

Metal Whiskers:

Failure Modes and Mitigation Strategies

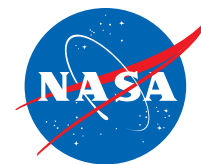
Jay Brusse / Perot Systems

Dr. Henning Leidecker / NASA Goddard

Lyudmyla Panashchenko / Univ. of MD-CALCE Graduate Student

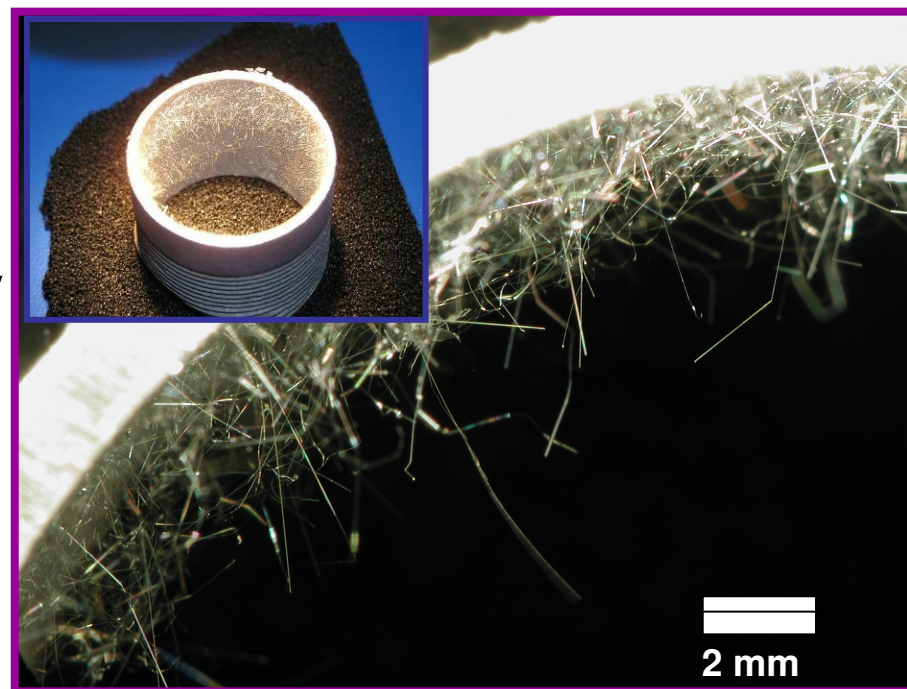


<http://nepp.nasa.gov/whisker>



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

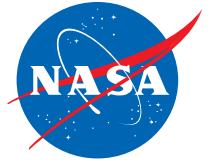


**Zinc Whiskers on
Hot Dip Galvanized Steel Pipe**

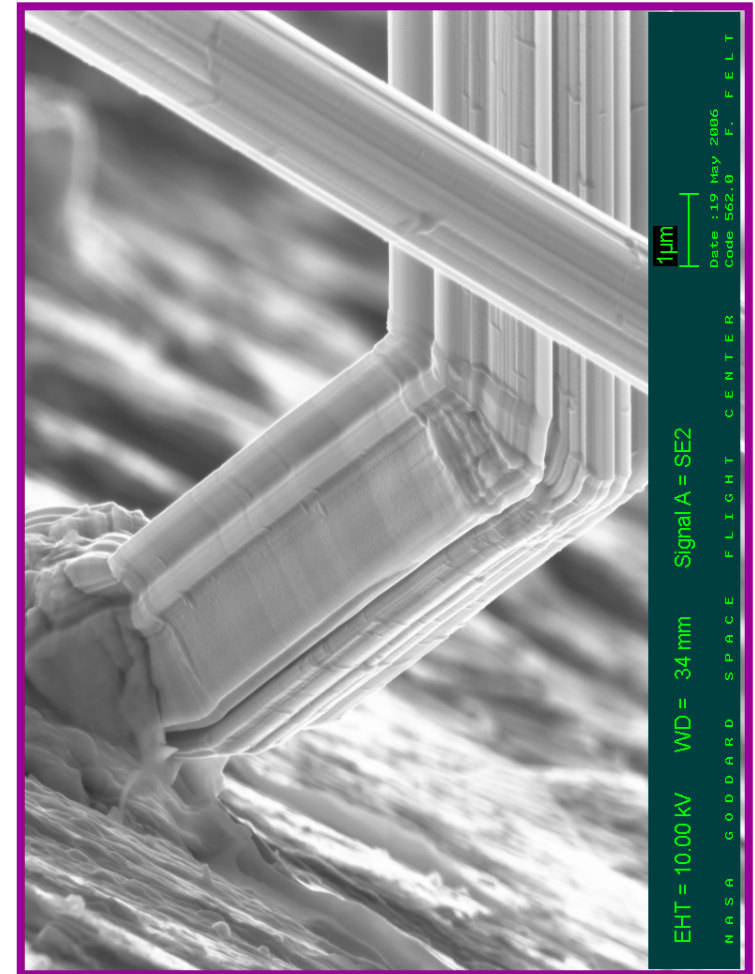
**Cover Photo:
Tin whiskers on Tin-Plated
Beryllium Copper PCB Card Rails**

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

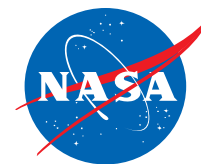
What are Tin or Zinc or Cadmium Whiskers?



- 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 μm
(Typical ~ 1 μm)
- **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



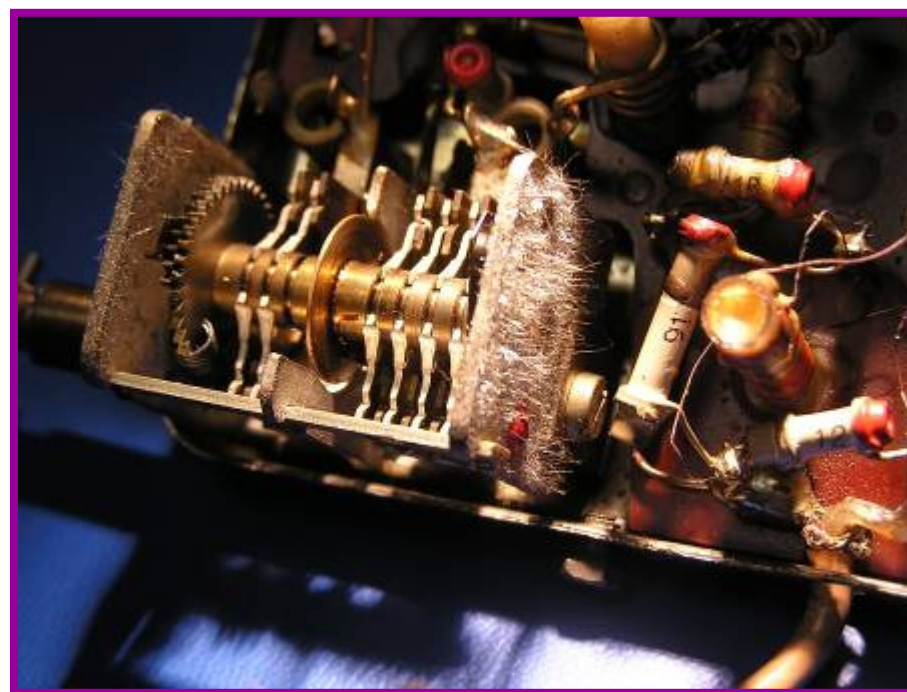
*Tin Whiskers on Tin-Plated
Electromagnetic Relay Terminals*



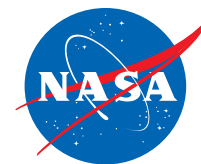
Metal Whiskers

“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!



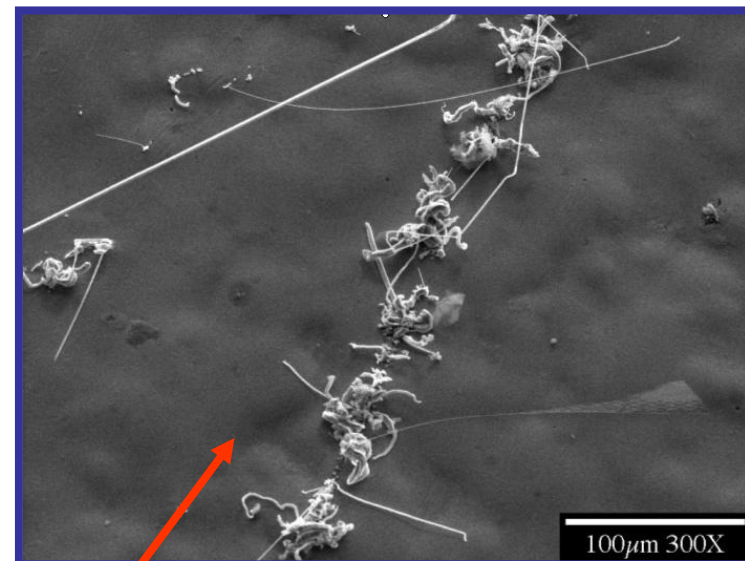
*Tin Whiskers on 1960's Era
Variable Air Capacitor*



Whisker Resistant Metal Coatings

"The Quest"

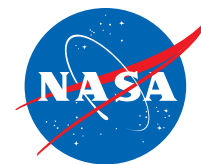
- 1950s and 60's ^[1] ^[2]:
Bell Labs worked through the periodic table to determine whether addition of some element to a Tin coating would "quench" whiskering
 - Adding 0.5 - 1% (by weight) of lead (Pb) works
 - Some additives seem to enhance whiskering
- Since 1990s:
Most US MIL specs require adding Pb to any tin coatings used around electronics.
 - Concentration is usually named as 2% to 3% Pb by weight for "margin"
- What additives quench zinc and cadmium whiskers?
 - We don't know, but certainly NOT chromate conversion finishes!



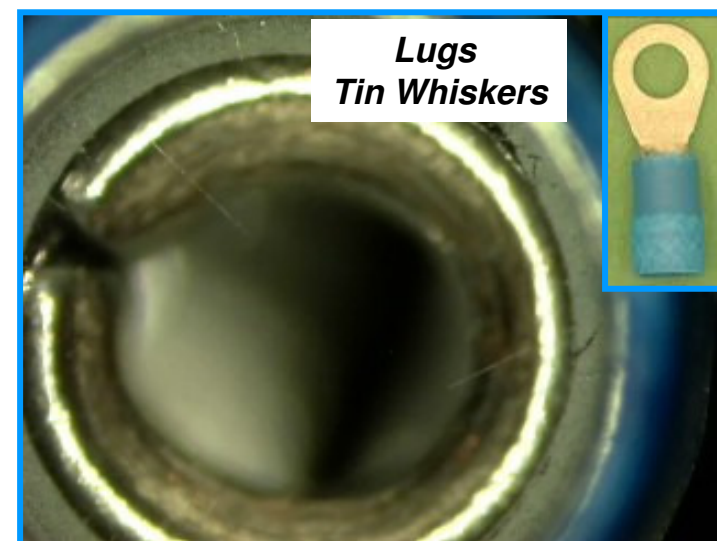
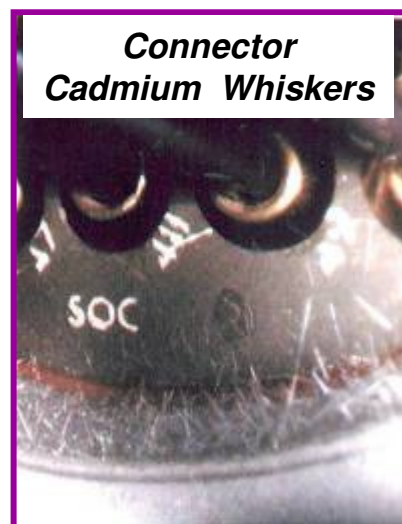
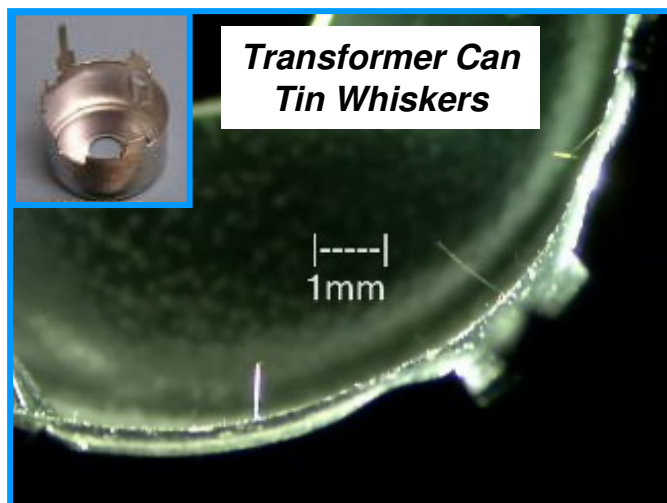
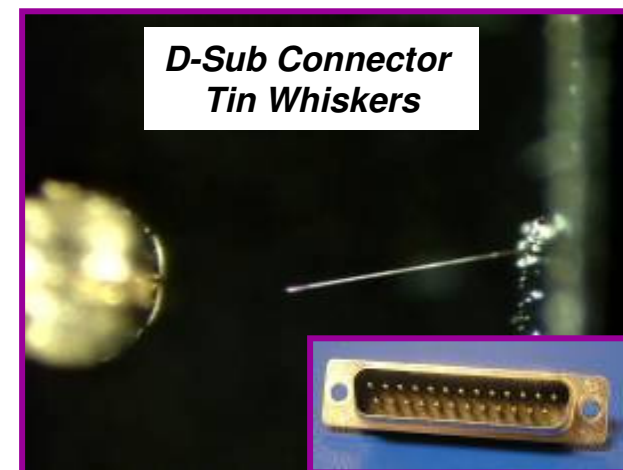
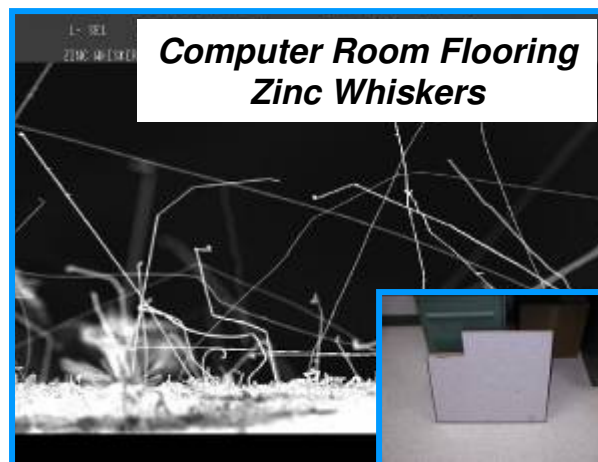
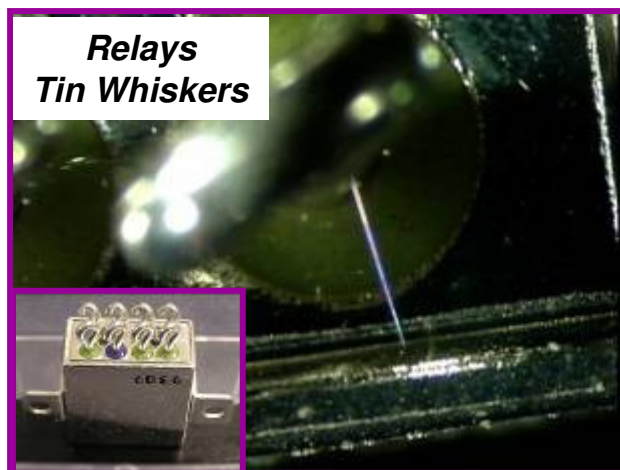
*Zinc Whiskers Growing from
Zinc-Plated Yellow Chromate Steel Bus Rail*

[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

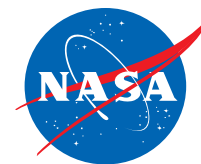


Metal Whiskers on Components



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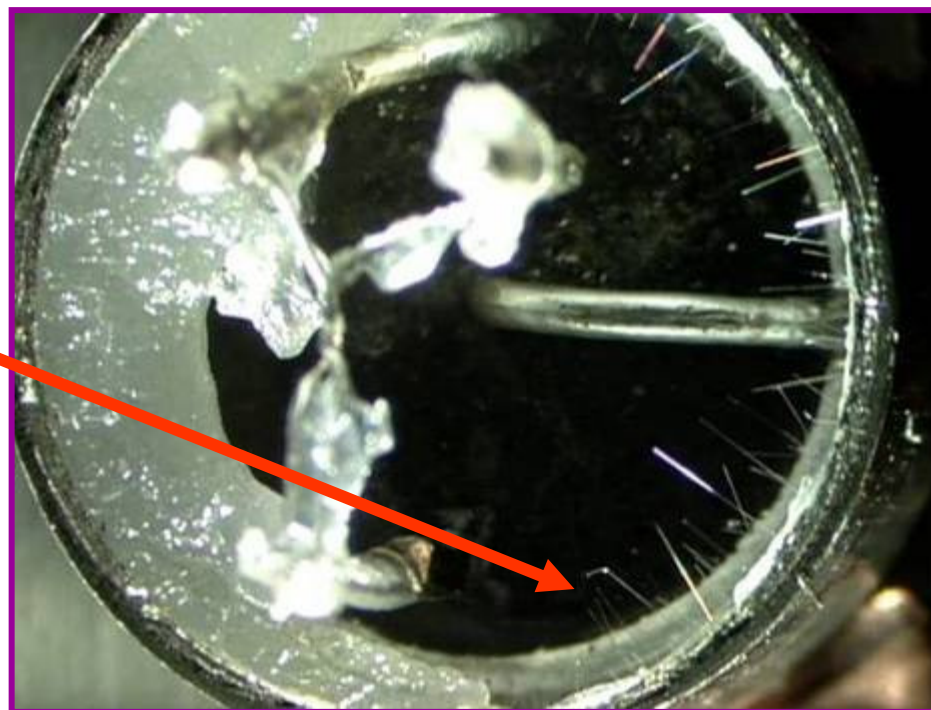
Metal Whiskers:
Failure Modes and Mitigation Strategies



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>

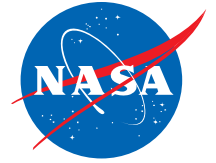
http://nepp.nasa.gov/whisker/reference/tech_papers/2006-Leidecker-Tin-Whisker-Failures.pdf

[illegible]

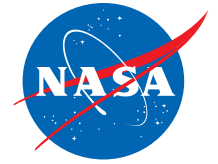
These are ~10% of the Problems We Know About

A Few Recent Whisker Experiences:

It's Not Just Tin Whiskers!!!



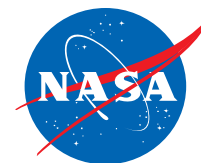
- **Tin Whiskers:**
 - **2005:** Tin Whiskers on diode leads shut down Connecticut Nuclear Power Plant
 - **2006:** Tin whiskers on card rails discovered in Space Shuttle Transportation System
Some 100 to 300 million whiskers were in OV-105's boxes
 - **2006:** Tin whiskers on watch crystals reported 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



“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
- Intermittent short if

$$I_{whisker} < I_{melt}$$
$$I_{whisker} > I_{melt}$$



Debris/Contamination

- Interfere with Sensitive Optics or MEMS
- Produce Shorts in Areas REMOTE From Whisker Origins
(Zinc Whiskers on raised flooring are a PRIME Example)



METAL VAPOR ARC

- If $I_{whisker} >> I_{melt}$ Whisker Can Vaporize into a Metal Gas
- If voltage is sufficiently high, then the metal gas can be ionized into a conductive PLASMA of Metal Ions
- Plasma Can Form an Arc Capable of Carrying **HUNDREDS OF AMPS!**
- Depends on arc gap length, voltage, current, pressure, etc.

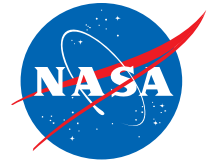


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Metal Whiskers:
Failure Modes and Mitigation Strategies

Metal Whisker Melting Current -- Pt. 1

(In Vacuum)



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

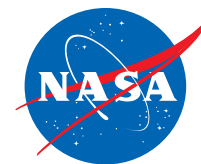
See Backup Slides for Derivation

- Where $L_z \sim 2.45 \cdot 10^{-8} (V/K)^2$ 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

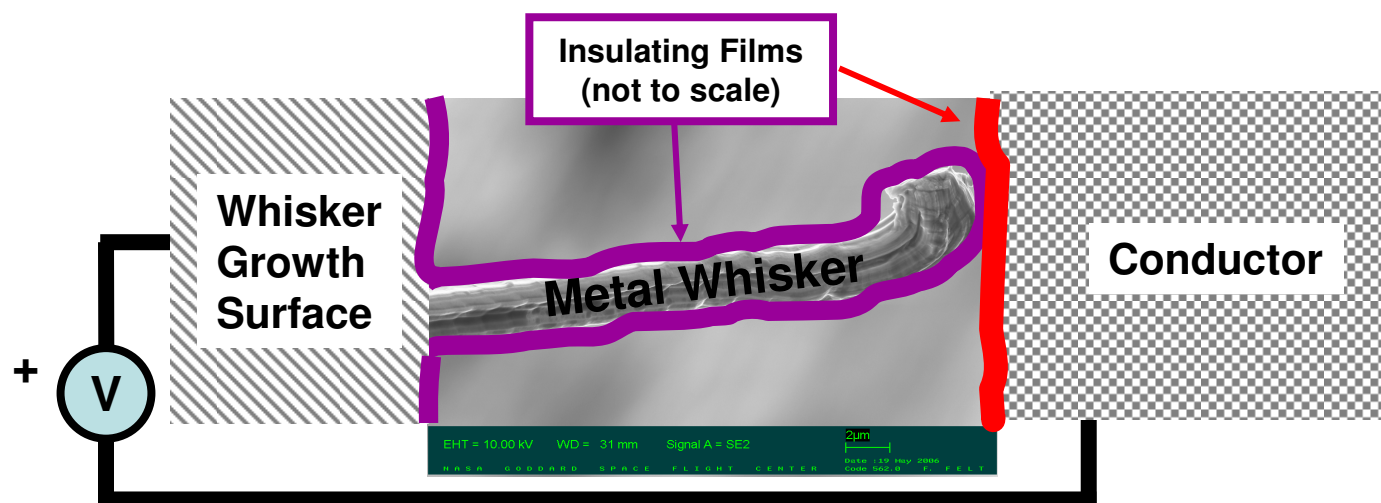
If $V_{whisker} > V_{melt}$
Then the Whisker will Fuse Open

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 $\sim 0.2\text{V}$ to $\sim 45\text{V}$

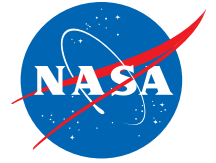


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Metal Whiskers:
Failure Modes and Mitigation Strategies

13

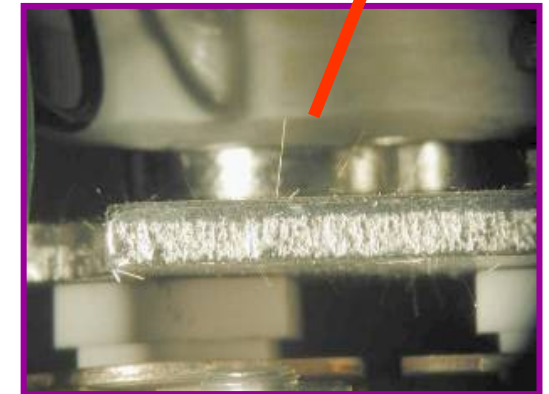
Sustained Metal Vapor Arcing Initiated by Metal Whisker



- 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
- NASA testing of FM08 style fuses with metal filaments ~5 mm long finds ~ 75 volts at more than 30 amperes is needed to generate a sustained arc across this arc gap when P ~1 torr

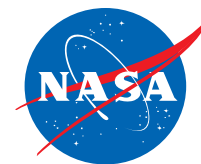
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Metal Whiskers:
Failure Modes and Mitigation Strategies



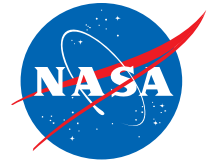
Tin Whiskers Growing on Armature Of Relay Produced Metal Vapor Arc

G. Davy, "[Relay Failure Caused by Tin Whiskers](http://nepp.nasa.gov/whisker/reference/tech_papers/davy2002-relay-failure-caused-by-tin-whiskers.pdf)", 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

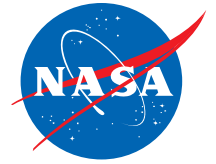


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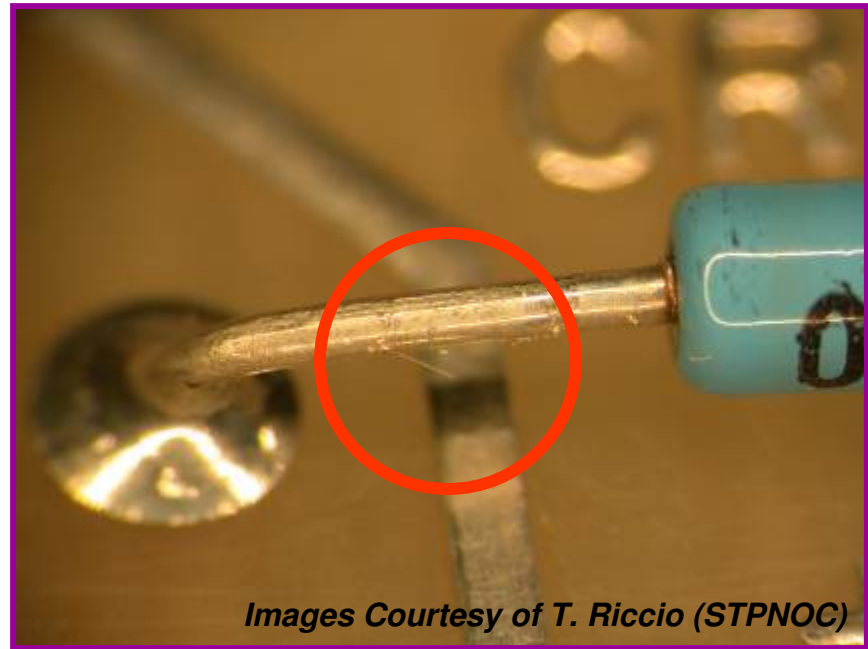
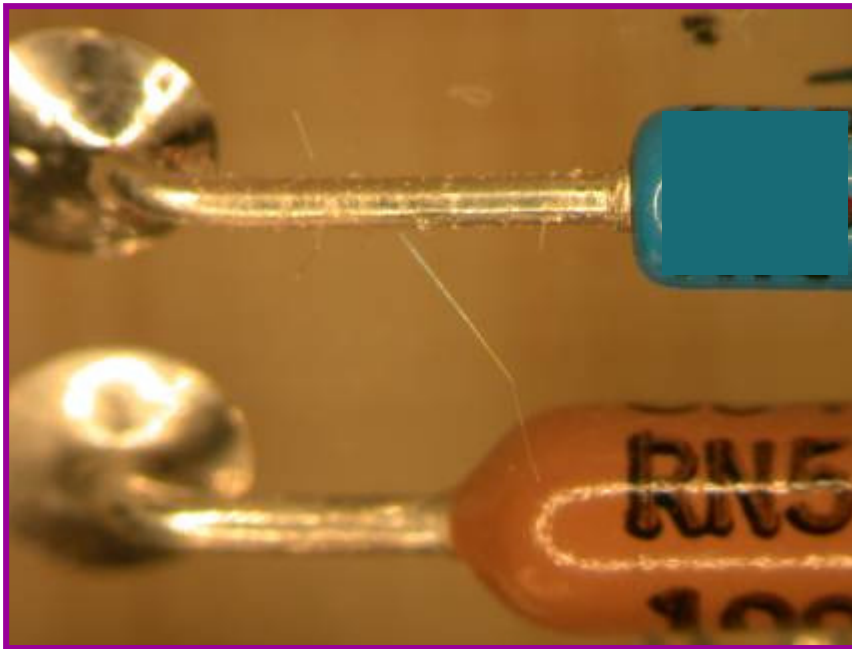
Metal Whiskers:
Failure Modes and Mitigation Strategies

16

A Case for Whisker Mitigation Strategies?

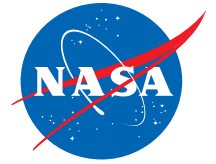


Tin Whiskers on Tin-Plated Axial Leaded Diodes

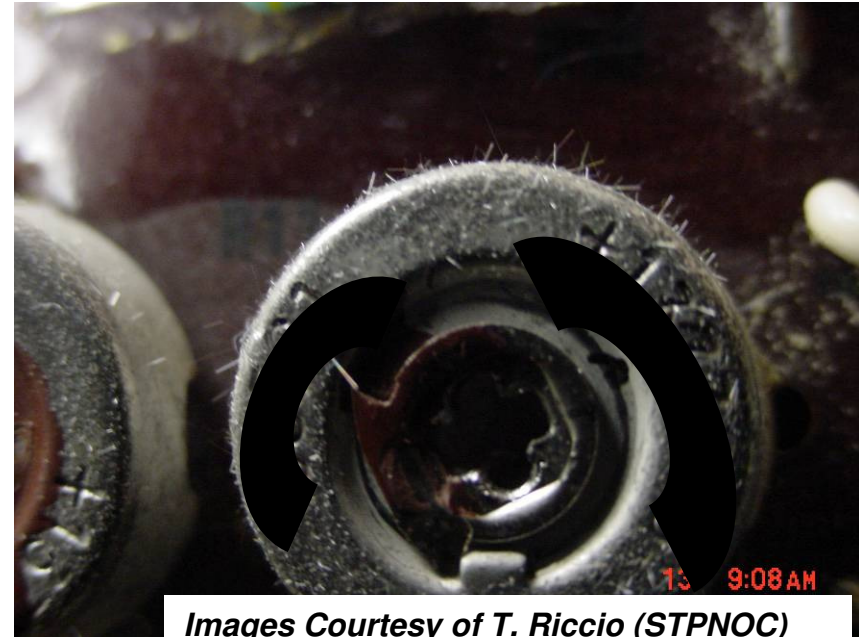


- Diode Leads were **NOT Hot Solder Dipped** prior to assembly
- PWB and components were **NOT Conformal Coated**

Another Case for Whisker Mitigation Strategies?

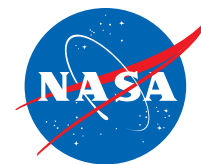


Metal Whiskers on External Case of Potentiometers



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



Three Whisker Mitigation Strategies

Mitigation – to make less severe or painful

Merriam-Webster Dictionary

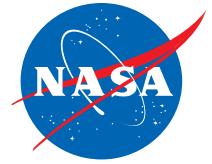
Risk “Mitigation” $\neq$ Risk “Elimination”

- Avoid Use of Whisker Prone Surface Finishes
 - Perform independent materials composition analysis
 - *“Trust, But VERIFY!”* using X-ray Fluorescence (XRF), Energy Dispersive X-ray Spectroscopy (EDS), etc.
- 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

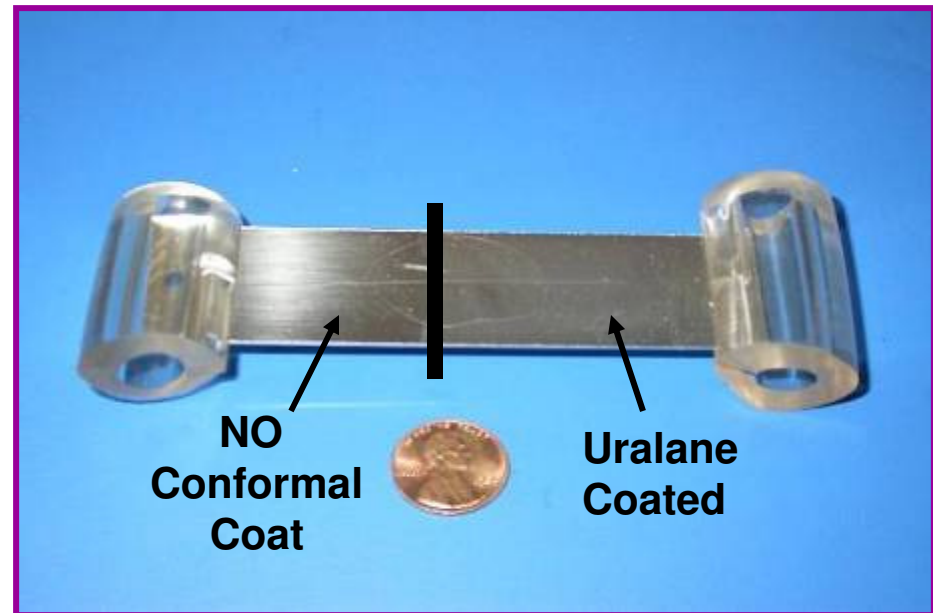
NASA Goddard Whisker Mitigation Study

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 1/2 of sample
 - Nominal Thickness = 2 mils
- **Storage Conditions:**
 - Office Ambient ~ 9 years

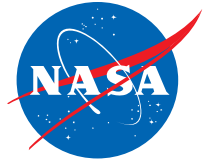


* *Uralane™ 5750 now known as Arathane™ 5750*

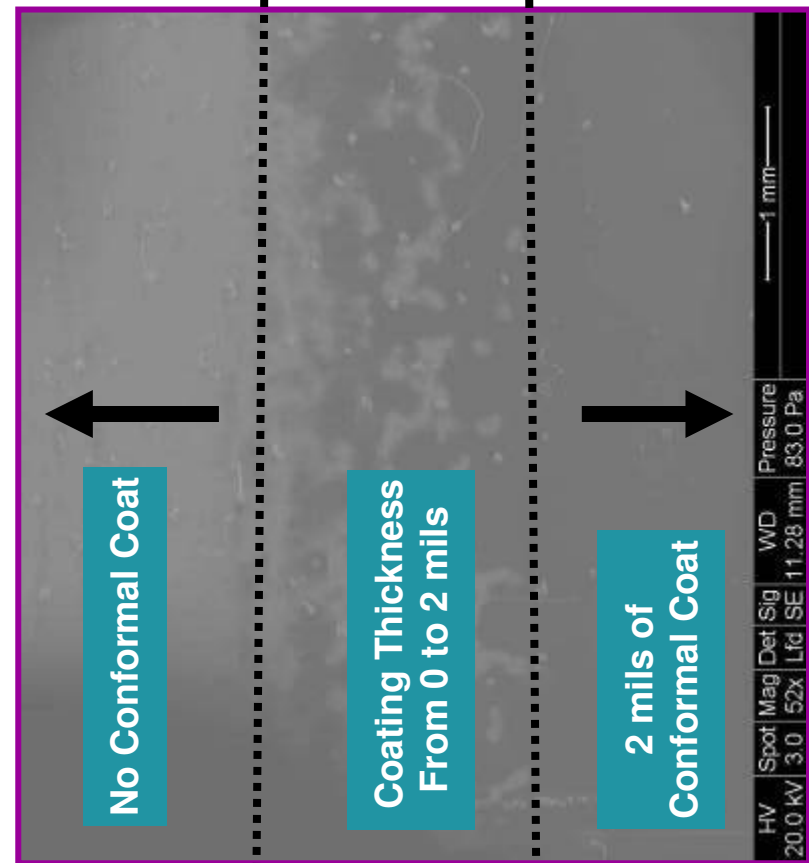
NASA Goddard Whisker Mitigation Study

Conformal Coat (Uralane 5750* Polyurethane)

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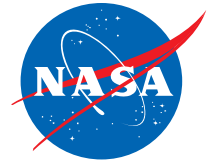
- Coating Thickness Can Vary Depending on Process Parameters
- Spray and masking techniques used produced a “transition” region ~2 mm wide where the conformal coating thickness was variable between 0 and 2 mils
 - *One must understand their own processes to ensure the coating thickness is sufficient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



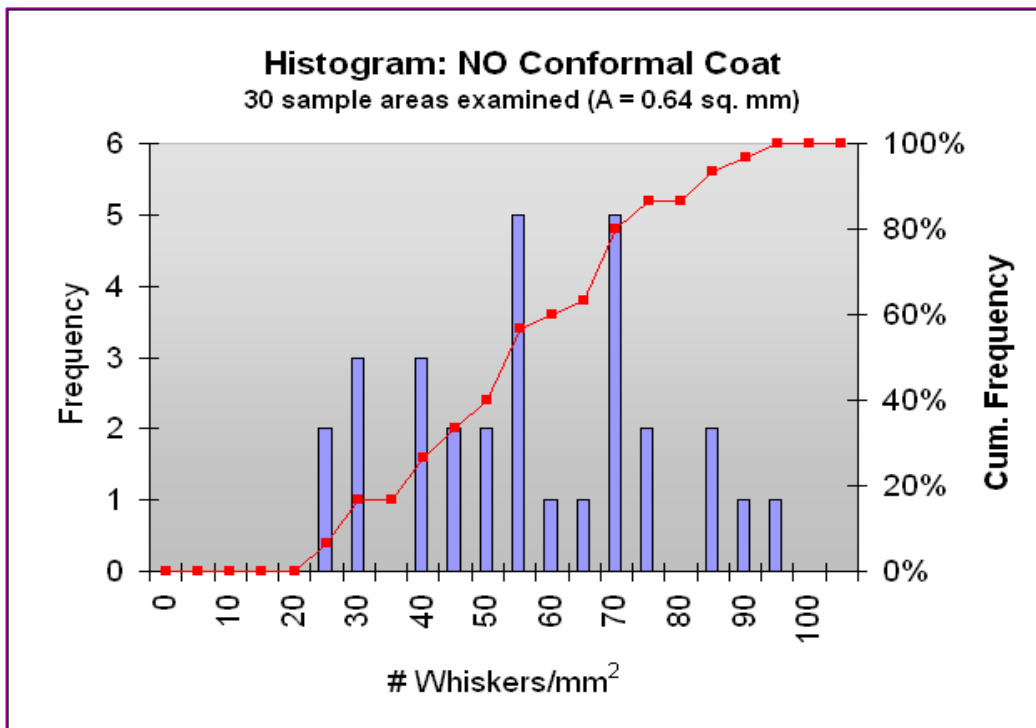
**NASA GSFC Conformal Coat
Tin Whisker Test Coupon**

* Uralane™ 5750 now known as Arathane™ 5750

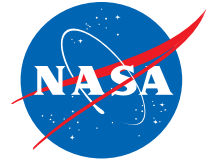
Control Areas – No Conformal Coat 9-Years of Office Ambient Storage



- **Control Areas Grew Whiskers Abundantly**
 - 30 areas each 0.64 mm² were randomly examined for whisker density
 - Avg: 55 ± 19.6 whiskers / mm²
 - Range: 23 to 95 whiskers / mm²

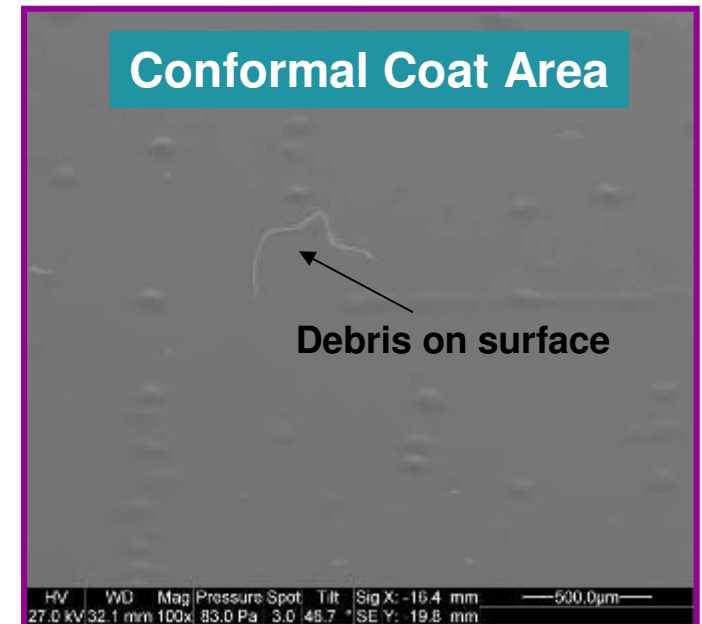
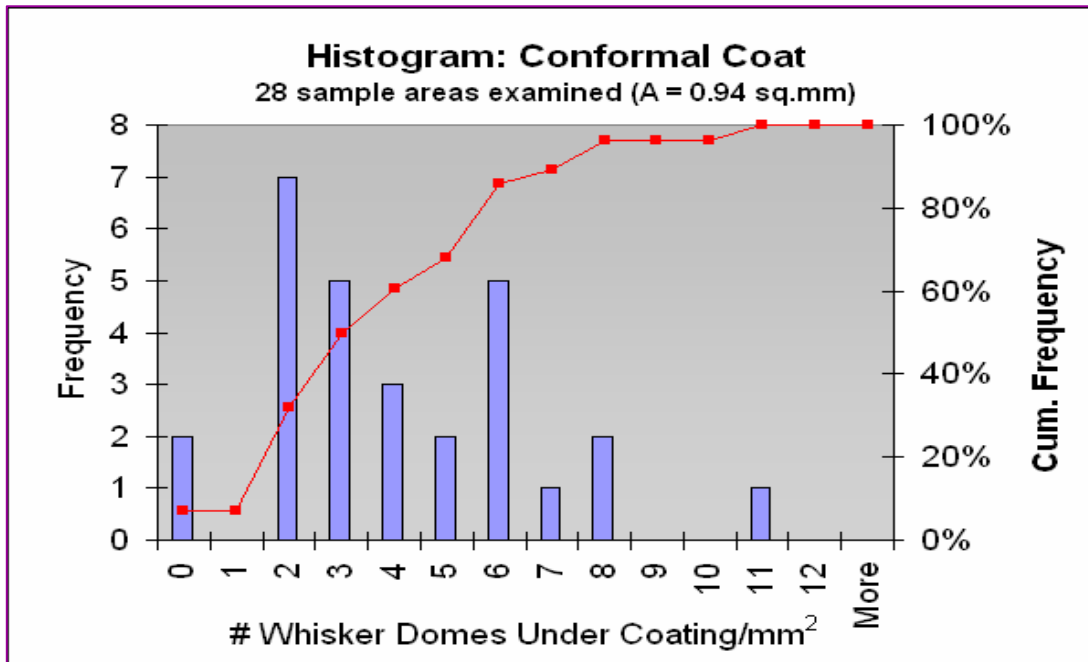


Uralane 5750 – 2 Mils Thick 9-Years of Office Ambient Storage



- Conformal Coated Areas Grew Whiskers Too
 - *To date ALL whiskers are contained beneath the coating that is 2 mils thick*
 - *With SEM we see “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”

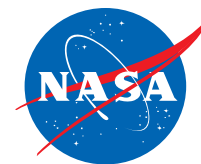


April 24, 2008

Metal Whiskers:
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23

Whisker Puncture vs. Coating Thickness



~2 mils of Uralane 5750



Whiskers completely contained
BENEATH the coating
With nominal thickness of 2 mils

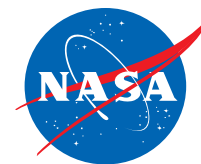
HV	WD	Mag	Pressure	Det	Spot	X: 17.6 mm	Tilt	200.0µm
800.0 V	26.7 mm	300x	---	ETD	3.0	Y: 6.8 mm	61.4 °	

Decreasing Coating Thickness



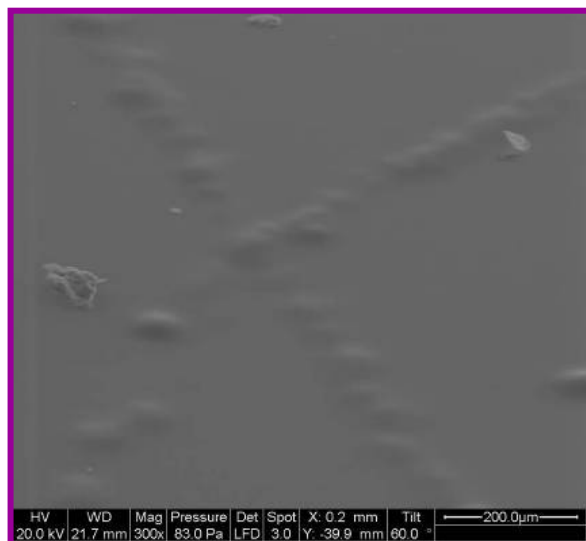
Whiskers punch through
in this region where
Coating thickness $\leq$ ~0.2 mils

HV	WD	Mag	Pressure	Det	Spot	X: 18.5 mm	Tilt	200.0µm
800.0 V	27.5 mm	300x	---	ETD	3.0	Y: 6.5 mm	61.4 °	



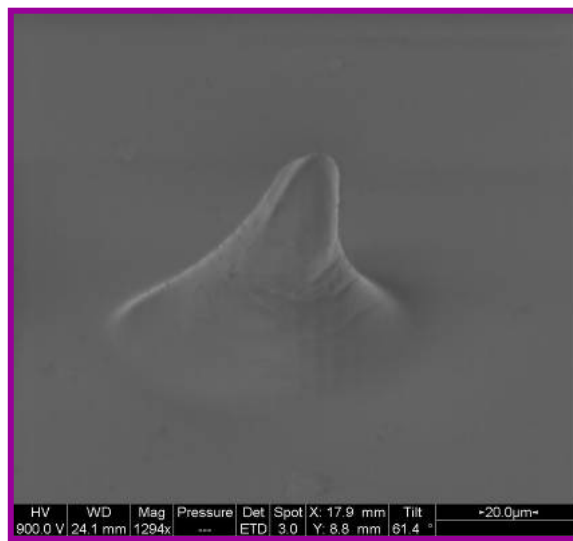
Uralane 5750 Conformal Coat - 9-Years of Office Ambient Storage

**2 Mils Uralane =
Very Effective**



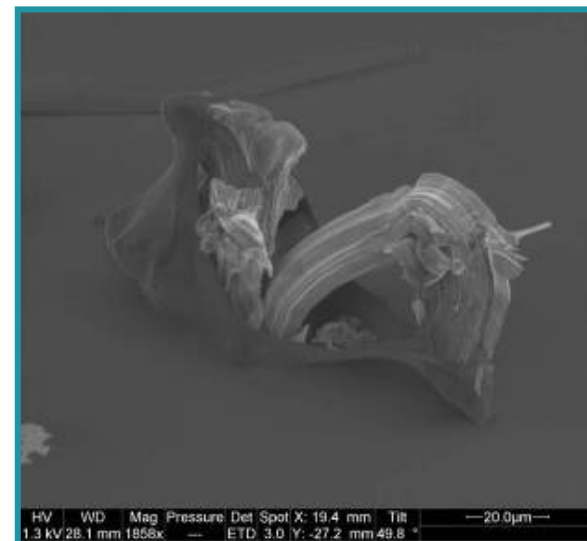
**Whiskers Completely
Entrapped Under the
Coating → Euler Buckling**

**~0.5 Mils Uralane =
Less Effective**

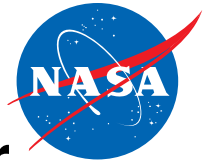


**Whisker “Lifting” Coating
into Shape of Circus Tent,
But Not Yet Penetrating**

**~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,

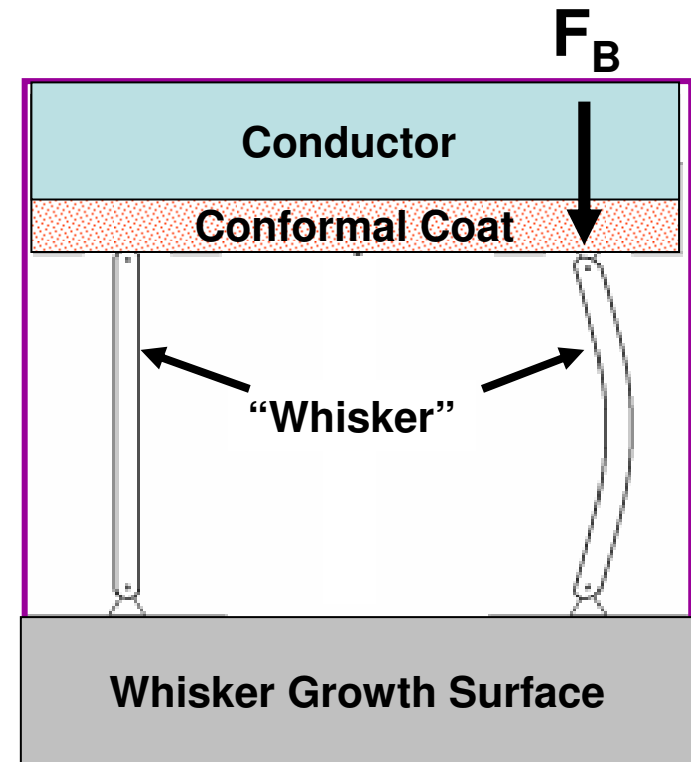
(e.g. $I = \pi d^4 / 64$ for circular cross section)

L = Length of whisker,

K = Column Effective Length Factor

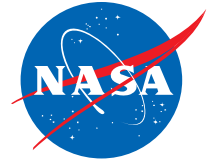
K = 0.5 for whisker fixed at both ends

K = 0.7 for fixed at one end, pinned at other

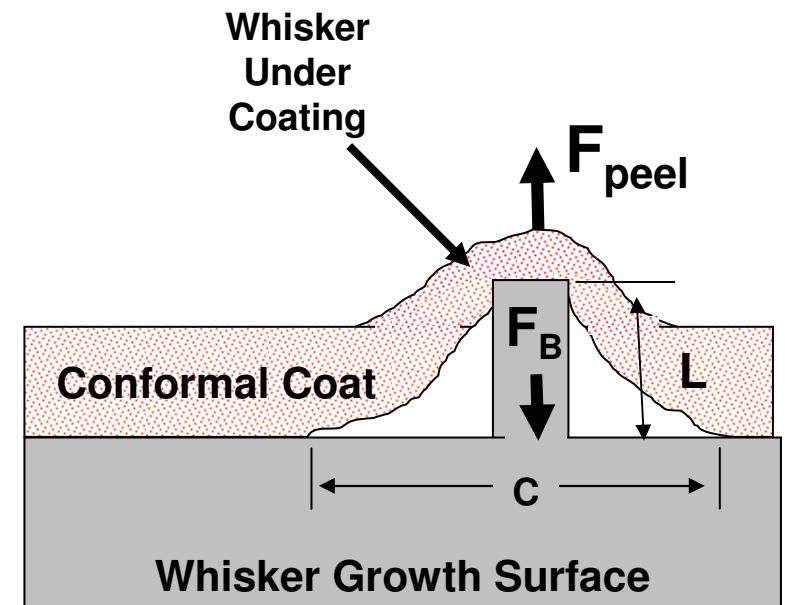


Whiskers Lift and Peel Conformal Coat Until Whisker Buckles OR Coating Fails

(F_{peel} vs. F_{Buckle})



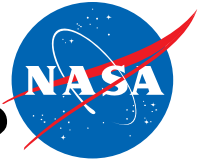
- As whisker first emerges it is short and stiff thus $F_B > F_{\text{peel}}$ and whisker begins to lift the coating forming a “circus tent” with height L = length of whisker;
- “Tent” joins the surface at a circle of circumference $C \sim 2\pi QL$,
 - Q describes the details of tent-like shape
- To peel conformal coating up and away from the surface, one needs to apply a force (F_{peel}) proportional to the circumference:
 - $F_{\text{peel}} = \Phi * C = 2 \pi Q \Phi L$
 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.



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

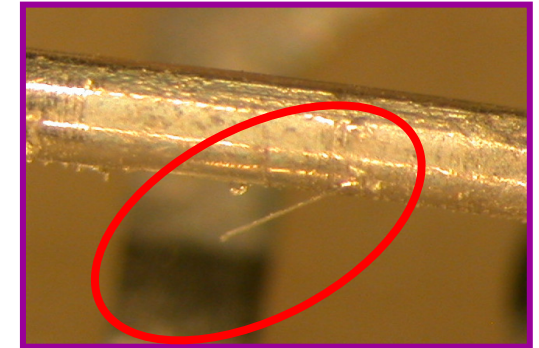
Additional Analysis Pending

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:

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



Where

D = Displacement of conformal coat

ν = Poisson's ratio

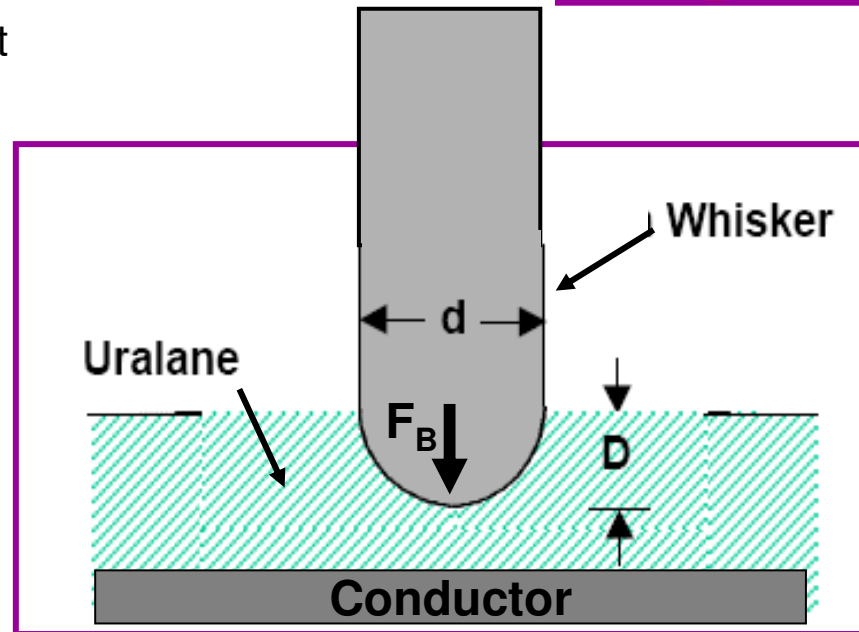
E_{coat} = Young's Modulus of coating

E_W = Young's Modulus of Whisker

d = "Diameter" of whisker

L = Length of whisker

F_B = Euler Buckling Strength of the whisker

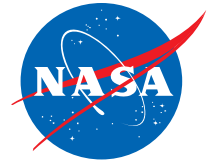


April 24, 2008

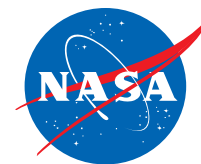
Metal Whiskers:
Failure Modes and Mitigation Strategies

28

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.

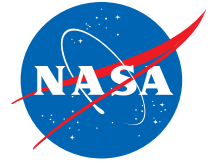


Thank Goodness for Euler Buckling and Conformal Coat on this PWB!!!



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

Effects of Conformal Coating -- 2

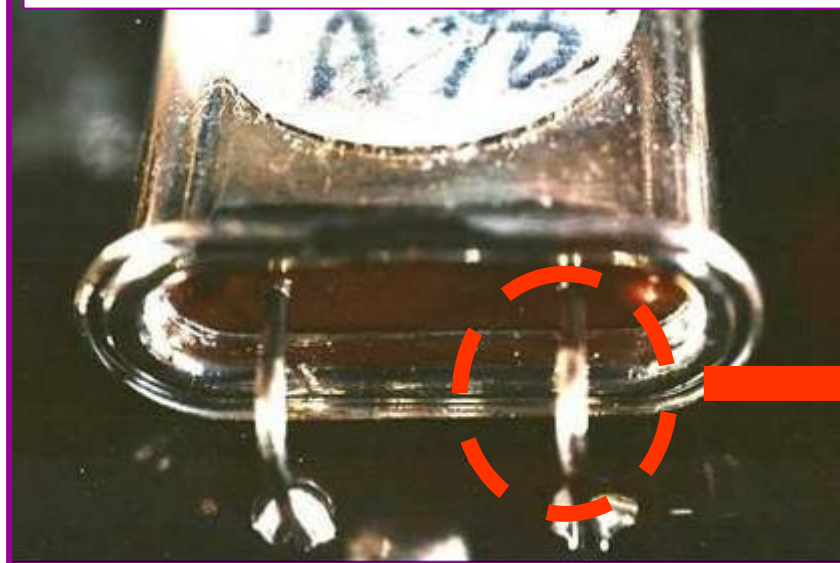


- Conclusion 1:
 - Uralane 5750, applied to at least 2 mils thickness, is a substantial improvement over an uncoated surface.
- Conclusion 2:
 - It is possible to suppose the surface is protected when it is not.
 - Coating processes can leave “weak zones” of thin coating allowing vertical escape
- Conclusion 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)**

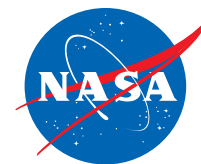


- Leads were Hot Solder Dipped (Sn63Pb37) within 50 mils of Glass Seal BEFORE Mounting to enhance solderability
- Dip was not 100% of leads due to concerns of inducing harm to glass seal

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

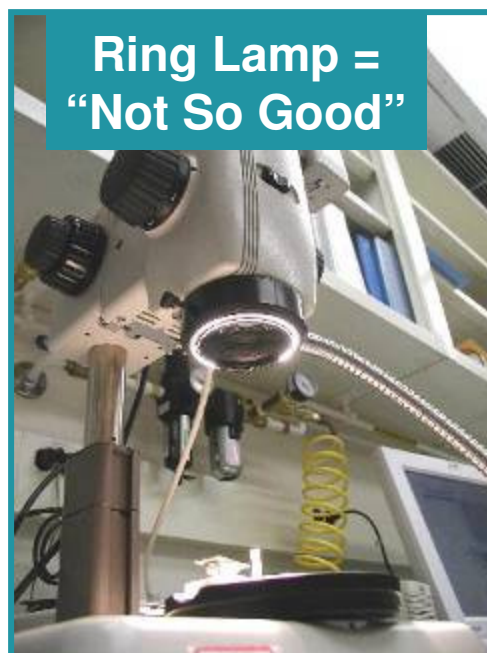


- No Whiskers on Hot Solder Dipped Surface
- ABUNDANT whiskers on the Non-Dipped Surface



Optical Inspection for Metal Whiskers

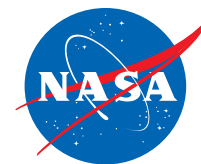
- Basic Equipment:
 - Binocular Microscope
 - Light Source: Flex Lighting PREFERRED over Ring Lamp
- Freedom to tilt sample and/or lighting to illuminate whisker facets is VERY IMPORTANT



April 24, 2008

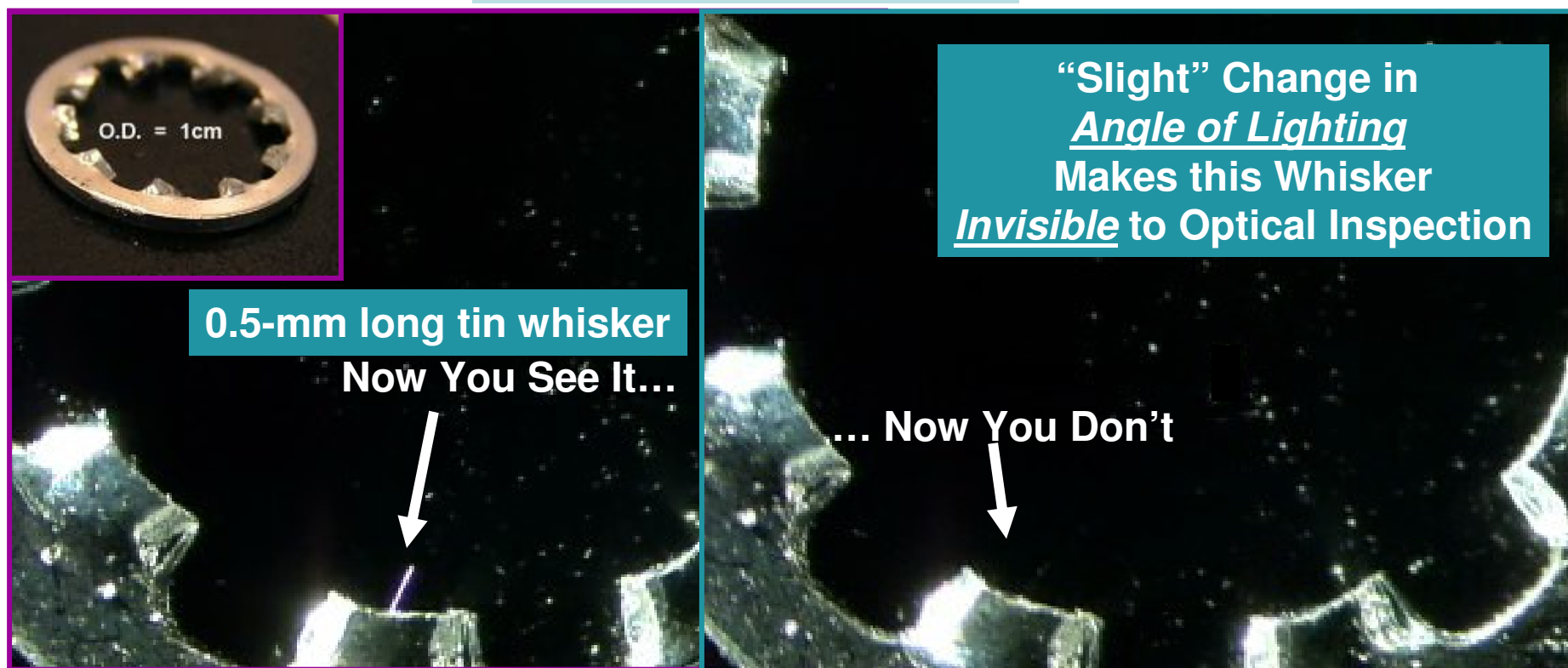
Metal Whiskers:
Failure Modes and Mitigation Strategies

33



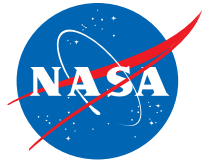
Evidence of “Absence of Whiskers”? (Optical Microscopy)

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!!!



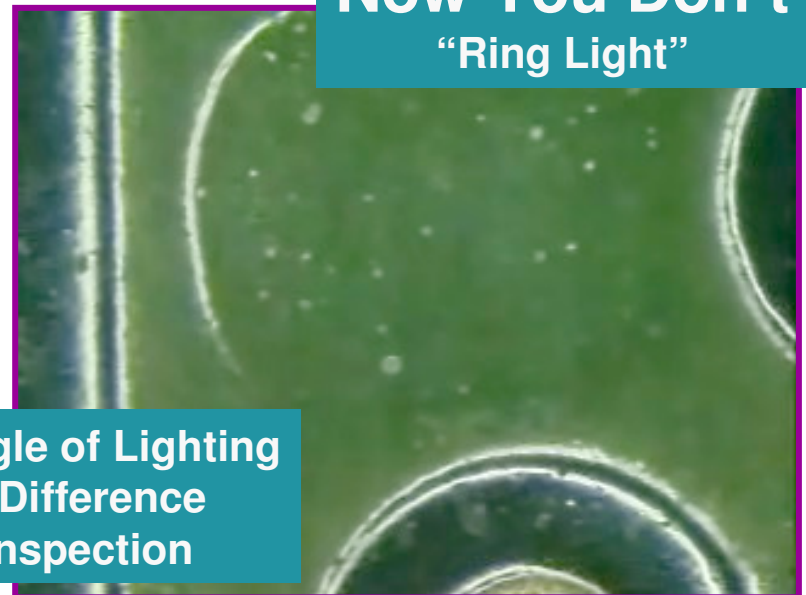
NASA GSFC has published videos to aid in optical inspection for metal whiskers

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

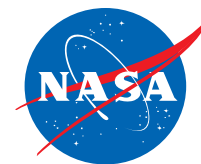
Now You See It
Incident Angle Lighting



Now You Don't
"Ring Light"



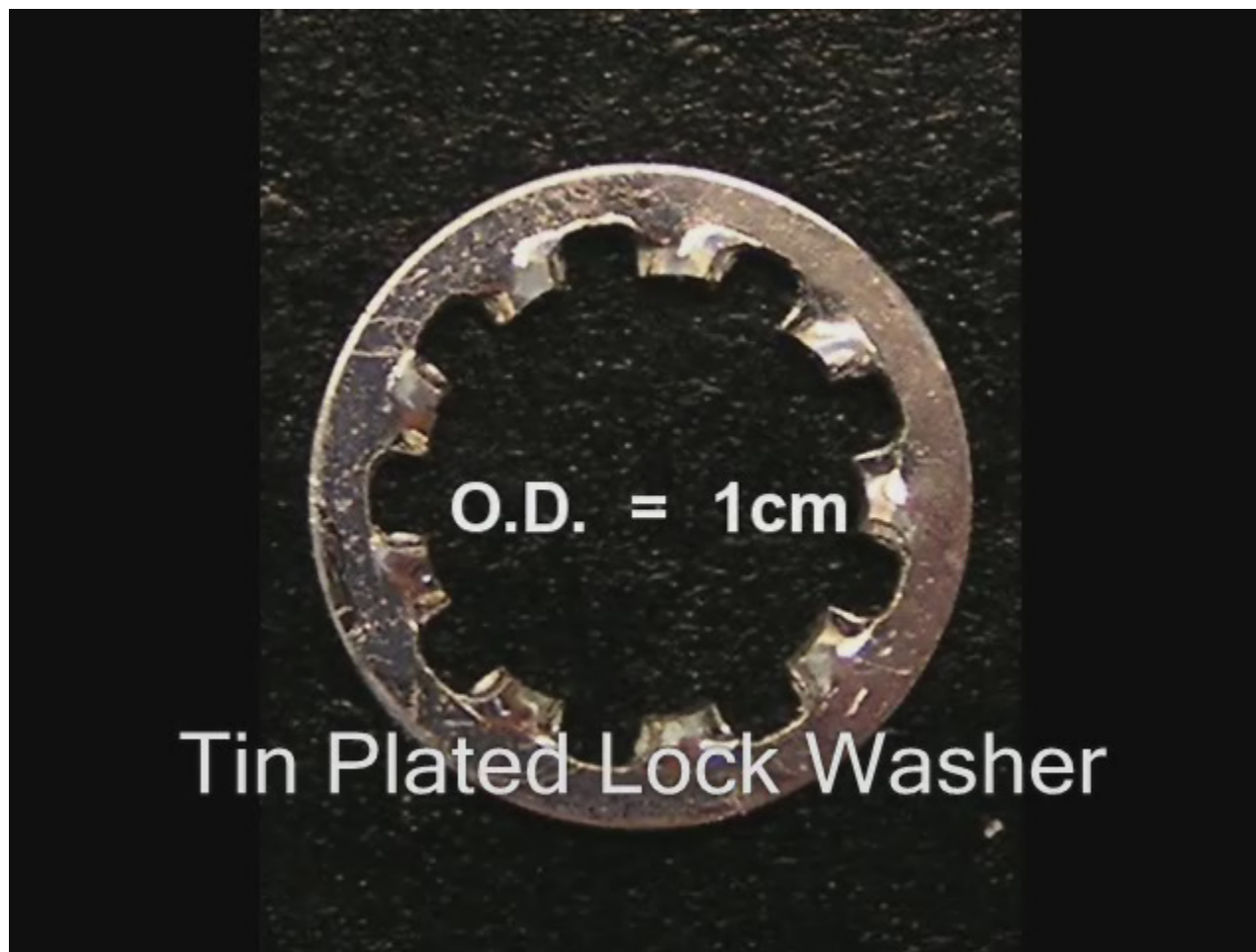
**Small Change in Angle of Lighting
Makes Dramatic Difference
During Optical Inspection**



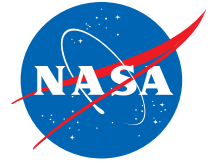
Video Demonstration

Optical Inspection For Metal Whiskers

(Click Image to Start Video)



Contact Information



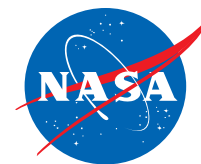
***Jay Brusse
Perot Systems at
NASA Goddard Space Flight Center
Jay.A.Brusse@nasa.gov***

***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)***

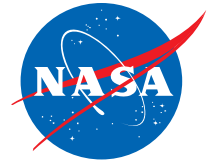
NASA Tin and Other Metal Whisker WWW Site

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

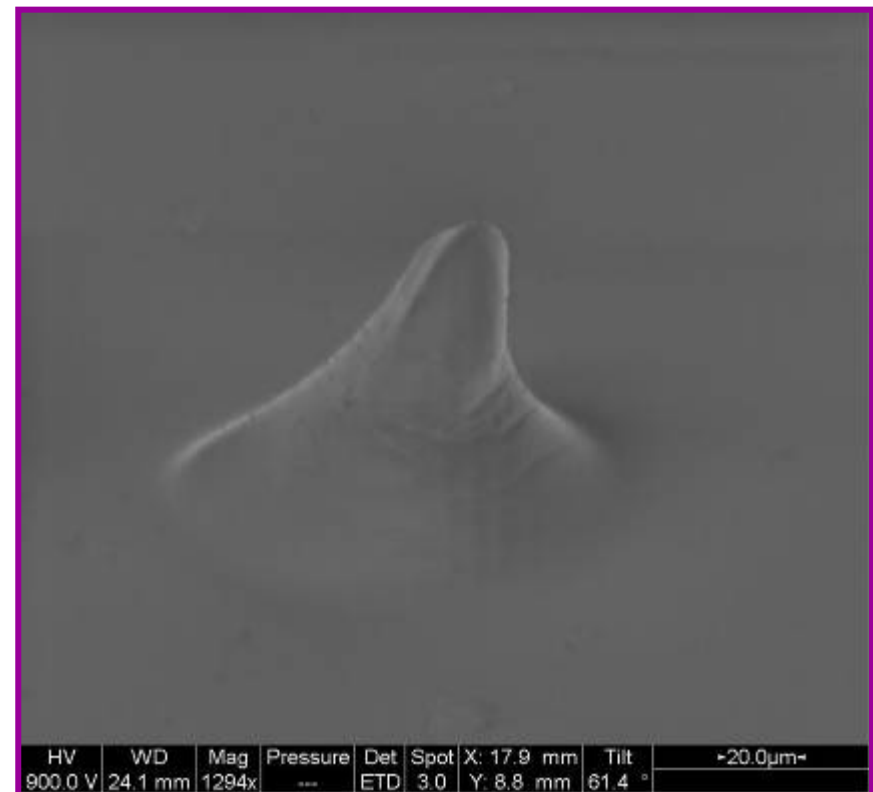
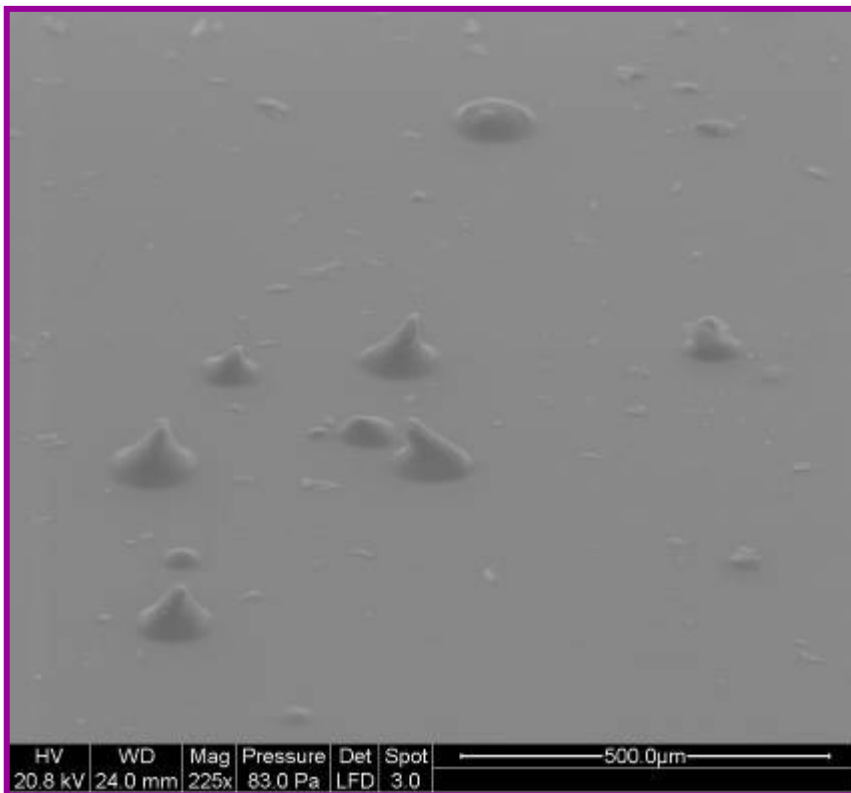


Backup Slides

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



Coating Thickness < 0.5 Mil

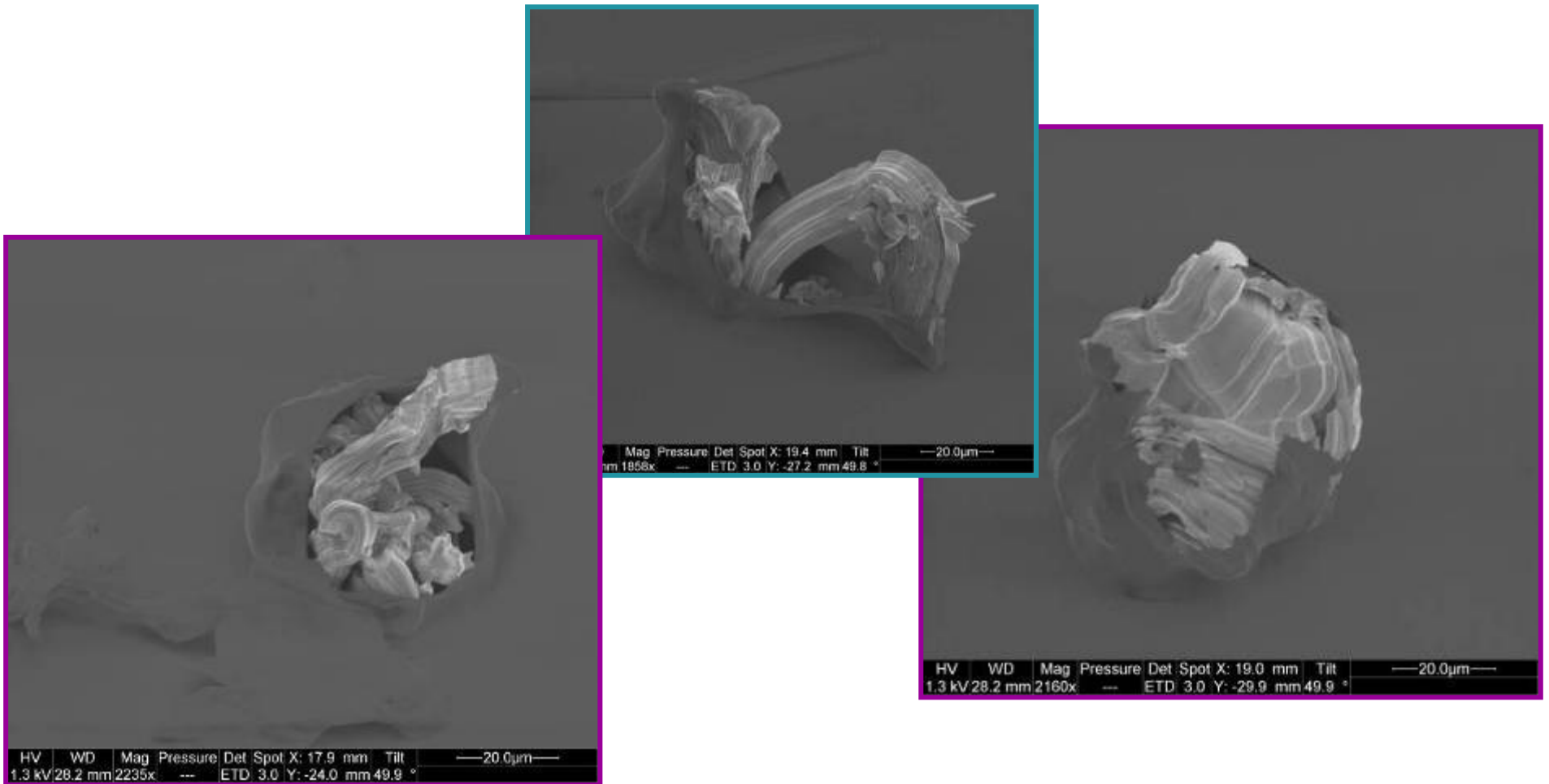
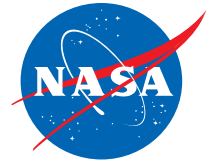


April 24, 2008

Metal Whiskers:
Failure Modes and Mitigation Strategies

39

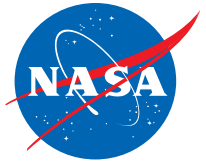
Tin Whiskers Rupturing THIN Coating ***~0.1 to 0.2 Mils Uralane 5750 Conformal Coat*** **9-Years of Office Ambient Storage**



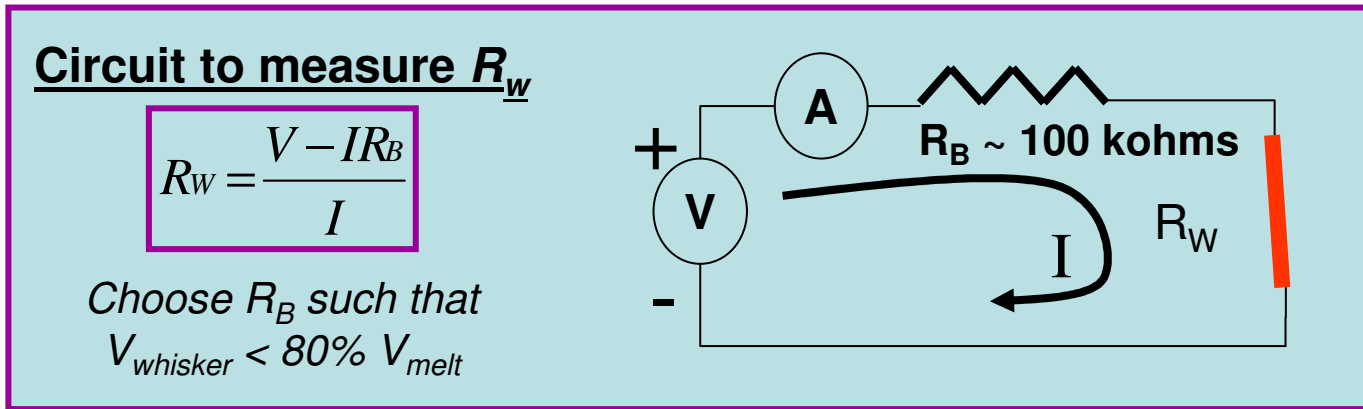
April 24, 2008

Metal Whiskers:
Failure Modes and Mitigation Strategies

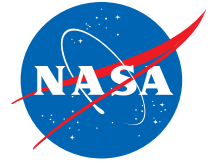
Circuit to Measure Resistance of a Metal Whisker



- 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 $V_{whisker} < V_{melt}$



Why Are Tin, Zinc, Cadmium Still Used?

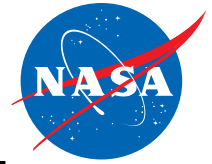


- Not all Tin (or Zinc or Cadmium) surfaces whisker!
 - Rough estimate: 3% to 30% do whisker.
- Not all metal whiskers cause shorts
 - Environment (geometry and electrical potentials matter).
 - Rough estimate: 3% to 30% do short.
- Not all whisker-induced shorts are traced to whiskers
 - They are very 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

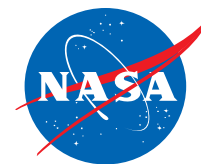
"We have metal whiskers? But they are so small. And you have only seen a few of them. How could a few small things possibly be a problem to our power supplies and equipment? These few whiskers should be easy to clean up."

Depression

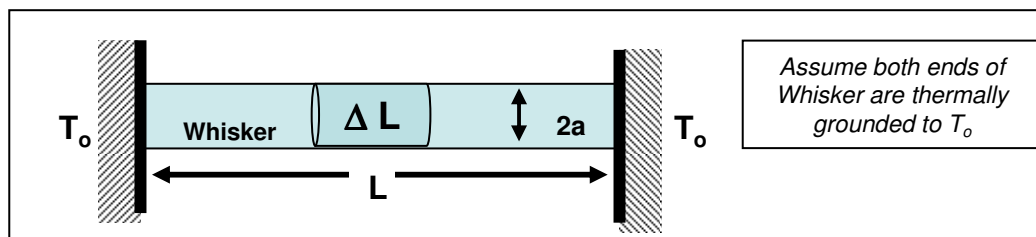
"Dang. Doomed. Close the shop --- we are out of business. Of all the miserable bit joints in all the world, metal whiskers had to come into mine... I'm retiring from here... Going to open a 'Squat & Gobble' on the Keys. "

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 warranties and service plans are up to date. On with life."



Derivation of Melting Current of a Metal Whisker in Vacuum



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

$\frac{du}{dt}$

+

Φ

=

source

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

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

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

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

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

Convection loss = 0 for vacuum
Neglect radiation loss

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

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

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

$$k_T = \frac{L_z \cdot T}{\rho}$$

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

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

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

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

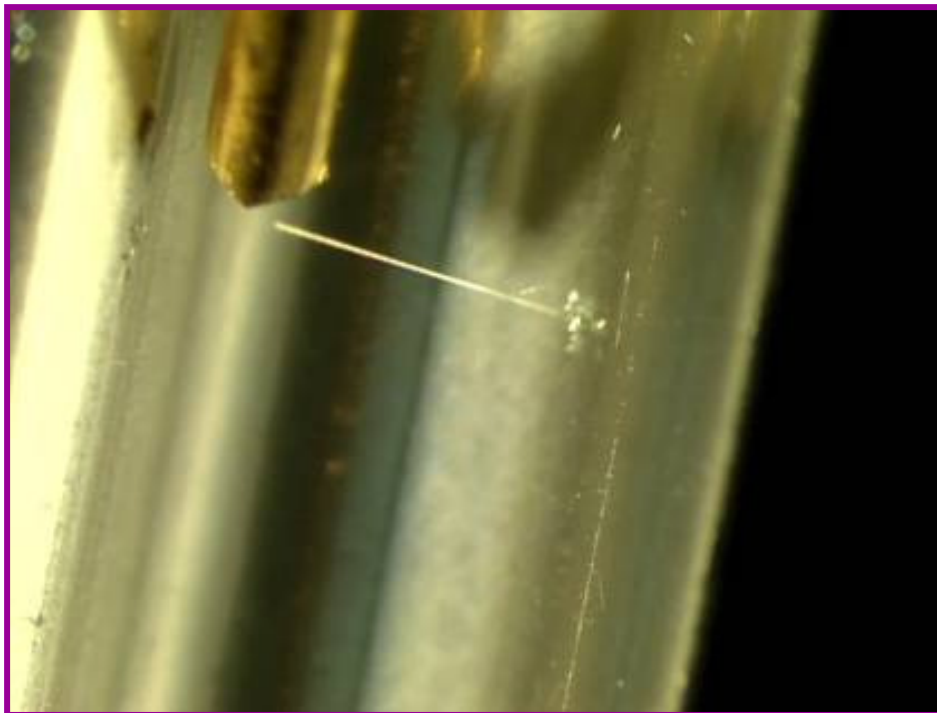
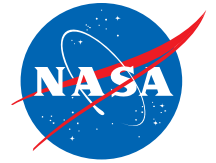
$$source = (J_e^2 \cdot A) \cdot \rho \cdot \Delta L$$

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

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

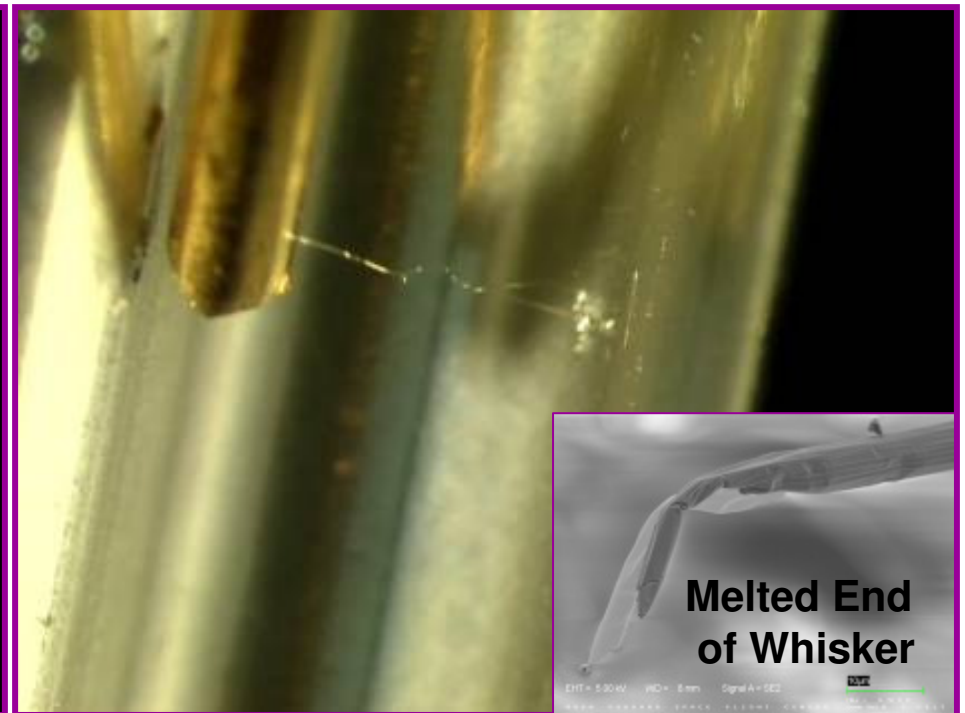
$$I_{melt,vac} = \left[\frac{2\sqrt{L_z T_0}}{R_0} \right] \cos^{-1} \left(\frac{T_0}{T_{melt}} \right)$$

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