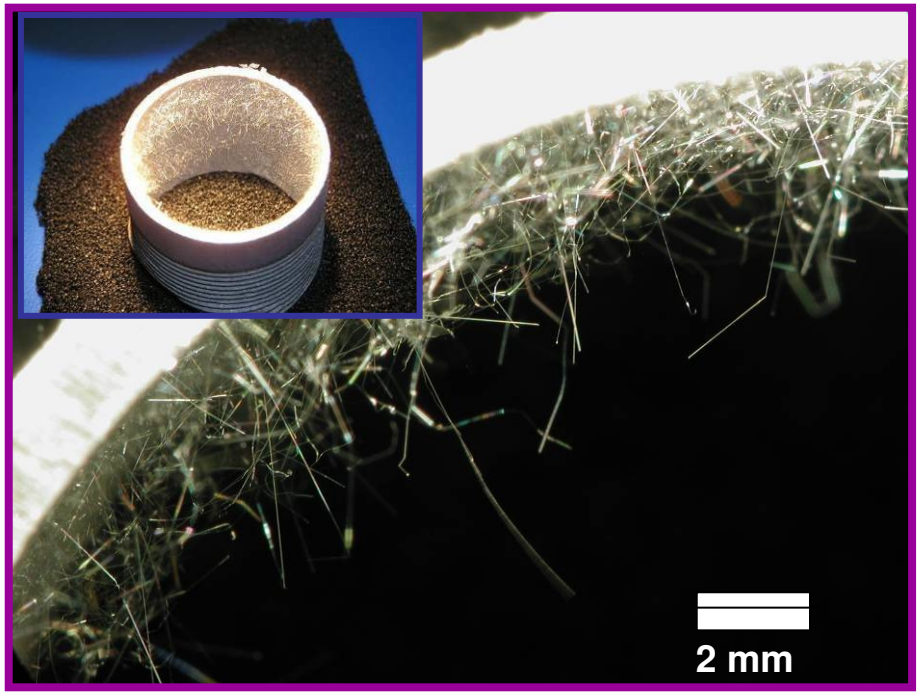


http://nepp.nasa.gov/whisker

Outline

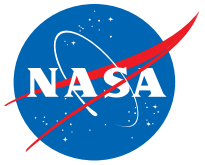
- A Brief History of Metal Whiskers
- System Failure Modes Caused by Metal Whiskers
- A Few Mitigation Strategies to Reduce Harm From Metal Whiskers
- Inspection Tips



Zinc Whiskers on Hot Dip Galvanized Steel Pipe

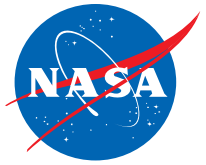
Cover Photo:
Tin whiskers on Tin-Plated Beryllium Copper PCB Card Rails

- *NO WHISKER GROWTH THEORY TO BE DISCUSSED!!!*



Could Metal Whiskers Impact the Medical Device Community?

1980s Tin Whiskers Lead to FDA Class I Pacemaker Recall



U.S. Food and Drug Administration
OFFICE OF REGULATORY AFFAIRS

Inspector's Technical Guide Number 42:
"Tin Whiskers – Problems, Causes, and Solutions
3/14/1986
http://www.fda.gov/ora/inspect_ref/itg/itg42.html

- FDA Class I recall of pacemakers from one manufacturer
  - Failure Mode: Loss of pacemaker output
  - Failure Mechanism: Tin whiskers from tin-plated case of a crystal short the case to crystal
- FDA publishes ITG #42 to describe the basics of tin whiskers
  - Recommends avoidance of tin coatings
  - Recommends INDEPENDENT verification of coating compositions
    - Pacemaker manufacturer's crystal specification required Au, Ni or solder (Sn-Pb) plating, but a batch of pure tin-plated cases was supplied in error
    - Manufacturer had no independent verification of plating composition

Trust… BUT VERIFY!!!

1980s/1990s Zinc Whiskers Lead to FDA Class I Apnea Monitor Recall

http://nepp.nasa.gov/whisker/reference/tech_papers/1994-downs-zinc-whisker-liability.pdf
http://www.fda.gov/bbs/topics/ENFORCE/ENF00065.html

- FDA Class I recall of >1500 apnea monitors made by Electronic Monitors, Inc
  - Failure Mode: Failure to alarm due to defective time delay switch
  - Failure Mechanism: Zinc whiskers from zinc-plated switch components cause low voltage short circuit
  - Investigation: *It took ~4 years + numerous experts before zinc whiskers recognized as cause of failure due to lack of familiarity with and complexity of identifying metal whiskers*
- Bankruptcy and Lawsuits
  - Electronic Monitors files for bankruptcy as a result of losses during this saga
  - Electronic Monitors sues Electro Switch and their suppliers of zinc-plated internal structures for product liability, negligence, fraud, breach of warranty, etc.
  - Case settled out of court
  - Electronic Monitors never recovered; company folded

The Phenomenon of Zinc Whisker Growth and the Rotary Switch

(or, How the Switch Industry Captured the Abominable Snowman)

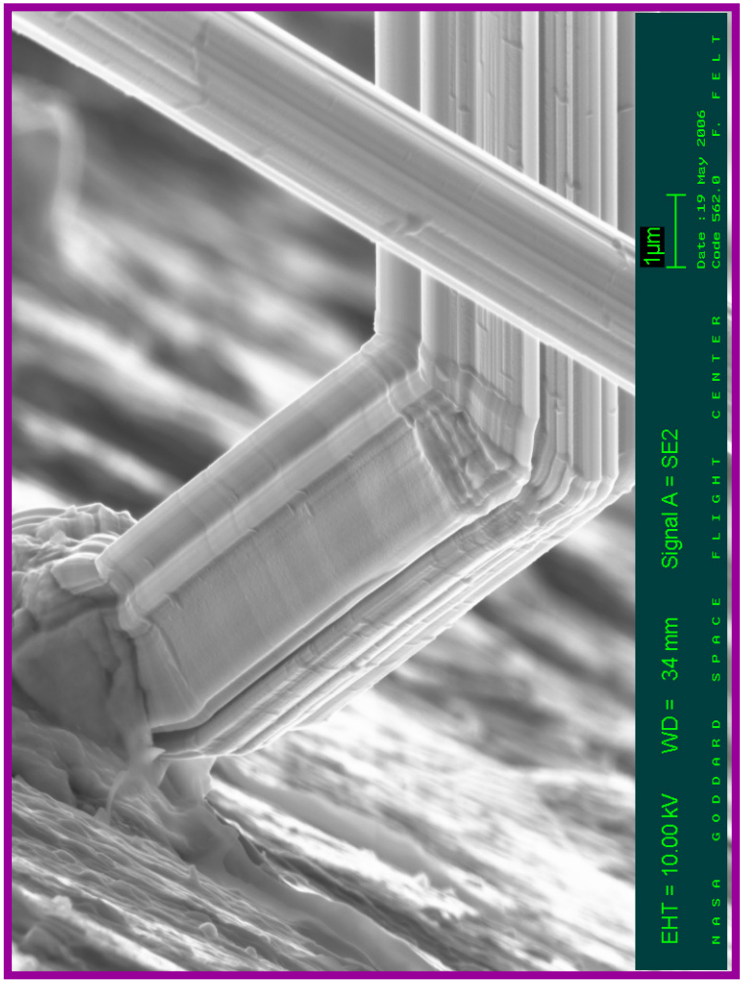
by Jay R. Downs,
Spear, Downs and Judin, Dallas
and R. Michael Francis,
Electro Switch Corp., Raleigh, N.C.

Metal Finishing Magazine, August 1994, pp. 23-25

Hangman's Noose Or Zinc Whisker?

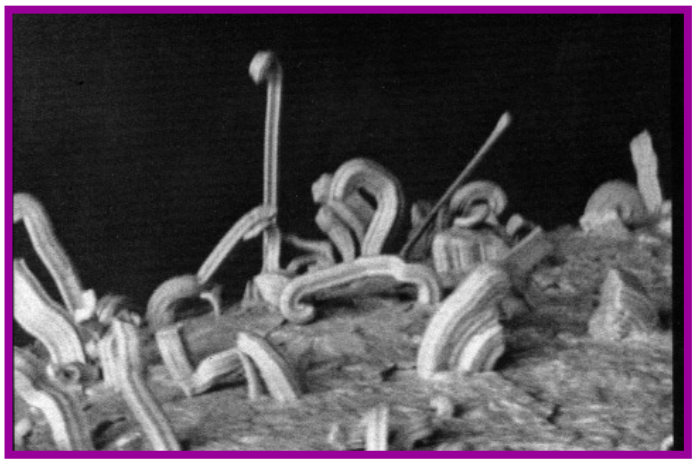
What are Tin or Zinc or Cadmium Whiskers?

- **Hair-like structures made of a single grain, or only a few grains, that sometimes erupt from a metal. Coatings of Tin, Zinc and Cadmium are especially able to develop whiskers; but, whiskers have been seen on Gold, Silver, Lead, and other metals too**
- **Growth occurs over time by accretion of metal ions at the base NOT the tip**
- **LENGTH:** **Log-normally distributed**
  Rarely up to 10 mm or more
  (Typically ~1mm or less)
- **THICKNESS:** **Range 0.006 to >10 um**
  (Typical ~ 1 um)
- **Fundamental theories for growth mechanism DO NOT enable prediction of the time-dependence of whisker density, whisker lengths or thicknesses**
  - **To be useful a theory should identify what we must control to make confident predictions**
  - **Such a theory has remained elusive**



Tin Whiskers on Tin-Plated Electromagnetic Relay Terminals

“Whiskers” are NOT “Dendrites”



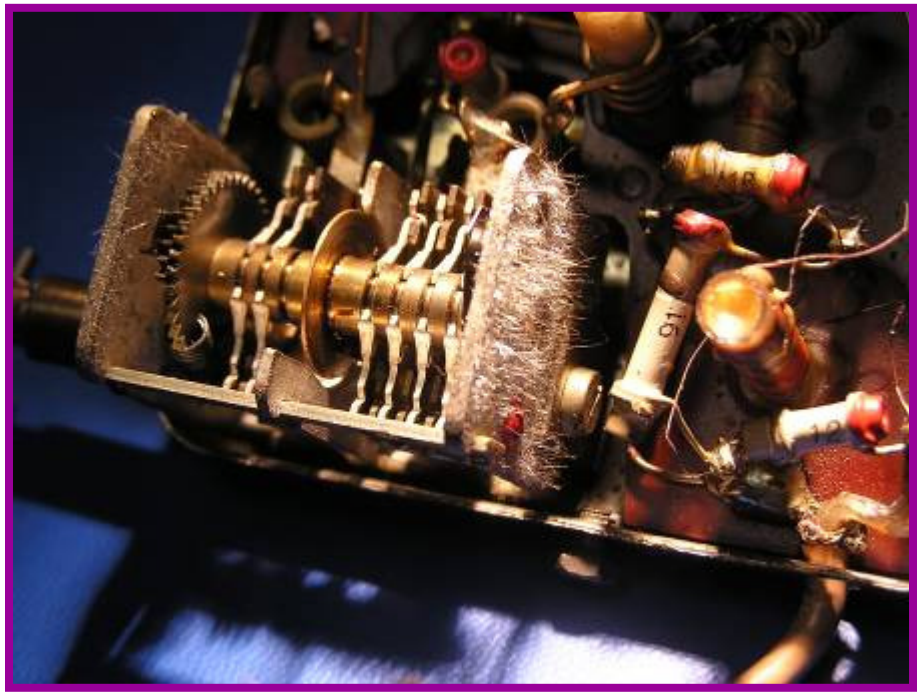
- Whisker Growth is
  - Filament-like, rarely branching
  - Outward/Away from surface
- Whisker Growth **Does NOT** Require
  - Solvents
  - Electric Fields
  - Moisture, Elevated temperature, T-Cycle

- Dendrite Growth is
  - Fern-like, branching
  - Along a surface
- Dendrite Growth **DOES** Require
  - Solvents to dissolve the metal into ionic species
  - Electric Fields to cause ion migration

Metal Whiskers
"The Early Years"

- **1946:**
  H. Cobb (Aircraft Radio Corp.) publishes earliest "known" account of CADMIUM whiskers inducing electrical shorting between plates of air capacitors used in military equipment. These events occurred during World War II (~1942 – 1943)

- **1952:**
  Since Cadmium coatings resulted in shorting, Tin and Zinc were used instead. But then K.G. Compton, A. Mendizza, and S.M. Arnold (Bell Labs) reported shorting caused by whiskers from these coatings too!



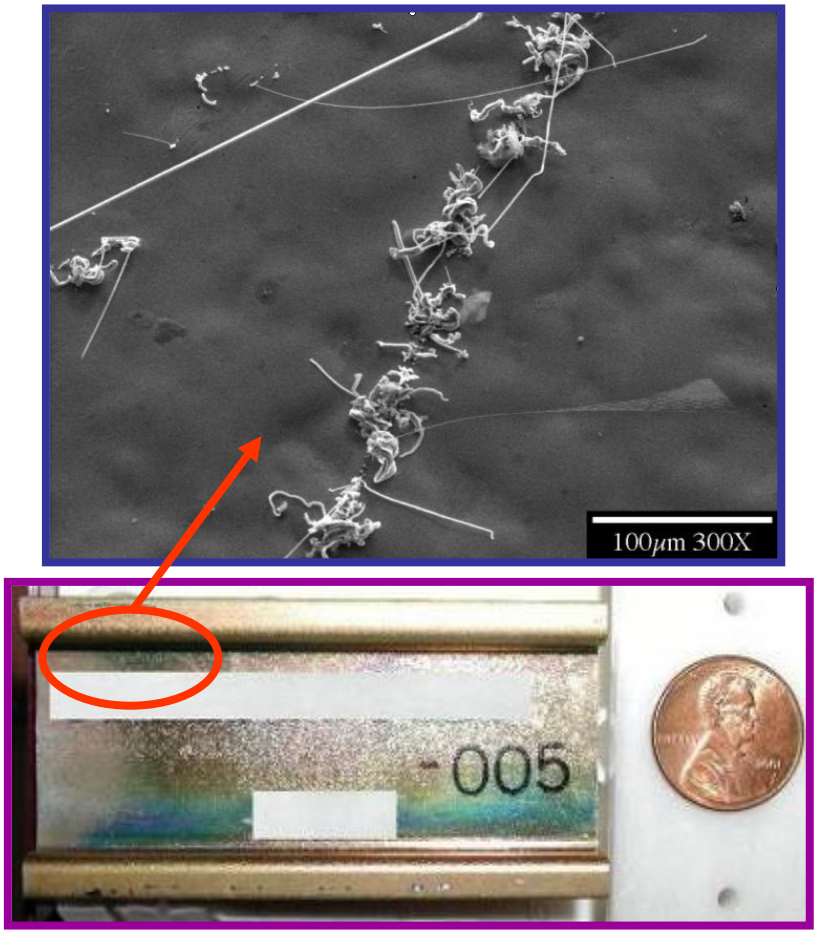
Tin Whiskers on 1960's Era Variable Air Capacitor

Whisker Resistant Metal Coatings
"The Quest"

- **1950s and 60's [1] [2]:**
  Bell Labs worked through the periodic table to determine whether addition of some element to a Tin coating would "quench" whiskering
  - ***Adding 0.5 - 1% (by weight) or more of Lead (Pb) into tin works***
  - ***Some additives seem to enhance whiskering***

- **Since 1990s:**
  To inhibit whiskers most US MIL specs require adding Pb to tin used around electronics.
  - **For design margin, the concentration is usually named as 2% to 3% Pb by weight**

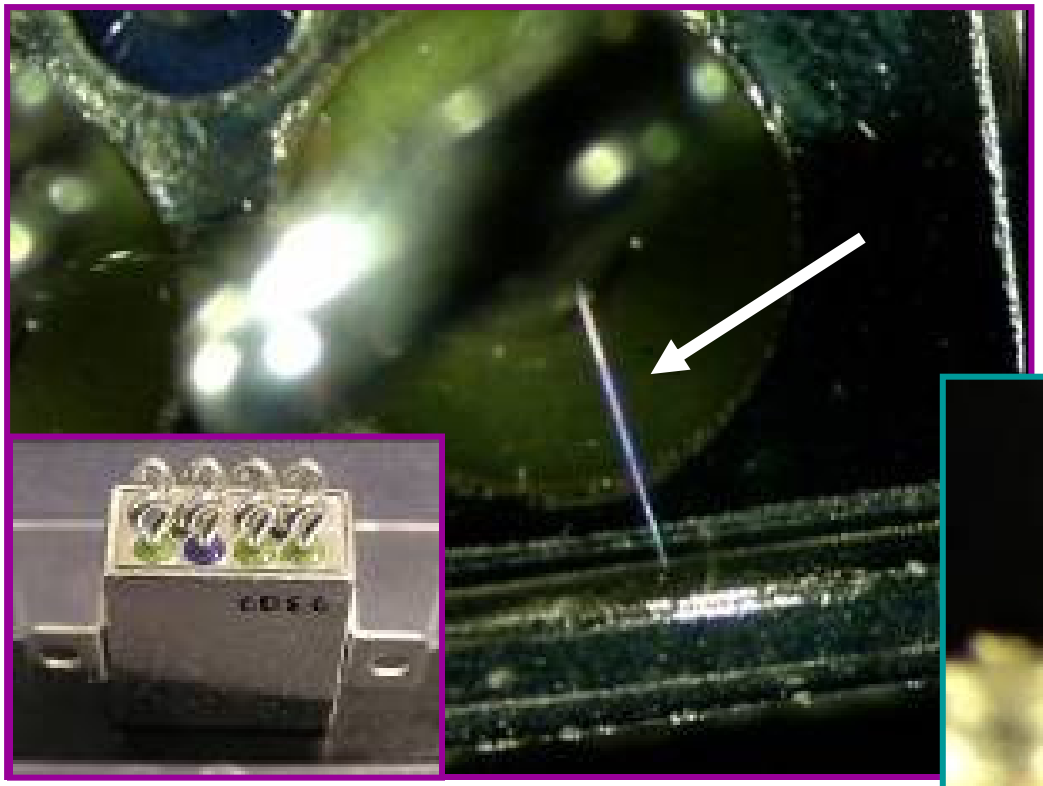
- **What additives quench Zn & Cd whiskers?**
  - **We don't know, but certainly NOT chromate conversion finishes!**



Zinc Whiskers Growing from Zinc-Plated Yellow Chromate Steel Bus Rail

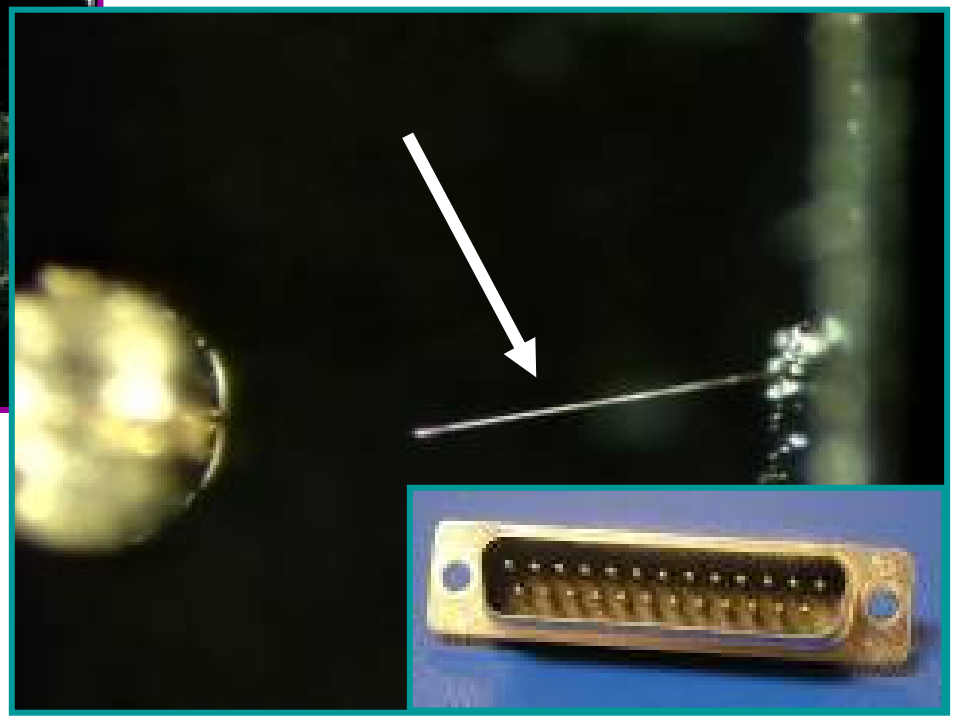
[1] S. Arnold, "Repressing the Growth of Tin Whiskers," *Plating*, vol. 53, pp. 96-99, 1966
[2] P. Key, "Surface Morphology of Whisker Crystals of Tin, Zinc and Cadmium," *IEEE Electronic Components Conference*, pp. 155-160, May, 1970

Examples of Metal Whiskers



Tin Plated Electromagnetic Relay
Tin Whisker Shorting
Terminals and Case

Tin-Plated D-Sub Connector Shell
Advertised as "RoHS Compliant"

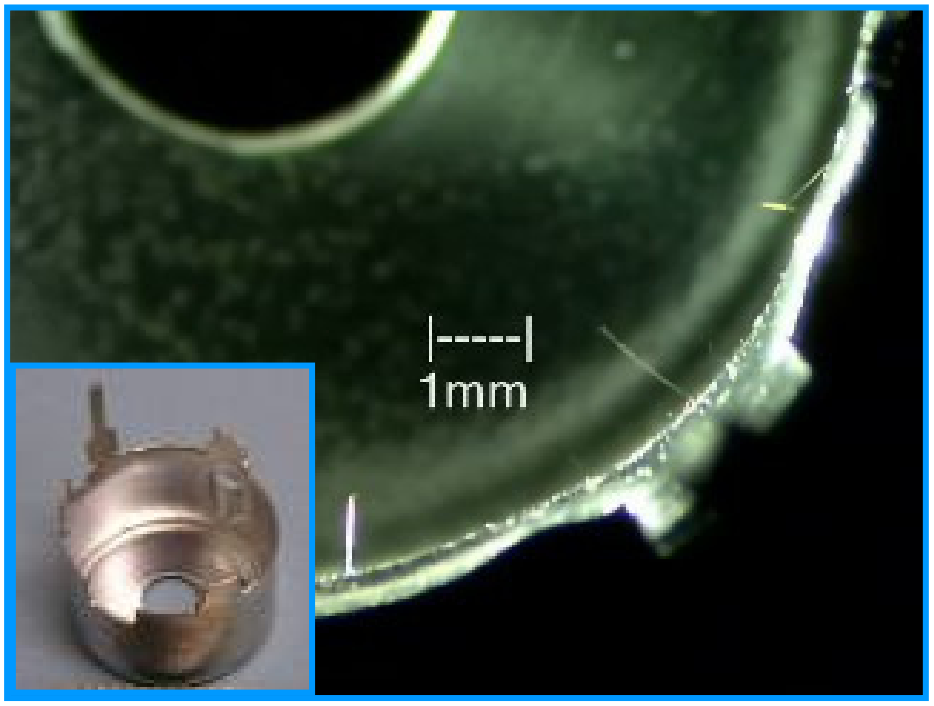


NOTE: Procurement Spec PROHIBITED Tin-Plating!

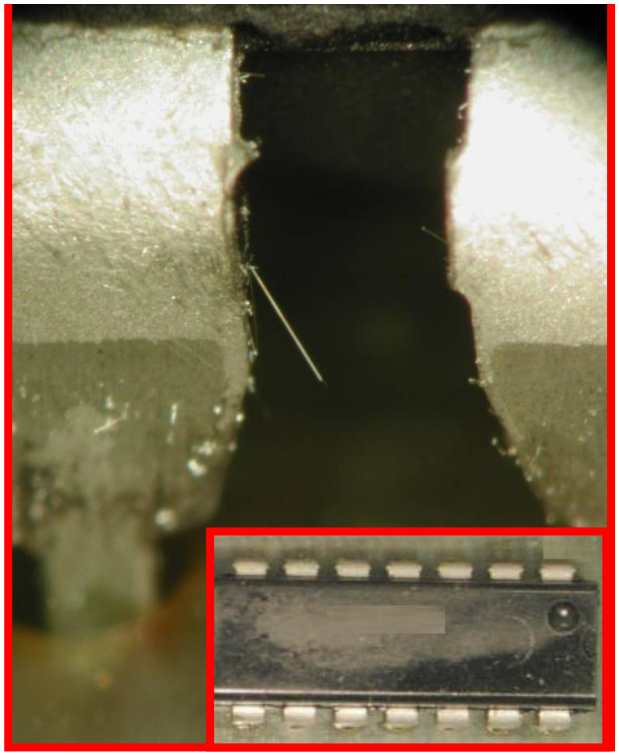
Examples of Metal Whiskers

Tin-Plated Transformer Can
Tin Whiskers "As Received"

Note: Supplier Changed to Pure Tin
WITHOUT Warning Customers

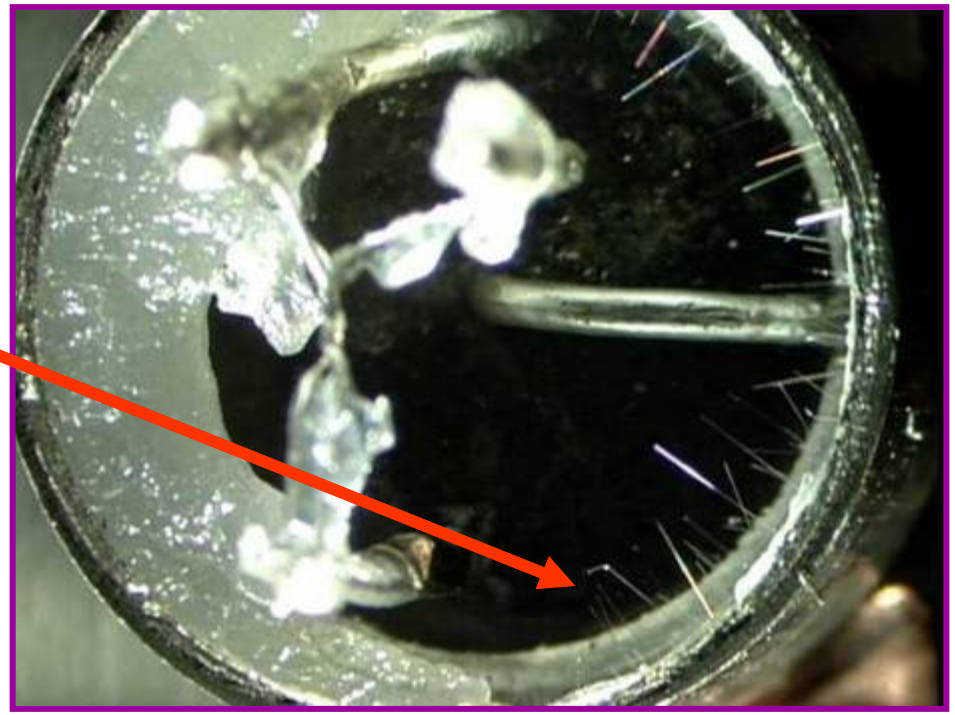


Tin-Plated DIP IC Leads
Tin Whiskers Produce Field Failures
After 20 Years in Field!



Guess What's Lurking Inside?

1960's Vintage Transistor



Transistor Package is Tin-Plated Inside.

Many Vintage Radio Malfunctions Have Been Attributed to Whiskers Shunting Case to Terminals

http://www.vintage-radio.net/forum/showthread.php?t=5058

2006- NASA GSFC Presented
A Partial History of Documented
Metal Whisker Problems

http://nepp.nasa.gov/whisker/reference/tech_papers/2006-Leidecker-Tin-Whisker-Failures.pdf

Year**	Application	Industry	Failure Cause	Whiskers on?
1946	Military	Military	Cadmium Whiskers	Capacitor plates
1948	Telecom Equipme			
1954	Telecom Equipme			
1959	Telecom Equipme			
1959	Telecom Equipme			
1959	Telecom Equipme			
	• • • •			
1986	F15 Radar			
1986	Heart Pacemaker			
1986	Phoenix Missile			
1987	Dresden nuclear Station			
1987	MIL/Aerospace P			
1988	Missile Program			

Year**	Application	Industry	Failure Cause	Whiskers on?
1990	Apnea Monitors	Medical (RECALL)	Zinc Whiskers	Rotary Switch
1990	Duane Arnold Nuclea Power Station			
1992	Missile Program "C"			
1993	Govt. Electronics			
1995	Telecom Equipment			
1996	Computer Routers			
1996	MIL Aerospace			
1998	Aerospace Electroni			
1998	Computer Hardware			
1998	DBS-1 (Side 1)			
1998	Dresden nuclear Pov Station			
1998	GALAXY IV (Side 2)			
1998	GALAXY VII (Side 1)			
1998	Military Aerospace			
1998	PAS-4 (Side 1)			
1999	Eng Computer Cente			
1999	SOLIDARIDAD I (Side			
1999	South Texas Nuclear			
199X	Telecom Equipment			

Year**	Application	Industry	Failure Cause	Whiskers on?
2000	GALAXY VII (Side 2)	Space (Complete Loss)	Tin Whiskers	Relays
2000	Missile Program "D"	Military	Tin Whiskers	Terminals
2000	Power Mgmt Modules	Industrial	Tin Whiskers	Connectors
2000	SOLIDARIDAD I (Side 2)	Space (Complete Loss)	Tin Whiskers	Relays
2001	GALAXY IIIR (Side 1)	Space	Tin Whiskers	Relays
2001	Hi-Rel	Hi-Rel	Tin Whiskers	Ceramic Chip Caps
2001	Nuclear Power Plant	Power	Tin Whiskers	Relays
2001	Space Ground Test Eqpt	Ground Support	Zinc Whiskers	Bus Rail
2002	DirecTV 3 (Side 1)	Space	Tin Whiskers	Relays
2002	Electric Power Plant	Power	Tin Whiskers	Microcircuit Leads
2002	GPS Receiver	Aeronautical	Tin Whiskers	RF Enclosure
2002	MIL Aerospace	MIL Aerospace	Tin Whiskers	Mounting Hardware (nuts)
2002	Military Aircraft	Military	Tin Whiskers	Relays
2002	Nuclear Power Plant	Power	Tin Whiskers	Potentiometer
2003	Commercial Electronics	Telecom	Tin Whiskers	RF Enclosure
2003	Missile Program "E"	Military	Tin Whiskers	Connectors
2003	Missile Program "F"	Military	Tin Whiskers	Relays
2003	Telecom Equipment	Telecom	Tin Whiskers	Ckt Breaker
2004	Military	Military	Tin Whiskers	Waveguide
2005	Communications	Radio (1960s vintage)	Tin Whiskers	Transitor TO Package
2005	Millstone Nuclear Power	Power	Tin Whiskers	Diode (Axial Leads)

These are ~10% of the Problems We Know About
So Why Do People Continue to Use Tin, Zinc, Cadmium?

“There is a name for those who suppose that doing the same thing will produce different results.

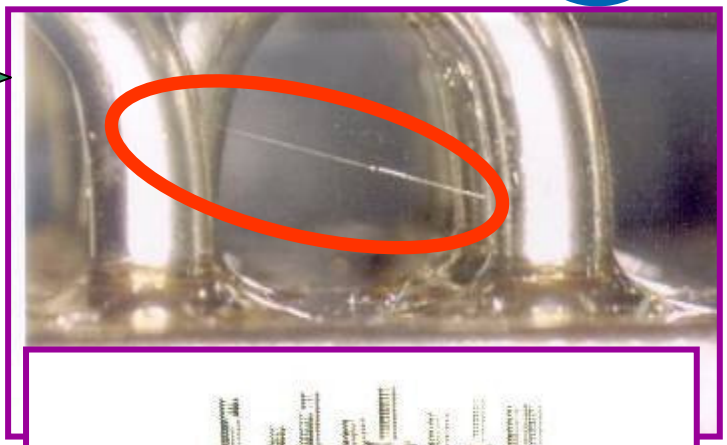
That name is ‘Idiot’.”

- Albert Einstein

Basic Whisker Failure Modes

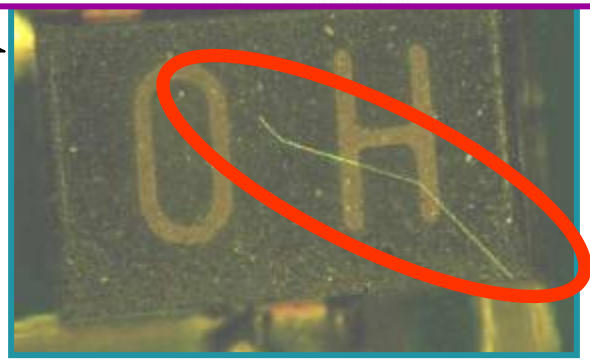
Electrical Short Circuits

- Continuous short if current $I_{whisker} < I_{melt}$
- Intermittent short if $I_{whisker} > I_{melt}$
- ***Metal Vapor Arc!!!*** *See Discussion*
  Up to HUNDREDS of AMPERES can be Sustained!!!



Debris/Contamination

- **Dislodged whiskers become foreign object debris**
  - **Produce Shorts in Areas REMOTE From Whisker Origins**
    (Zinc Whiskers on raised flooring are a PRIME Example- Please See Backup Slide)
  - **Interfere with Sensitive Optics or MEMS**



Metal Whisker Melting Current -- Pt. 1

(In Vacuum)

$$I_{melt,vac} = \left[\frac{2\sqrt{LzT_0}}{R_0}\right]\cos^{-1}\left(\frac{T_0}{T_{melt}}\right)$$

See Backup Slides for Derivation

- ***Where*** ***Lz ~ 2.45*10^{-8} (V/K)^2 is the Lorenz number, T_{melt} = melting temperature, T_0 = ambient temperature, R_0 = whisker resistance at ambient***

Material	***T_{melt}***	***$I_{melt, vac}$***	***$V_{melt} = R_0 * I_{melt, vac}$***
Tin	505.1K	87.5 mV / R_0	***88 mV***
Cadmium	594.2K	97.1 mV / R_0	***97 mV***
Zinc	692.7K	104.4 mV / R_0	***104 mV***

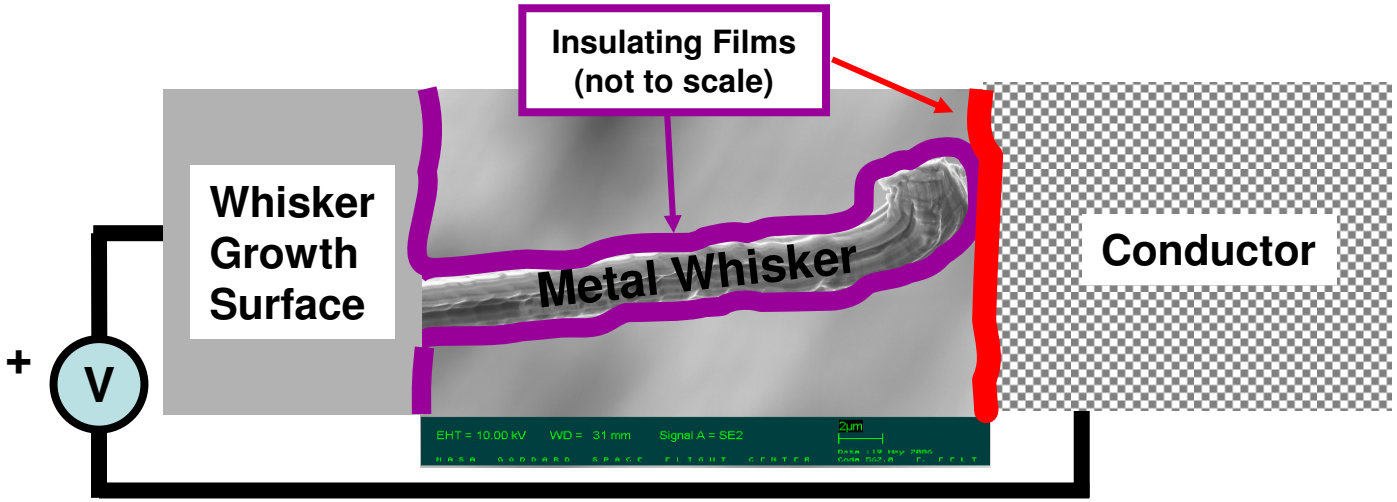
If $V_{whisker} > V_{melt}$
Then the Whisker will Fuse Open

But there is MORE to this story

Metal Whisker Melting Current -- Pt. 2

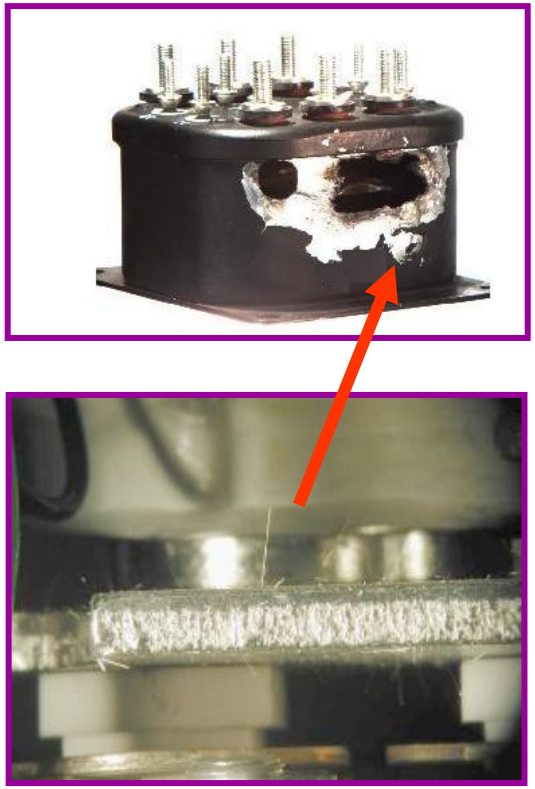
- Electrically insulating films naturally form on metal surfaces INCLUDING surfaces of metal whiskers
  - Examples: oxides, hydroxides, sulfides, moisture films, etc.

- Direct **MECHANICAL** contact by the whisker to another conductor does NOT guarantee **ELECTRICAL** contact
  - For Electrical Contact, the potential difference must exceed "dielectric breakdown" of the insulating films
  - For tin and zinc whiskers, independent groups have confirmed the film breakdown can range from ~ 0.2V to ~ 45V



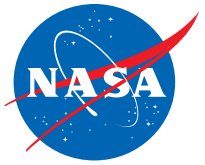
Sustained Metal Vapor Arcing Initiated by Metal Whisker

- When a metal whisker shorts two conductors at different potentials, a sustained arc can occur if
  - Current is high enough to vaporize the whisker (i.e., metal gas)
  - Voltage is high enough to ionize the metal gas
- Sustained arcing between metal conductors is possible for voltages as low as ~12 to 14 volts when
  - Arc gap is ***SMALL*** ~ a few tens of microns
  - Available current > ~100 to 300 mA
  - See “Electrical Contacts - Part III” by Paul G. Slade
- However, as arc gap increases, sustaining the arc requires
  - Higher voltage to ionize the metal gas
  - Higher current to boil enough additional metal gas to keep plasma dense enough to sustain it
  - Vacuum (i.e., low pressure) is NOT required, but can reduce the threshold voltage and current required for arcing
- Relevant metal vapor arc testing by NASA of FM08 style fuses with metal filaments ~5 mm long
  - ~75 volts at more than 30 amperes is needed to generate a sustained arc across this arc gap when P ~1 torr



Tin Whiskers Growing on Armature Of Relay Produced Metal Vapor Arc

G. Davy, "Relay Failure Caused by Tin Whiskers", Northrop Grumman, Technical Article, October 2002
http://nepp.nasa.gov/whisker/reference/tech_papers/davy2002-relay-failure-caused-by-tin-whiskers.pdf



How do People with "Whiskers" Cope?

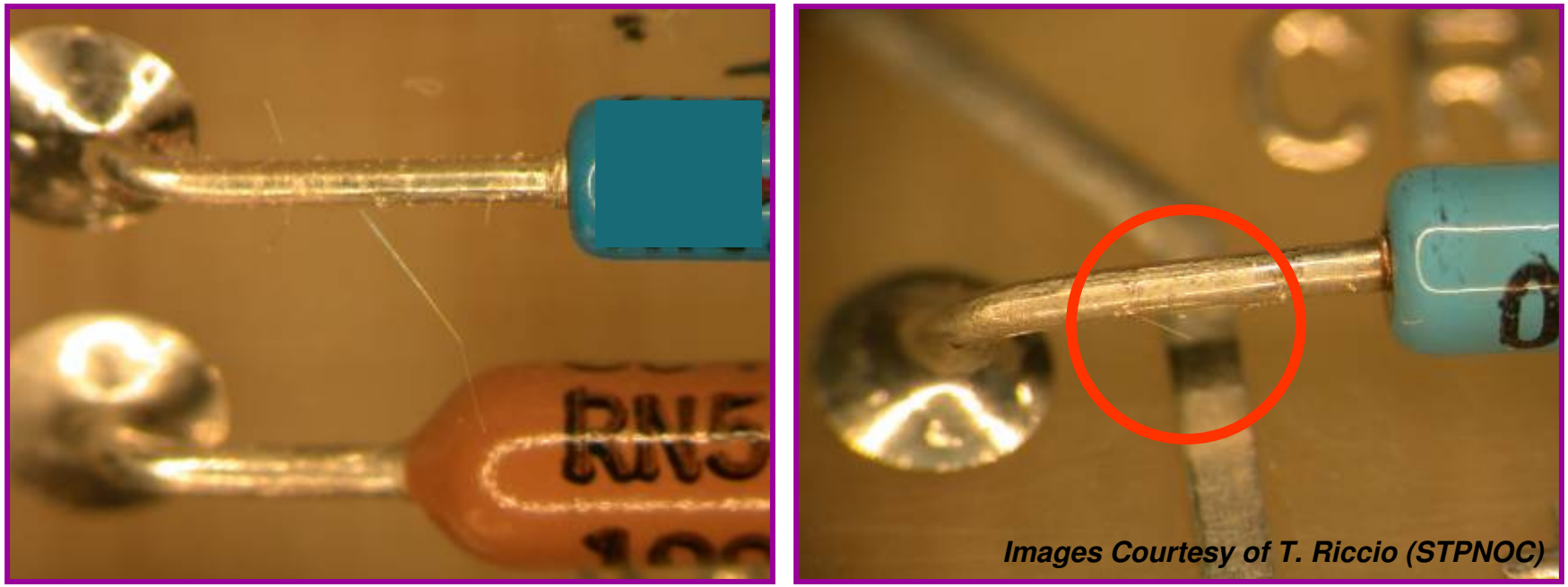
My Whisker *"Stress Relaxation Theory"*

Man with "Facial Whiskers"
Does YOGA!

Men with "Metal Whiskers"
Find Innovative Ways to Relieve Stress

A Case for Whisker Mitigation Strategies?

Tin Whiskers on Tin-Plated Axial Leaded Diodes



- Diode Leads were **NOT Hot Solder Dipped** prior to assembly
- PWB and components were **NOT Conformal Coated**

Three Whisker Mitigation Strategies

*Mitigation – to make **less** severe or painful*
Merriam-Webster Dictionary

Risk "Mitigation" ≠ Risk "Elimination"

- Avoid Use of Whisker Prone Surface Finishes
  - Perform materials composition analysis at incoming inspection using X-ray Fluorescence (XRF), Energy Dispersive X-ray Spectroscopy (EDS), etc.
  - *"Trust your supplier, But VERIFY!"*
- Conformal Coat: Electrically Insulating Barrier
  - Benefit #1: When applied on top of a whisker prone surface, conformal coat can sometimes keep whiskers from pushing through
  - Benefit #2: When applied to a distant conductor, can block whiskers from electrically shunting distant conductors
  - Benefit #3: Provides insulating barrier against loose conductive debris
- Remove/Replace Tin Finishes When Practical
  - Hot Solder Dip using lead-tin (Pb-Sn) solders
  - "First, Do No Harm" Principle

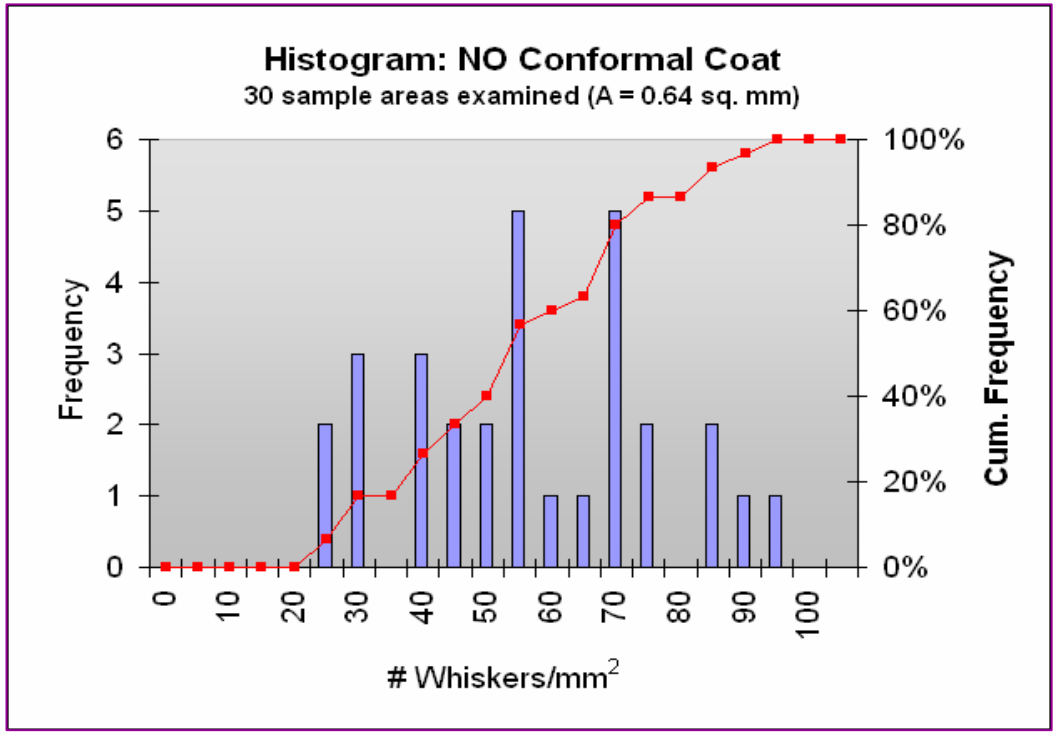
NASA Goddard Whisker Mitigation Study
Conformal Coat (Uralane 5750* Polyurethane)
~9 Years of Office Ambient Storage

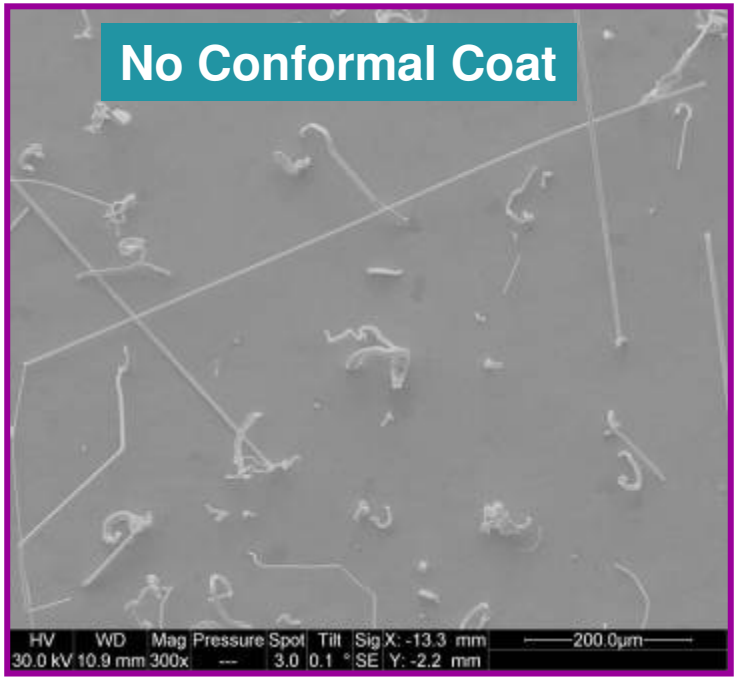
- **Specimens:**
  - 1” x 4”x 1/16” Brass 260
  - Tin-Plated 200 microinches
  - A few intentional scratches created after plating to induce localized whisker growth
- **Conformal Coating:**
  - Uralane 5750 on ½ of sample
  - Nominal Thickness = 2 mils
  - Locally THIN Regions also examined
- **Storage Conditions:**
  - Office Ambient ~ 9 years

** Uralane™ 5750 now known as Arathane™ 5750*

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

- **Control Areas Grew Whiskers Abundantly within the First Year. After 9 years of storage we found the following:**
  - **30 areas each 0.64 mm^2 were randomly examined for whisker density**
  - **Avg: 55 ± 19.6 whiskers / mm^2**
  - **Range: 23 to 95 whiskers / mm^2**

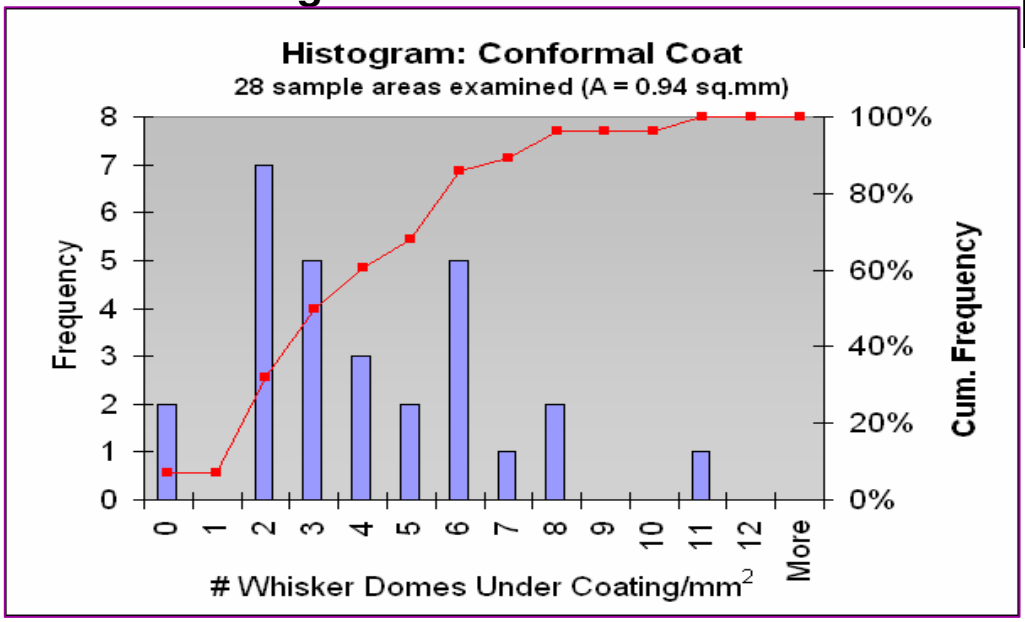


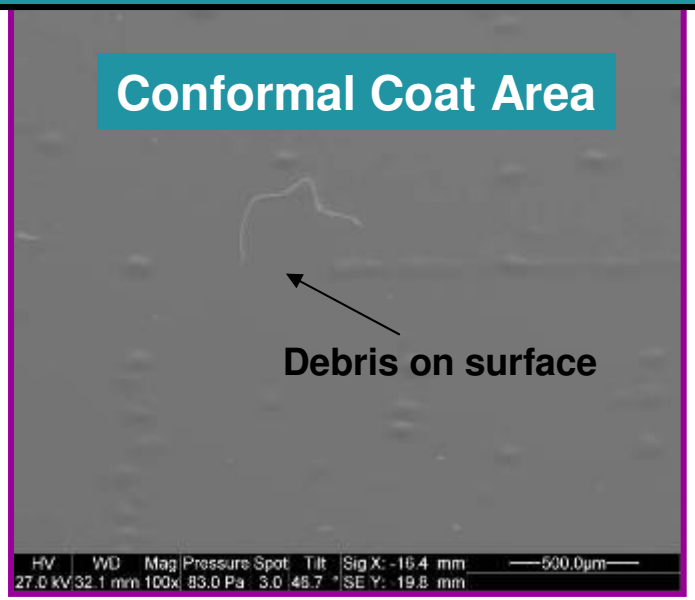


Uralane 5750 – 2 Mils Thick
9-Years of Office Ambient Storage

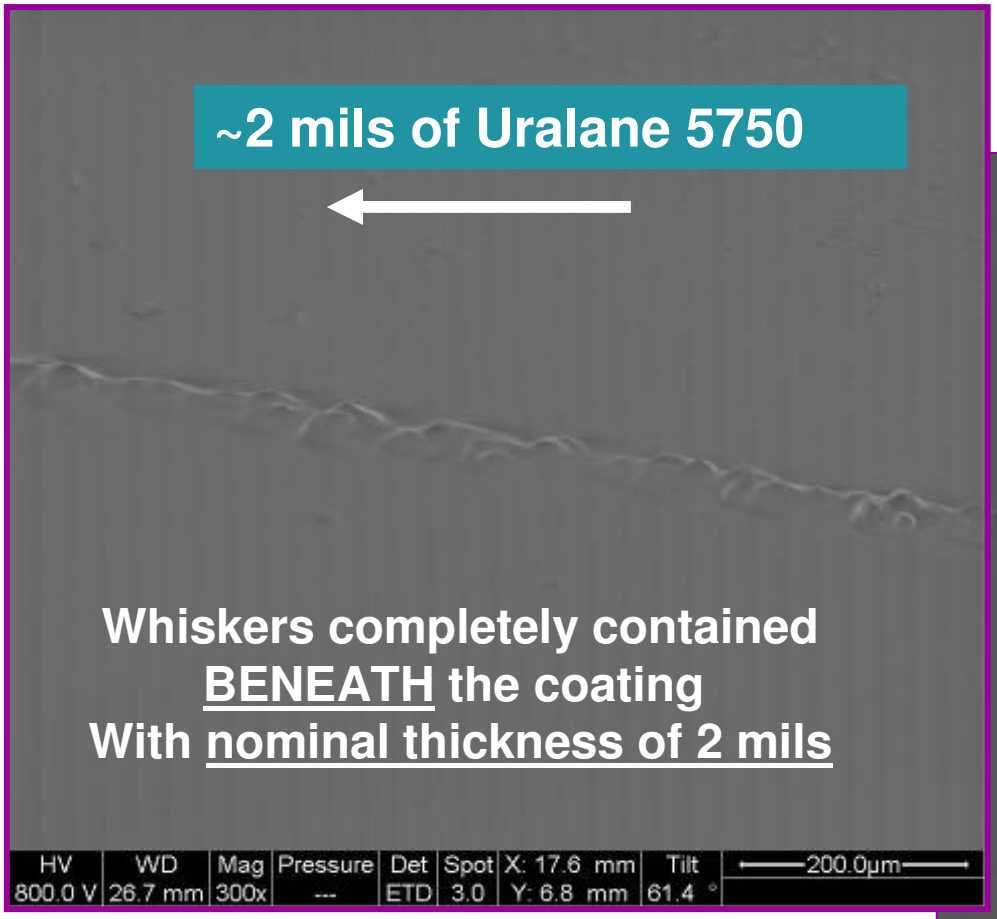
- **Conformal Coated Areas Grew Whiskers Too within the First Year. After 9 years of storage we find the following:**
  - ***To date ALL whiskers are contained beneath the coating that is 2 mils thick***
  - ***SEM cannot see INTO coating. Thus we see only "domes" caused by whiskers that lift coating slightly***
  - **Avg: 3.4 ± 2.6 domes / mm²**
  - **Range: 0 to 10.6 domes / mm²**

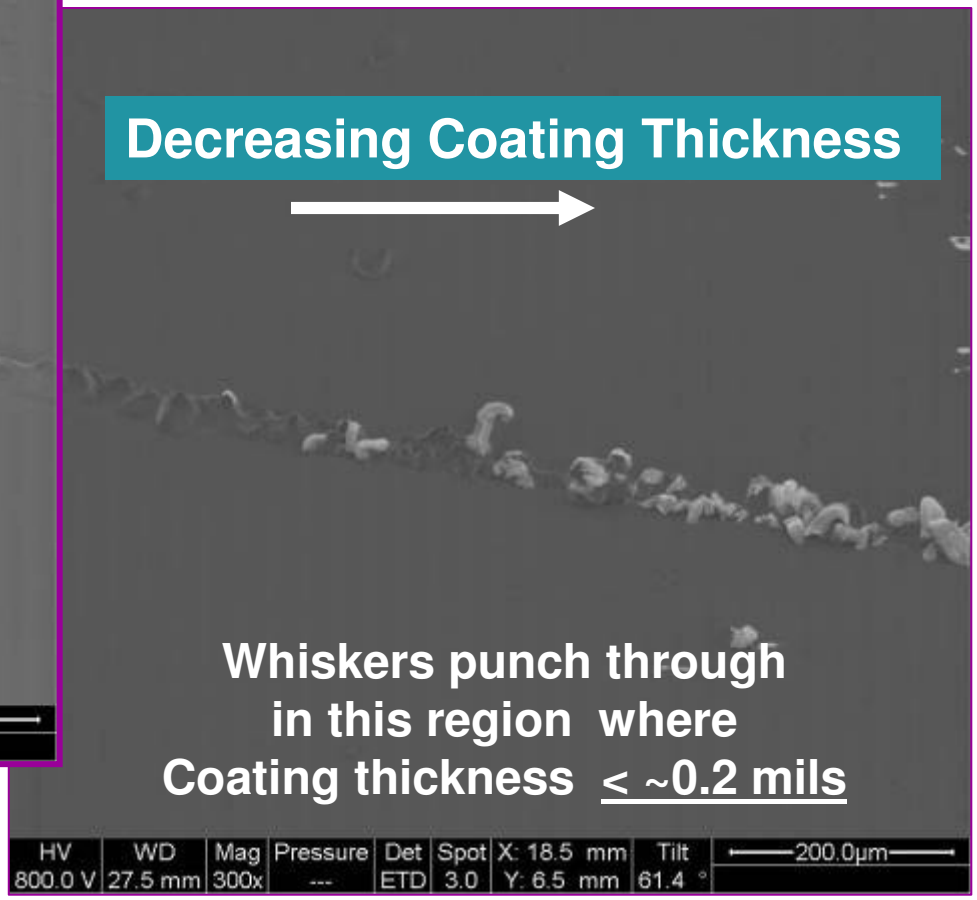
We suspect we are only counting "thick" whiskers in this statistic because the "thin" ones mechanically buckle before they can lift the coating enough to produce visible "domes"





Whisker Puncture vs. Coating Thickness



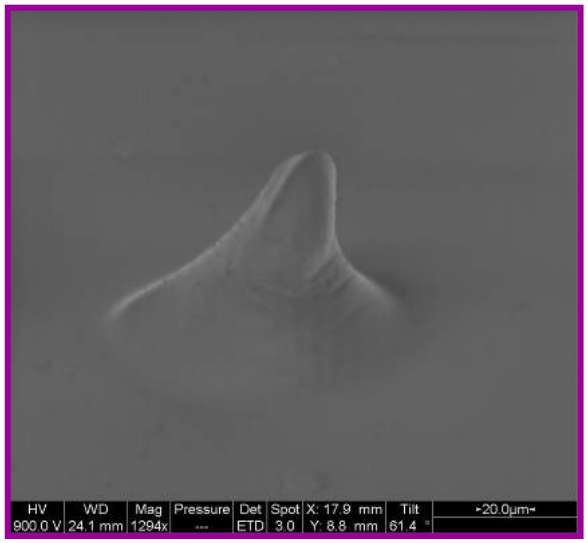


Uralane 5750 Conformal Coat -
9-Years of Office Ambient Storage

2 Mils Uralane = Very Effective

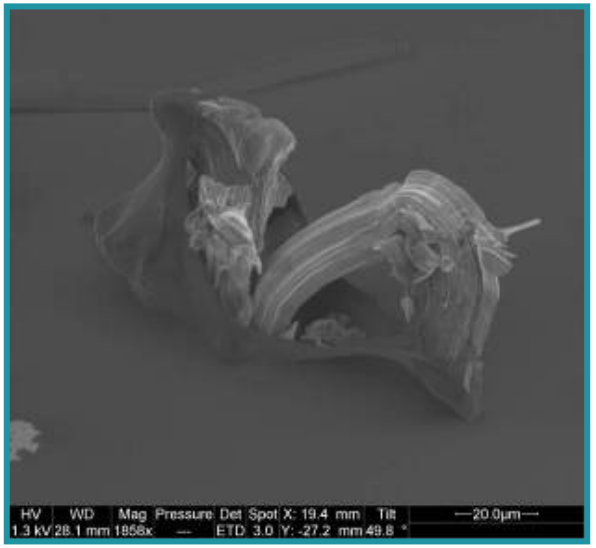
Whiskers Completely Entrapped Under the Coating → Euler Buckling

~0.5 Mils Uralane = Less Effective



Whisker "Lifting" Coating into Shape of Circus Tent, But Not Yet Penetrating

~0.1 Mils Uralane = Not Effective

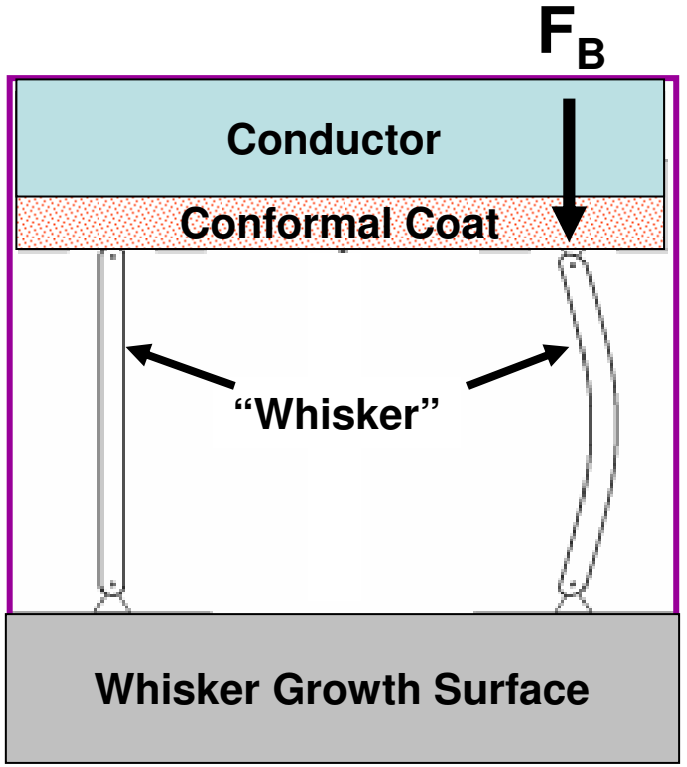


Whiskers Breaking Through "Thin" Coating

Euler Buckling
Axial Force Required to Buckle a Metal Whisker

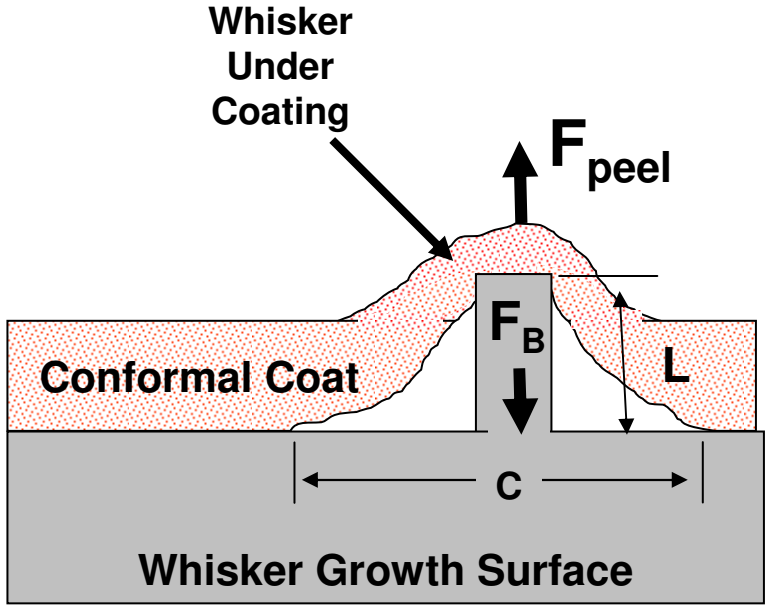
$$F_B = \frac{\pi^2 EI}{(KL)^2} \approx \left(\frac{\pi^3 \cdot E}{32}\right)\left(\frac{d^4}{L^2}\right)$$

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 $C \sim 2\pi QL$,
  - 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:
  - $F_{peel} = \Phi * C = 2 \text{ pi } Q \Phi L$
    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.



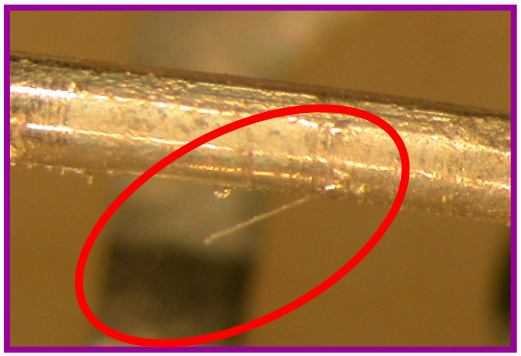
Uralane 5750 has better self-cohesion than adhesion to a tin surface

Additional Analysis Pending

Will a Whisker Buckle Before It's Tip Punctures Conformal 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

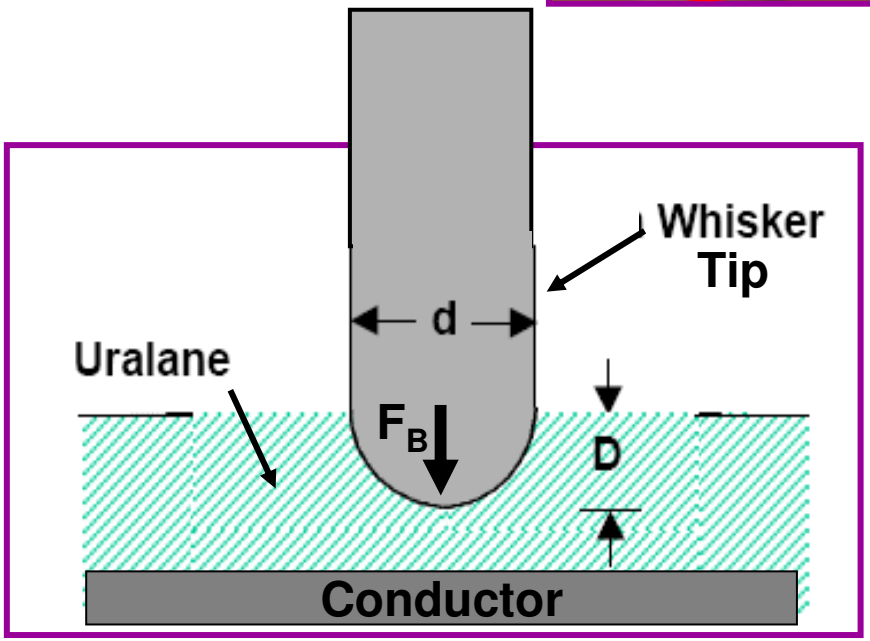
E_{coat} = Young's Modulus of coating

E_W = Young's Modulus of Whisker

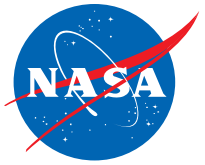
d = "Diameter" of whisker

L = Length of whisker

F_B = Euler Buckling Strength of the whisker



Effects of Conformal Coating -- 1



- Numerous sorts of coatings have been tried:
  - Reports of success vary from “none” to “perfect”, sometimes for the same sort of coating.

- NASA GSFC has used Uralane 5750, applied to pre-primed tin-plated surfaces to a thickness of 2 mils (=50 micrometers) +/- 10%:
  - After ~9 years of office ambient storage, these surfaces have whiskered abundantly, but the number of whiskers escaping through the 2 mil thick areas has been zero

- Dr. Thomas Woodrow (Boeing) has studied Urethane (acrylic) coatings, a silicone coating, and Parylene C coating of varying thicknesses up to ~ 4 mils (= 100 micrometers):
  - Some whiskers have penetrated even the thickest coatings when exposed to 25°C / 97% R.H.
  - "Evaluation of Conformal Coatings as a Tin Whisker Mitigation Strategy, Part 2", T. Woodrow, SMTAI, Sept. 2006
    http://nepp.nasa.gov/whisker/reference/tech_papers/2006-Woodrow-Conformal-Coating-PartII.pdf

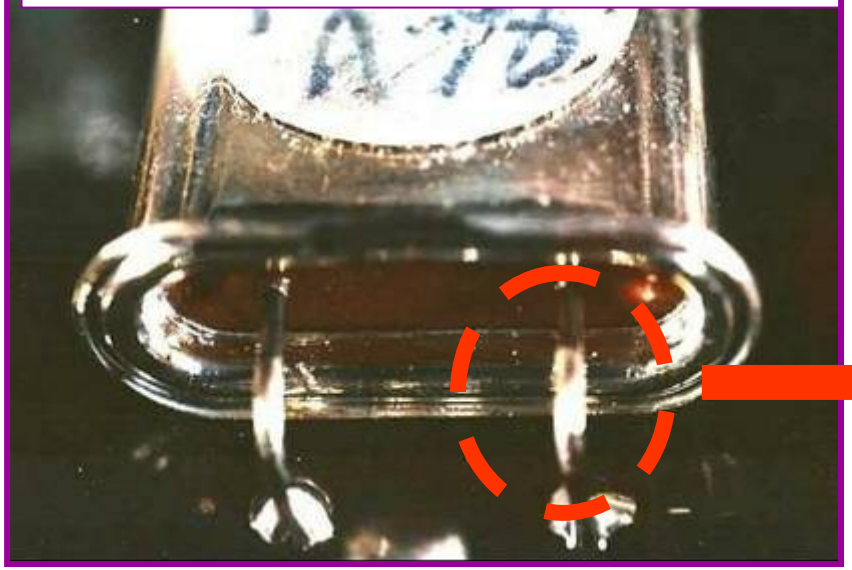
Effects of Conformal Coating -- 2

- Conclusion 1:
  - Uralane 5750, applied to at least 2 mils thickness, is a substantial improvement over an uncoated surface.
- Conclusion 2:
  - It is possible to suppose the surface is protected when it is not.
  - Coating processes can leave “weak zones” of thin coating allowing vertical escape
- Conclusion 3:
  - Even “poor” coatings can offer some protection against a whisker coming from a distant source and attempting to contact the protected surface --- long whiskers bend easily (Euler Buckling).
  - Conformal coat protects against a conductive bridge from detached whiskers lying across a pair of conductors

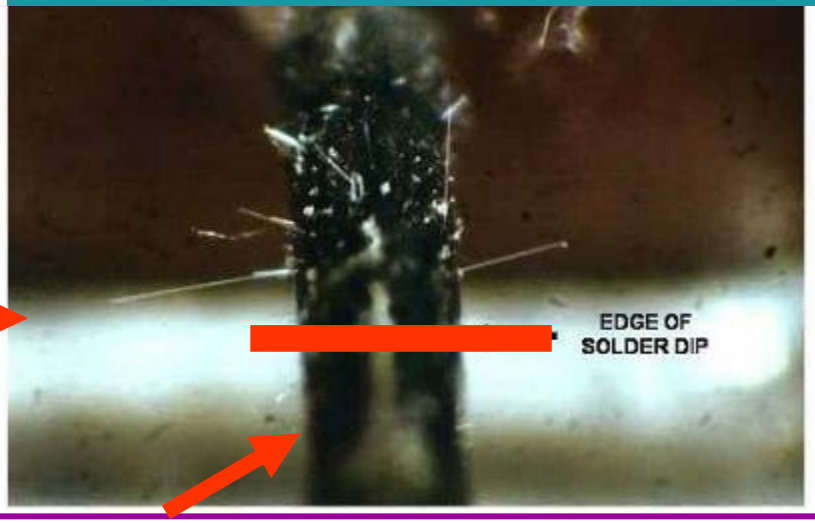
Hot Solder Dip
Benefits & Limitations

***Field Failure ONE Year* After Assembly**

Crystal with Tin-Plated Kovar Leads (with Nickel Underplate)



Tin Whiskers (~60 mils) Grew on *NON-Dipped* Region Shorting to Case Causing Crystal to Malfunction

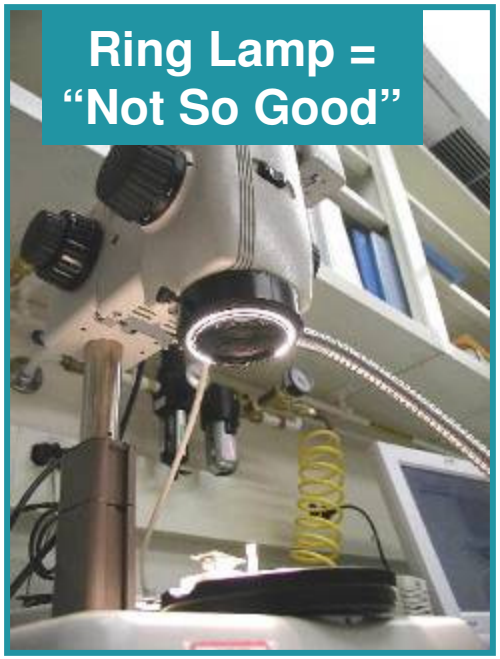


- Leads were *Hot Solder Dipped* (Sn63Pb37) *within 50 mils* of Glass Seal BEFORE Mounting to enhance solderability
- Dip was not 100% of leads due to concerns of inducing harm to glass seal

- No Whiskers on Hot Solder Dipped Surface
- ABUNDANT whiskers on the Non-Dipped Surface

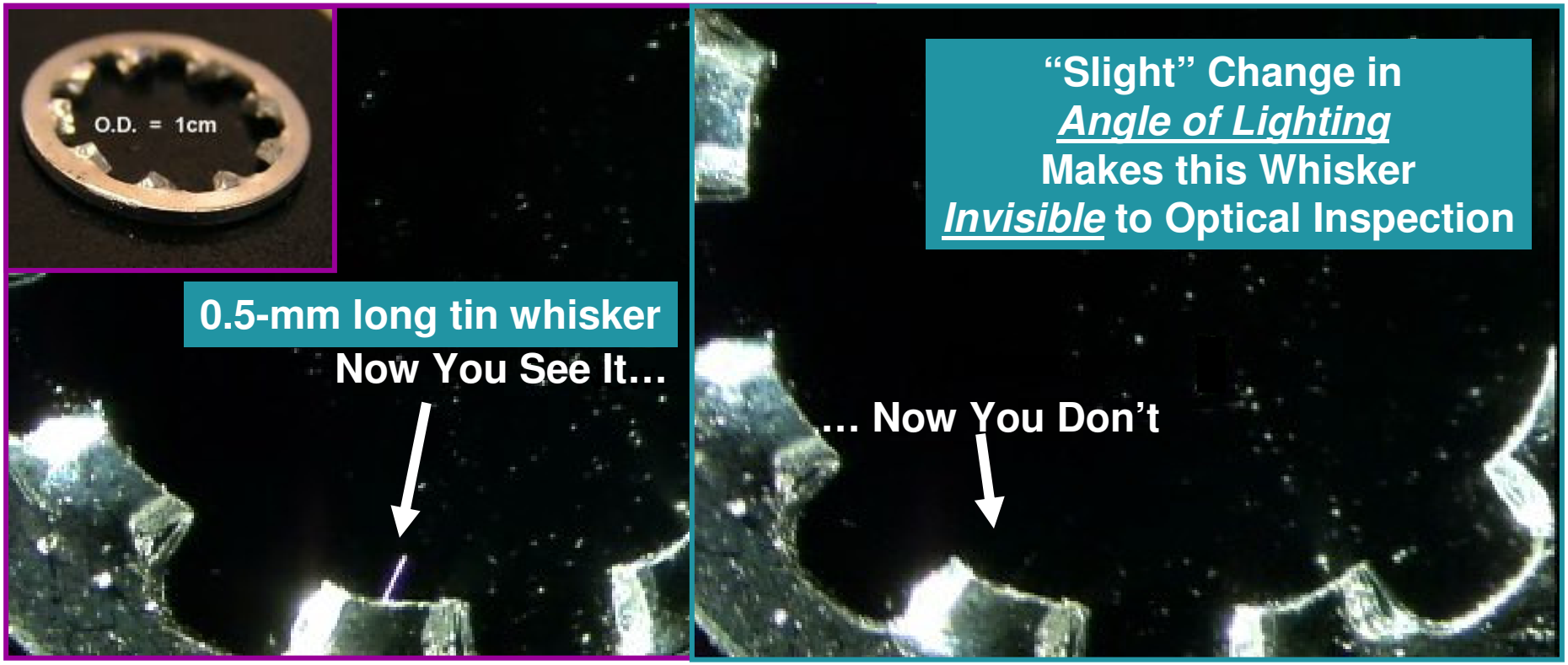
Optical Inspection for Metal Whiskers

- Basic Equipment:
  - Binocular Microscope
  - Light Source: Flex Lighting PREFERRED over Ring Lamp
- Freedom to tilt sample and/or lighting to illuminate whisker facets is VERY IMPORTANT



Evidence of "Absence of Whiskers"? (Optical Microscopy)

Tin-Plated Lock Washer

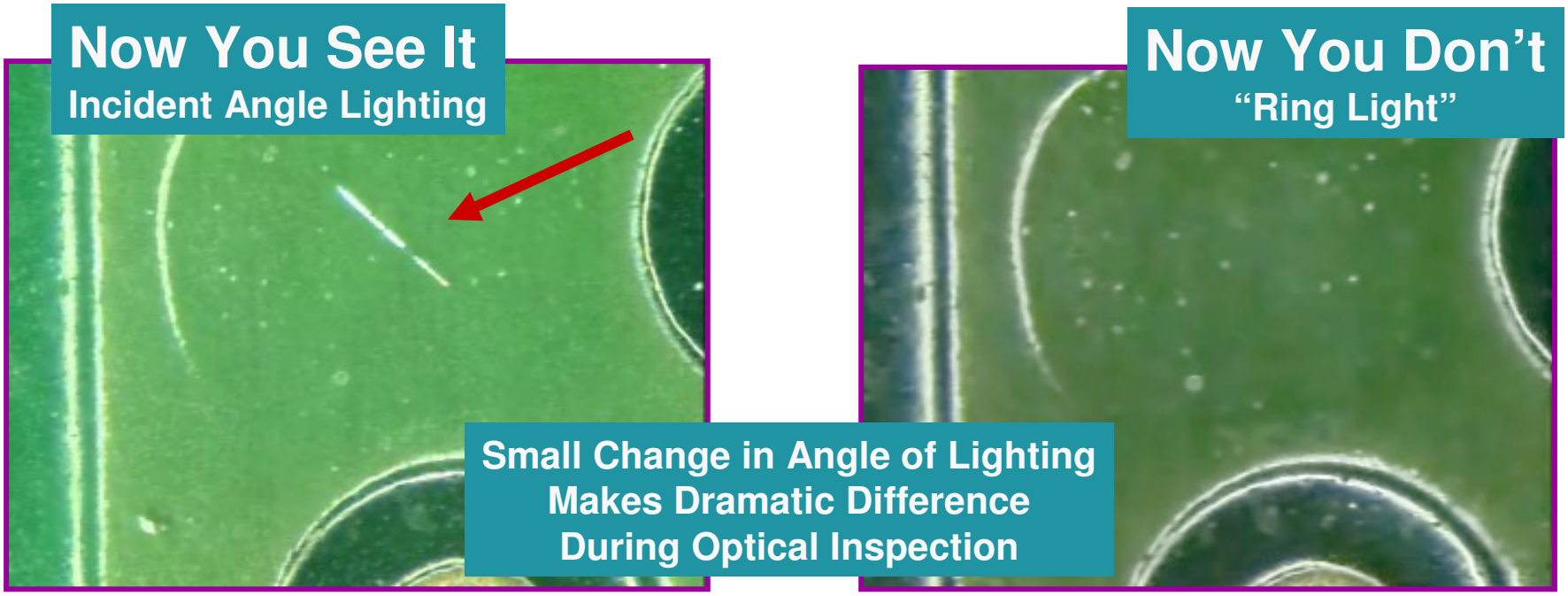


The absence of evidence is NOT evidence of absence

Field Technicians and Failure Analysts Need To Be Acquainted with Metal Whiskers!!!

NASA GSFC has published videos to aid in optical inspection for metal whiskers

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



Video Demonstration
Optical Inspection For Metal Whiskers
(Click Image to Start Video)

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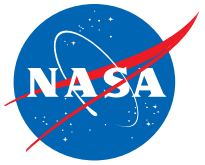
Work Performed in Support of the NASA Electronic Parts and Packaging (NEPP) Program

Acknowledgment to Dr. Michael Osterman
University of MD – Center for Advanced Life Cycle Engineering (CALCE)

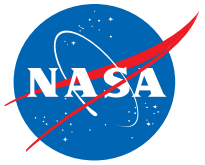
NASA Tin and Other Metal Whisker WWW Site

http://nepp.nasa.gov/whisker



Backup Slides

Why Are Tin, Zinc, Cadmium Still Used?



- Not all Tin (or Zinc or Cadmium) surfaces whisker!
  - Rough estimate: 3% to 30% do whisker.
- Not all metal whiskers cause shorts
  - Environment (geometry and electrical potentials matter).
  - Rough estimate: 3% to 30% do short.
- Not all whisker-induced shorts are traced to whiskers
  - They are very hard to see and failure analysis techniques often destroy evidence
  - Rough estimate: 0% to 10% are correctly traced.
- Not all identified whisker adventures are reported
  - Rough estimate: 0% to 3% are reported, once identified
- Hence, we expect between 0.00% and 0.03% of shorting problems caused by these coatings to be reported
  - While some 0.1% to 10% of these coatings are actually causing shorts.
  - With such a few public cases, many say “What, me worry?”
- Whiskering is dramatically inhibited when 0.5% (or more) lead (Pb) is added to Tin coatings: the shorting rate then approaches zero
  - This has been the case for the Hi-Rel community
  - But Pb use is being restricted by international legislation, and so the shorting rate may jump to 10% from zero **==> SWATCH GROUP <==**

"The Five Stages of Metal Whisker Grief"

By Henning Leidecker

Adapted from Elisabeth Kubler-Ross in her book "On Death and Dying", Macmillan Publishing Company, 1969

Denial

"Metal whiskers?!? We ain't got no stinkin' whiskers! I don't even think metal whiskers exist! I KNOW we don't have any!"

Anger

"You say we got whiskers, I rip your $%#@ lungs out! Who put them there --- I'll murderize him! I'll tear him into pieces so small, they'll fit under one of those *^&$#% whiskers!"

Bargaining

"We have metal whiskers? But they are so small. And you have only seen a few of them. How could a few small things possibly be a problem to our power supplies and equipment? These few whiskers should be easy to clean up."

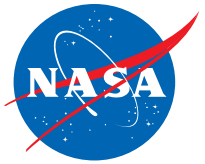
Depression

"Dang. Doomed. Close the shop --- we are out of business. Of all the miserable bit joints in all the world, metal whiskers had to come into mine... I'm retiring from here... Going to open a 'Squat & Gobble' on the Keys. "

Acceptance

"Metal whiskers. How about that? Who knew? Well, clean what you can. Put in the particle filters, and schedule periodic checks of what the debris collectors find. Ensure that all the warrantees and service plans are up to date. On with life."

A Few Recent Whisker Experiences:
It's Not Just Tin Whiskers!!!

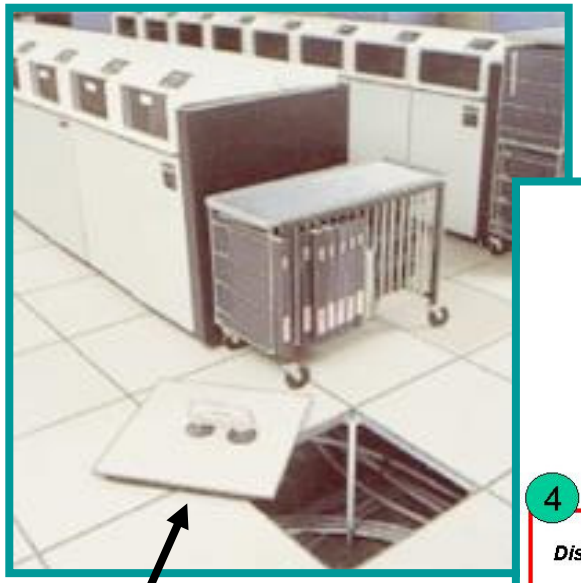


- **Tin Whiskers:**
  - **2005:** Tin Whiskers on ***diode leads*** shut down ***Connecticut Nuclear Power Plant***
  - **2006:** Tin whiskers on ***card rails*** discovered in ***Space Shuttle Transportation System*** Some 100 to 300 million whiskers were in OV-105's boxes
  - **2006:** Tin whiskers on ***watch crystals*** reported by ***SWATCH Group***. 30% of new RoHS-compliant Sn-Cu solder sprouting whiskers. 5% catastrophically shorted within months.
- **Zinc Whiskers:**
  - **2005:** Zinc whiskers on ***raised floor tiles*** cripple ***Colorado State Government*** data center. Forced to build a new "disaster recovery center"
  - **2005**: Zinc whiskers on ***raised floor tiles*** destroy 75% of the computer equipment in a particular data center. ***Investigation takes ~8 months to properly identify root cause***
  - **2006:** Zinc whiskers identified as root cause of persistent ***NAVY weapon system failures***
- **Cadmium Whiskers:**
  - **2006**: Cadmium whiskers found on ***electrical switch*** proposed for spaceflight program
  - **2007**: Cadmium whiskers on ***connector shells*** cause failure during T-Vac testing

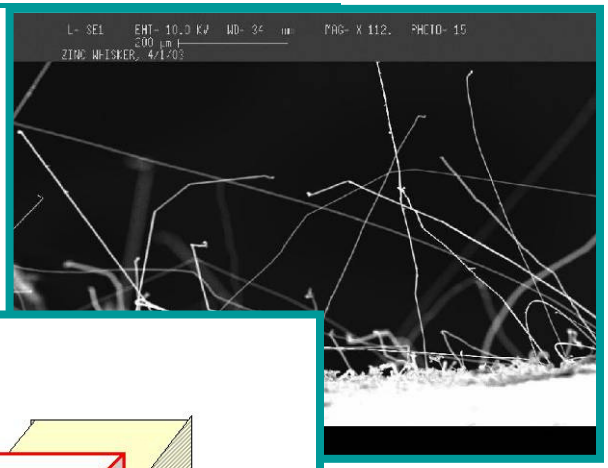
Dozens of Zinc Whisker Disasters!!!

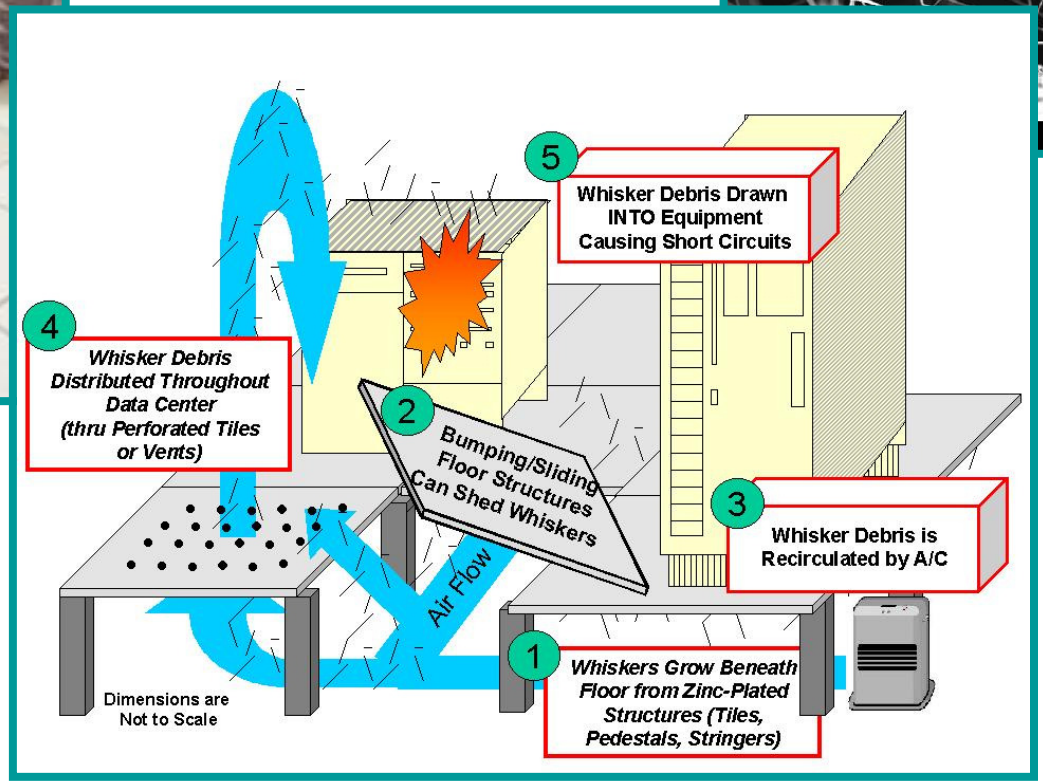
Computer Room Raised Floor Panels and Support Structures

http://nepp.nasa.gov/whisker/other_whisker/index.htm#zinc



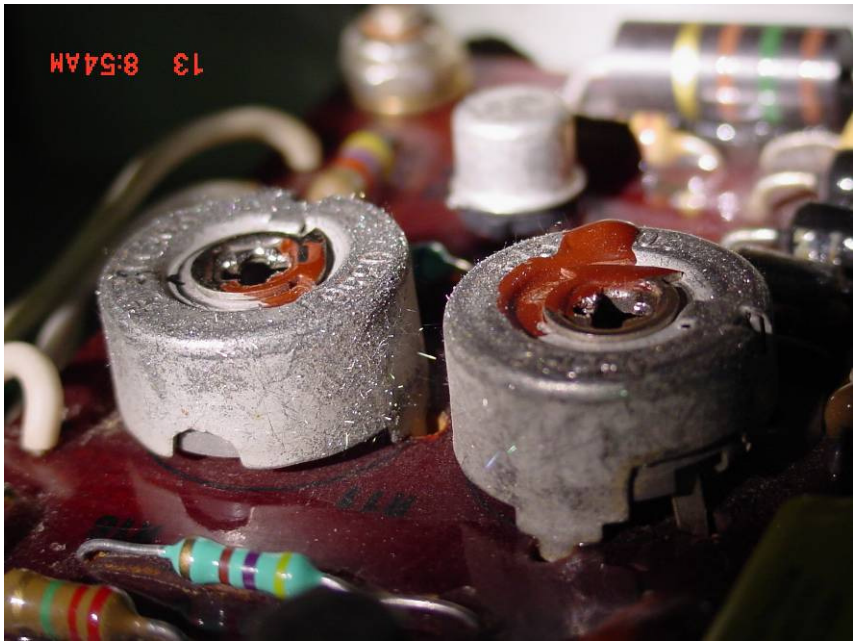
Underside of Raised Floor Panels Frequently uses Zinc-Coated Steel

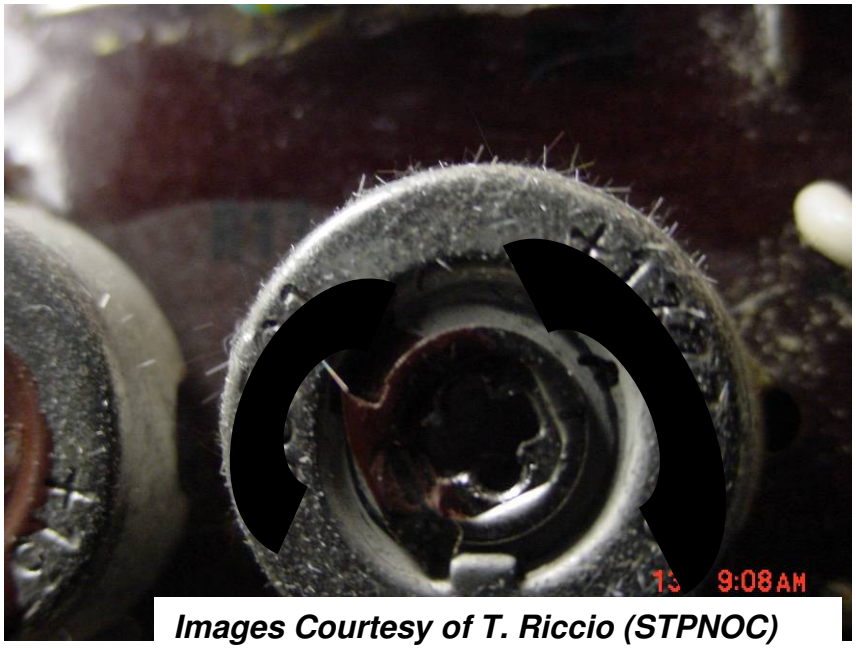




Another Case for Whisker Mitigation Strategies?

Metal Whiskers on External Case of Potentiometers



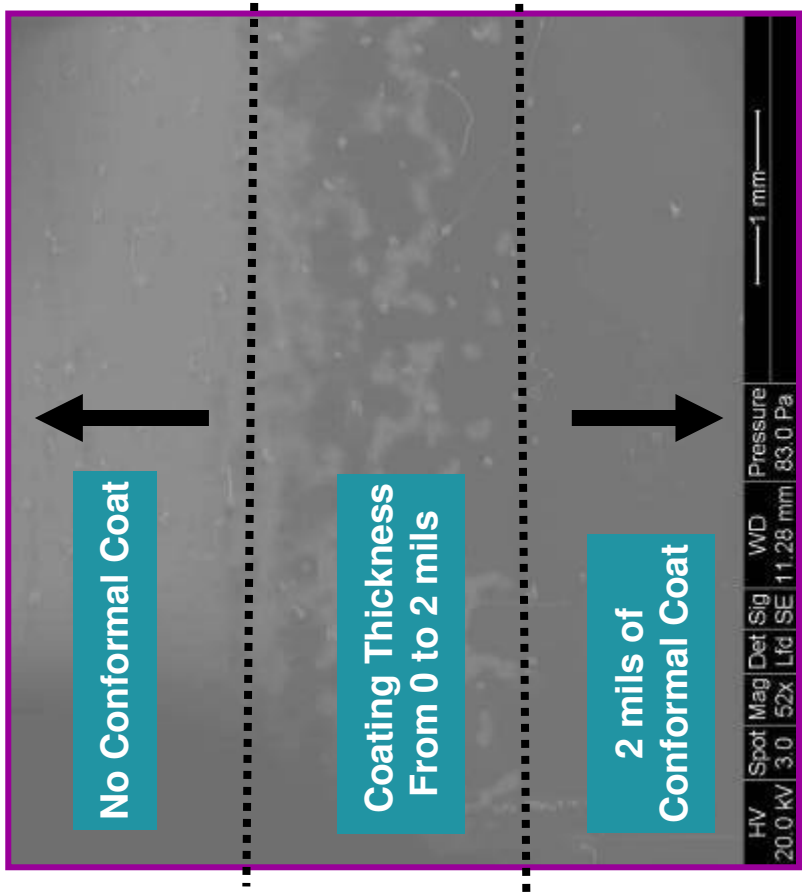


Images Courtesy of T. Riccio (STPNOC)

- Potentiometer cans are electrically connected to circuitry
- Metal whiskers bridging between the cases caused circuit malfunction
- No electrically insulating materials were used on these cases to act as a barrier to electrical shorting

NASA Goddard Whisker Mitigation Study
Conformal Coat (Uralane 5750* Polyurethane)
~9 Years of Office Ambient Storage

- **Coating Thickness Can Vary Depending on Process Parameters**
- **Spray and masking techniques used produced a "transition" region ~2 mm wide where the conformal coating thickness was variable between 0 and 2 mils**
  - ***One must understand their own processes to ensure the coating thickness is sufficient everywhere you intend it to be!!***

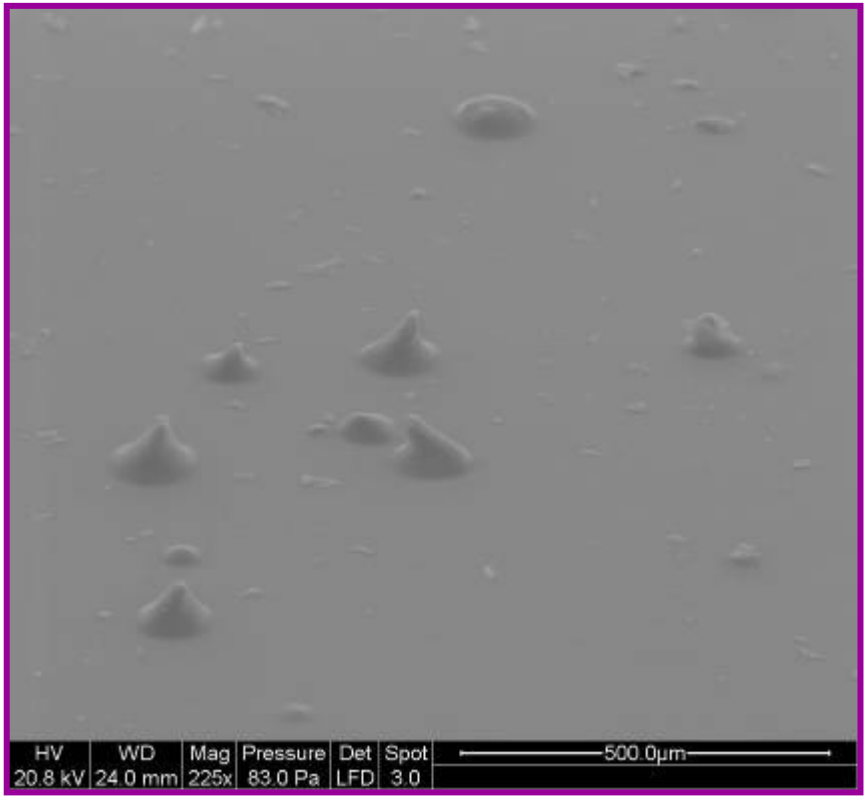


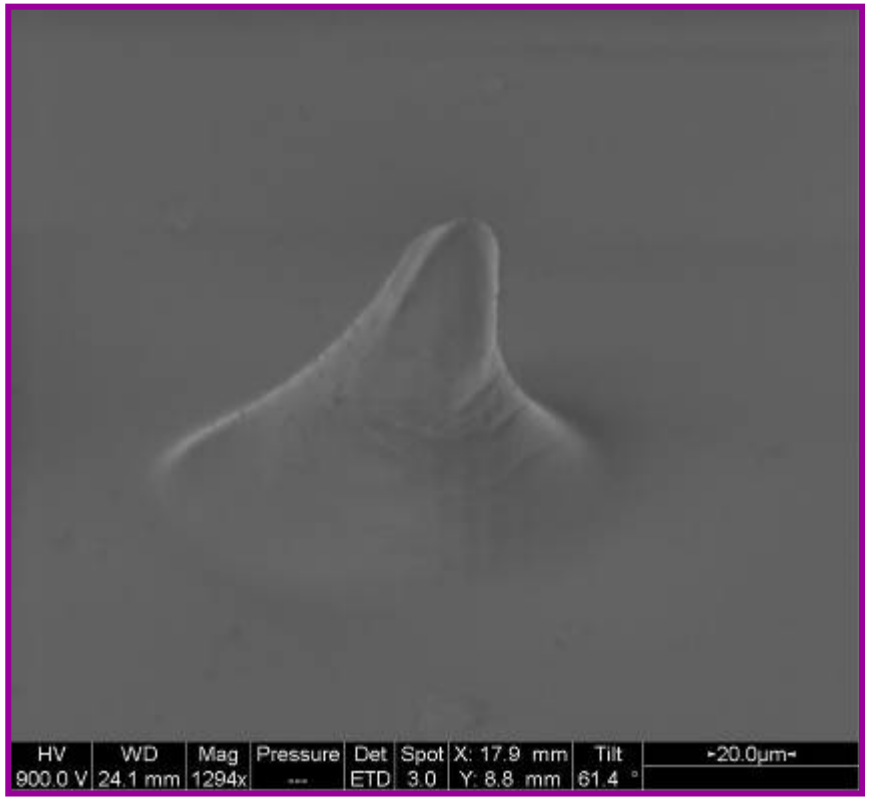
NASA GSFC Conformal Coat Tin Whisker Test Coupon

** Uralane™ 5750 now known as Arathane™ 5750*

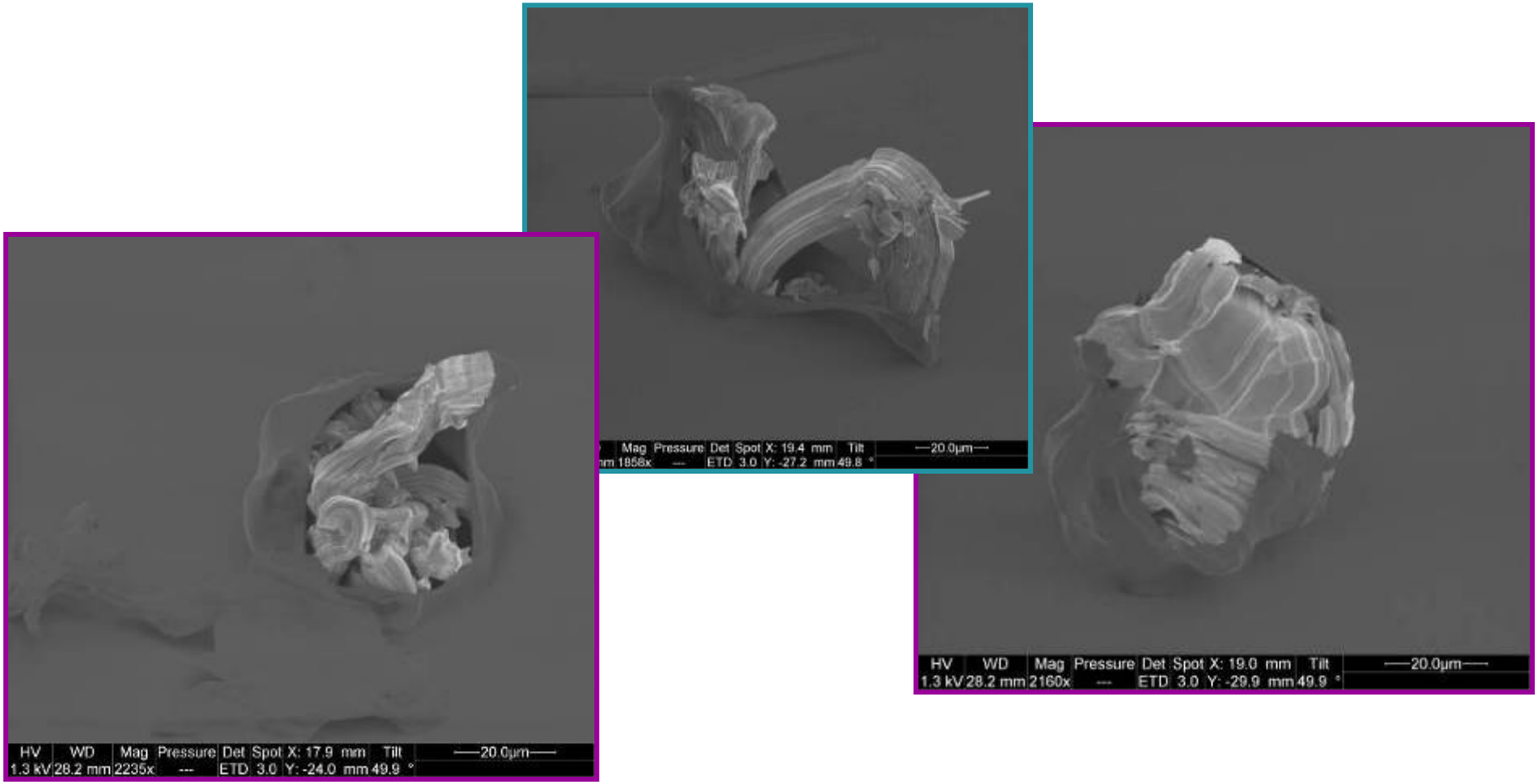
Tin Whiskers Forming "Circus Tents" in Thin Uralane 5750 Conformal Coat - 9-Years of Office Ambient Storage

Coating Thickness < 0.5 Mil





Tin Whiskers Rupturing THIN Coating
~0.1 to 0.2 Mils Uralane 5750 Conformal Coat
9-Years of Office Ambient Storage



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

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

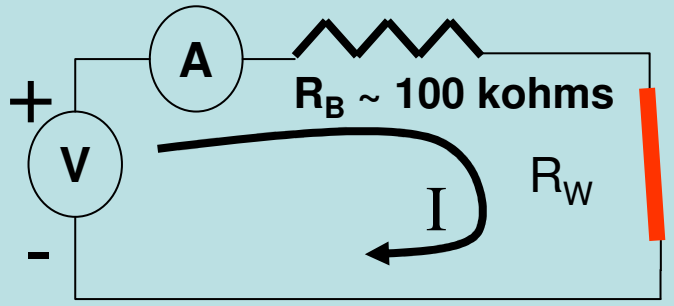
Circuit to Measure Resistance of a Metal Whisker

- **Use of a simple "Ohmmeter" to measure the resistance of a metal whisker is NOT preferred**
  - **Ohmmeter may supply $V_{out} < V_{breakdown}$ for the insulating films (oxides, moisture) that form on a metal whisker**
  - **Ohmmeter may supply $V_{out} > V_{melt}$ causing the whisker to melt before resistance can be measured**
- **Instead, a variable power supply and a ballast resistor should be used to overcome the above complications**
  - **Adjust $V_{out} > V_{breakdown}$ of insulating films on whisker**
  - **When $V_{out} > V_{breakdown}$, R_B quickly drops $V_{whisker} < V_{melt}$**

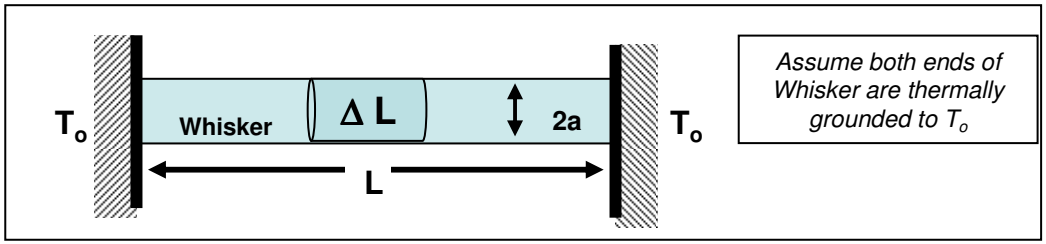
Circuit to measure R_w

$$R_W = \frac{V - IR_B}{I}$$

Choose R_B such that $V_{whisker} < 80\%\ V_{melt}$



Derivation of Melting Current of a Metal Whisker in Vacuum



Assume both ends of Whisker are thermally grounded to T_o

$$\frac{du}{dt} + \Phi = source$$

du/dt **+** ***Φ*** **=** ***source***

$$u = C \cdot T \qquad c = \frac{C}{V}$$

$$u = \left(\frac{C}{V}\right) \cdot V \cdot T = c \cdot V \cdot T$$

$$u = c \cdot \Delta L \cdot A \cdot T$$

$$\boxed{\frac{du}{dt} = c \cdot \Delta L \cdot A \cdot \frac{\partial T}{\partial t}}$$

$$\Phi = \left(\frac{\partial J}{\partial x}\right) \cdot \Delta L \cdot A$$

Convection loss = 0 for vacuum
Neglect radiation loss

$$J = -k_T \cdot \frac{\partial T}{\partial x} \qquad \frac{\partial J}{\partial x} = -k_T \cdot \frac{\partial^2 T}{\partial x^2}$$

$$\Phi = -k_T \cdot \left(\frac{\partial^2 T}{\partial x^2}\right) \cdot \Delta L \cdot A \qquad k_T = \frac{Lz \cdot T}{\rho}$$

$$\boxed{\Phi = -\frac{L_z T}{\rho}\left(\frac{\partial^2 T}{\partial x^2}\right) \cdot \Delta L \cdot A}$$

$$source = I^2 \cdot R$$

$$I = J_e \cdot A \qquad R = \frac{\rho \cdot \Delta L}{A}$$

$$source = \left(J_e{}^2 \cdot A^2\right) \cdot \left(\frac{\rho \cdot \Delta L}{A}\right)$$

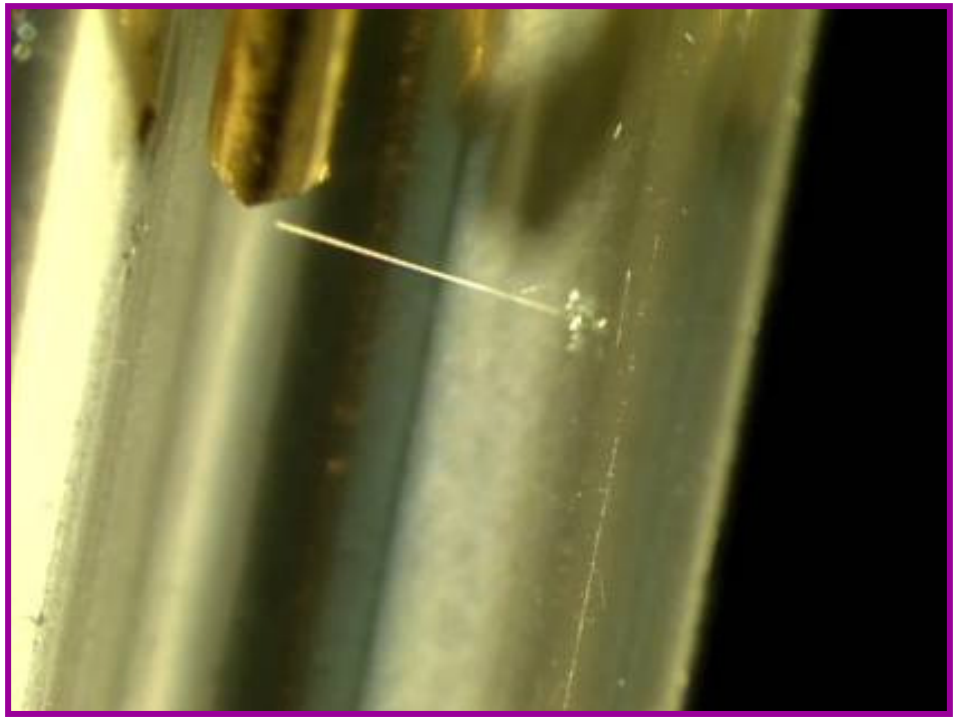
$$\boxed{source = \left(J_e{}^2 \cdot A\right) \cdot \rho \cdot \Delta L}$$

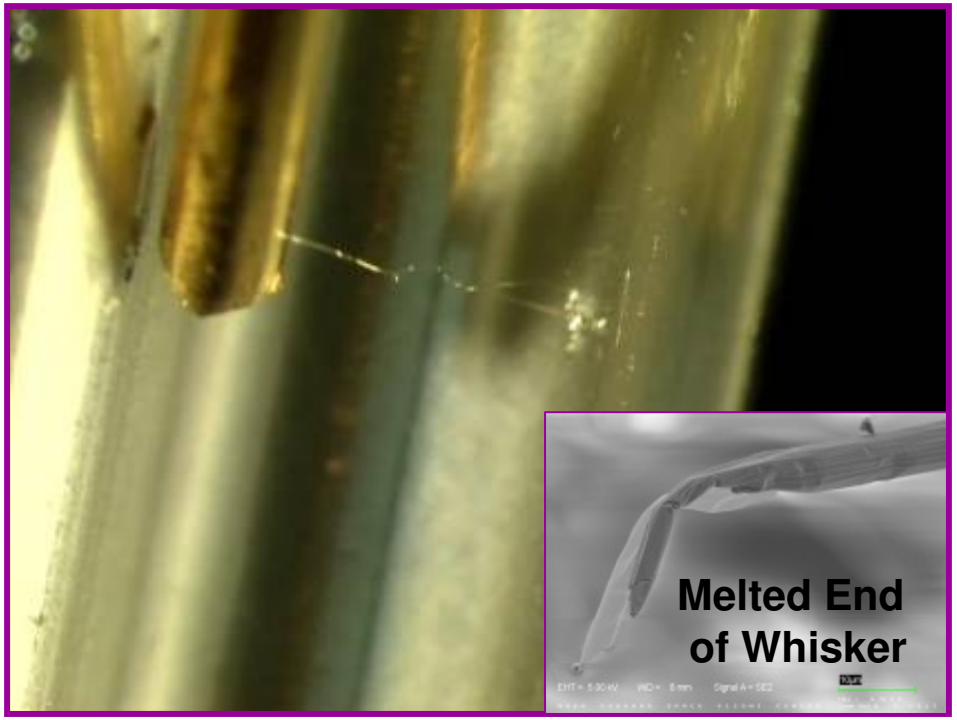
$$\left[c \cdot \Delta L \cdot A \cdot \frac{\partial T}{\partial t}\right] - \left[\frac{L_z \cdot T}{\rho}\left(\frac{\partial^2 T}{\partial x^2}\right) \cdot \Delta L \cdot A\right] = J^2 \cdot \rho \cdot \Delta L \cdot A$$

$$\left[c \cdot \frac{\partial T}{\partial t}\right] - \left[\frac{Lz \cdot T}{\rho}\left(\frac{\partial^2 T}{\partial x^2}\right)\right] = J^2 \cdot \rho$$

$$\boxed{I_{melt,vac} = \left[\frac{2\sqrt{LzT_0}}{R_0}\right] \cos^{-1}\left(\frac{T_0}{T_{melt}}\right)}$$

An Example of "Melting" a Tin Whisker





Before Contact

1. Gold-Plated Test Probe has +3 Volts Relative to Tin Whisker

After Contact

1. Tip of whisker micro-welds to gold test probe
2. Whisker melts mid-length
3. Small section of whisker root remains attached to substrate