Metal Whiskers
A Discussion of Risks and Mitigation

Jay Brusse / Perot Systems
Dr. Henning Leidecker / NASA Goddard
Lyudmyla Panashchenko / Univ. of MD-CALCE Graduate Student

http://nepp.nasa.gov/whisker

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Outline

• A Brief History of Metal Whiskers
  No Growth Theory
  To Be Discussed!!!

• Electrical Properties of Metal Whiskers
  Character of Short Circuits

• NASA Whisker Mitigation Study
  Arathane 5750 Conformal Coat

Cover Photo:
Tin whiskers on Tin-Plated Diode Terminals (Courtesy Ted Riccio - STPNOC)
What are Metal Whiskers?

• DESCRIPTION:
  – Hair-like, metallic crystals that UNPREDICTABLY grow out from a metal surface
    • Straight or kinked filaments, nodules, odd-shaped eruptions
    • Filaments usually have uniform cross section along entire length
  – Tin, Zinc and Cadmium coatings are most common sources
  – Whiskers are also less frequently seen on metals like Indium, Silver, Lead, Gold and other metals

• GROWTH TIMELINE:
  – Incubation: Absence of growth may last hours to years
  – Growth: Accretion of metal ions at base of whisker NOT at tip
  – Growth Rate: < 1 mm/yr (typical)
    Highly variable (up to 9mm/yr reported)

• LENGTH: Log-normal distribution (CALCE, et al)
  ~1 mm or less (typical)
  Rarely up to 10 mm or more

• THICKNESS: A few microns (typical)
  Range 0.006 to >10 um
  10 to >100 times thinner than a human hair!!!
The Good News:
Not All Tin, Zinc or Cadmium Surfaces Will Grow Whiskers
(See Back Up Slide for Discussion)

The Bad News:
Current theories and test methods **DO NOT** have predictive power of the time-dependence of Whisker Density, Length or Thickness Distributions

A useful theory should identify what we must control to make confident predictions. Such a theory has remained elusive
Metal Whiskers
“The Early Years”

• 1946: Cadmium Whiskers
  H. Cobb (Aircraft Radio Corp.) published earliest known account of CADMIUM whiskers on cadmium-coated variable air capacitor plates. Cd whiskers induced electrical shorting in military aircraft radio equipment. These events occurred during WW II (~1942 – 1943)

• 1951: Tin and Zinc Whiskers
  After learning of electrical failures from Cd whiskers, Bell Labs opted to use Tin and Zinc coatings. But then Compton, Mendizza, and Arnold reported shorting caused by whiskers from these coatings too!

  Tin Whiskers on 1960’s Era Variable Air Capacitor
  Similar to Types Described By Cobb in 1946

Whisker Resistant Metal Coatings
“The Quest”

• 1950s and 60’s \cite{Arnold1966} \cite{Key1970}:
  Bell Labs worked through the periodic table to determine whether co-deposition of some element with Tin would “inhibit” whiskering
  \begin{itemize}
    \item Adding 0.5 - 1\% by weight or more of \textbf{Lead (Pb)} into tin inhibits whiskering
    \item Alloying with metals other than Pb sometimes ENHANCES whiskering
  \end{itemize}

• Since 1990s:
  To inhibit whiskers most US MIL specs require adding Pb to tin coatings used near electronics
  \begin{itemize}
    \item For design margin, greater than 2\% to 3\% Pb by weight is usually specified
  \end{itemize}

• What additives quench Zn & Cd whiskers?
  \begin{itemize}
    \item There appear to be no active efforts to investigate
    \item Chromate conversion finishes DO NOT appear to stop whisker formation
  \end{itemize}

\footnotesize
Examples of Metal Whiskers

Zinc-Plated Steel Bus Rail
with Yellow Chromate Conversion Finish

Zinc whiskers grew up to several mm-long and shorted power to ground producing a metal vapor arc that disrupted the testing of a spacecraft system.
Examples of Metal Whiskers

*Tin-Plated D-Sub Connector Shell*

Connector Advertised as “RoHS Compliant”
Examples of Metal Whiskers

Tin-Plated Electromagnetic Relay

Procurement Specification for this Relay Required >2% Pb in the Tin-Plating, However, Pure Tin-Plated Relays were Supplied

TRUST BUT VERIFY!!!
Examples of Metal Whiskers

*Tin-Plated Terminal Lugs*
Examples of Metal Whiskers

**Tin-Plated Transformer Can**

“We appreciate your loyalty for so many years and your email concerning the whisker growth (in our products). The push to be RoHS compliant has caused us to switch our plating process and introduce new materials that are environmentally friendly but they in turn created other problems.”

-- “Manager of xxx” (July 2006)

Tin whiskers observed in “as-received” cans Coincidental with Mfr Switch from Tin-Lead to Pure Tin Finish
Examples of Metal Whiskers

Cadmium-Plated Connector Shell

*Cadmium whiskers on a feedthru connector for a thermal-vacuum chamber
Cd whiskers grew to be several mm-long and produced electrical shorts from shell to connector pins that interrupted testing of a spacecraft system*
Electrical Properties of Metal Whiskers

Debris/Contamination

- Dislodged whiskers become foreign object debris
  - Produce Shorts in Areas REMOTE From Whisker Origins
    - Example: zinc whiskers are often detached from zinc-coated raised floor tiles by physical handling. Once detached they are re-distributed by air currents into nearby electronic assemblies


Electrical Short Circuits

\[
R = \frac{\rho \cdot L}{A}
\]

Where

- \( R \) = resistance of whisker
- \( \rho \) = resistivity
- \( L \) = length
- \( A \) = cross sectional area

- Continuous short if current \( I_{\text{whisker}} < I_{\text{melt}} \)
- Intermittent short if \( I_{\text{whisker}} > I_{\text{melt}} \)
- **Metal Vapor Arc!!!**
  - See Discussion
  - Up to HUNDREDS of AMPERES can be Sustained!!!
Whisker Melting Current and Voltage (in Vacuum)

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

\[
V_{\text{melt,vac}} = 2\sqrt{Lz} \sqrt{T_{\text{melt}}^2 - T_{\text{amb}}^2}
\]

- Where \( Lz \sim 2.45 \times 10^{-8} \text{ (V/K)}^2 \) is the Lorenz number, \( T_{\text{melt}} \) = melting temperature, \( T_{\text{amb}} \) = ambient temperature, \( T_0 \) = ref. temp, \( R_0 \) = whisker resistance at ref. temp

<table>
<thead>
<tr>
<th>Material</th>
<th>( T_{\text{melt}} )</th>
<th>( I_{\text{melt,vac}} ) for ( T_0 = T_{\text{amb}} = 293.15 K )</th>
<th>( V_{\text{melt,vac}} ) for ( T_{\text{amb}} = 293.15 K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tin</td>
<td>505.1K</td>
<td>87.3 mV / ( R_0 )</td>
<td>129 mV</td>
</tr>
<tr>
<td>Cadmium</td>
<td>594.2K</td>
<td>96.8 mV / ( R_0 )</td>
<td>196 mV</td>
</tr>
<tr>
<td>Zinc</td>
<td>692.7K</td>
<td>104.1 mV / ( R_0 )</td>
<td>162 mV</td>
</tr>
</tbody>
</table>

If \( V_{\text{whisker}} > V_{\text{melt}} \)
Then the Whisker will Fuse Open

But there is MORE to this story
Metal Whiskers and Adjacent Conductors Accumulate Insulating Films

- Electrically insulating films form on metal whiskers and adjacent conductors
  - Depending on the environment → Oxides, sulphides, sulphates, chlorides, etc.
- These films act as barriers to electrical current flow UNLESS applied voltage exceeds “dielectric breakdown” strength of the combined films
  - Direct MECHANICAL contact does NOT guarantee ELECTRICAL contact
  - Courey (NASA), et al have measured the breakdown voltage of films on tin whiskers
    - \( V_{BD} \) is a probability distribution with a wide range (~60mV to >45Volts)
    - Insulating effects of these films are important to recognize
      - May fool failure analysts when bench testing (e.g., ohmmeter) to detect shorts
      - May explain survival of some electronics in the field despite whisker infestation
Breakdown Potential of Insulating Films on 200 Tin Whiskers from ~19 Year Old Hardware

A few observations:
- Abrupt transition ~2.6V
- Larger sample size might better define distribution < 2.6V
- Median $V_{BD} = 4.9V$
- Accumulation of insulating films on these samples may be extensive due to age of specimens (19 years)

Analysis of Data from PhD Dissertation of Courey, K., “An Investigation of the Electrical Short Circuit Characteristics of Tin Whiskers”, 2008-03-04
http://etd.library.miami.edu/theses/available/etd-03082008-125933/
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

• Metal vapor arc testing by NASA of FM08 style fuses made 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
Resulting in Destruction of Device
A Case for Whisker Mitigation Strategies?

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
Some Whisker Mitigation Strategies

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

Risk “Mitigation” ≠ Risk “Elimination”

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

• Use Conformal Coat or Other Electrically Insulating Barriers
  – 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
  – Follow the Principle of “First, Do No Harm”
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

Parameters were Chosen in Hope of Producing Samples that are Prolific Whisker Growers!!!
NASA Goddard Whisker Mitigation Study
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 mm² were randomly examined for whisker density
  - Avg: $55 \pm 19.6$ whiskers / mm²
  - Range: 23 to 95 whiskers / mm²
NASA Goddard Whisker Mitigation Study
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”
NASA Goddard Whisker Mitigation Study
Uralane 5750 Conformal Coat -
9-Years of Office Ambient Storage

2 Mils Uralane = Very Effective

~0.5 Mils Uralane = Less Effective

~0.1 Mils Uralane = 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
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

Conductor
Conformal Coat
Whisker Growth Surface

“Whisker”

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

- 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 \( L = \text{length of whisker} \);

- “Tent” joins the surface at a circle of circumference \( C \sim 2\pi Q L \),
  - \( Q \) describes the details of tent-like shape

- To peel conformal coating up and away from the surface, one needs to apply a force \( (F_{\text{peel}}) \) proportional to the circumference:
  - \( F_{\text{peel}} = \Phi \ast C = 2\pi Q \Phi L \)
  - \( \Phi \) = 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
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
- \( \nu \) = 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

• NASA GSFC has used Uralane 5750, applied to pre-primed tin-plated surfaces to a thickness of 2 mils (50 microns) ± 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

• Numerous sorts of coatings have been examined by others:
  – Reports of success vary from “none” to “perfect”, sometimes for the same sort of coating.

• Dr. Woodrow (Boeing)[1] 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 after long term exposure of the coatings to 25°C / 97% R.H.
  – Urgent Need: Characterization of mechanical properties of conformal coatings as well as the degradation of these properties from various environment exposures (moisture, corrosive agents, elevated temperature, etc.)

Effects of Conformal Coating -- 2

• Conclusion 1: **2 mils Uralane 5750 Provides Substantial Protection**
  – Uralane 5750, applied to at least 2 mils thickness, is a substantial improvement over an uncoated surface.

• Conclusion 2: **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

• Conclusion 3: **Understand YOUR Conformal Coating Processes**
  – Conformal coating processes can leave “weak zones” with less than the nominal thickness of coating.
    • 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
Contact Information

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

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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
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 can 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 $V_{whisker} < V_{melt}$

\[
R_W = \frac{V - IR_B}{I}
\]

Choose $R_B$ such that $V_{whisker} < 80\% V_{melt}$
Guess What’s Lurking Inside?

Transistor Package is Tin-Plated **Inside**.
Many Radio Malfunctions Have Been Attributed to Whiskers Shorting Case to Terminals

http://www.vintage-radio.net/forum/showthread.php?t=5058
## A Partial History of Documented Metal Whisker Problems

2006- NASA Goddard Presented


<table>
<thead>
<tr>
<th>Year**</th>
<th>Application</th>
<th>Industry</th>
<th>Failure Cause</th>
<th>Whiskers on?</th>
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<tbody>
<tr>
<td>1946</td>
<td>Military</td>
<td>Military</td>
<td>Cadmium Whiskers</td>
<td>Capacitor plates</td>
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<td>Telecom Equipment</td>
<td>Telecom</td>
<td>Cadmium Whiskers</td>
<td>Channel Filters</td>
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<td>Tin Whiskers</td>
<td>-Copper Oxide Rectifier</td>
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<td>-Potentiometer</td>
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<td>-Protector Mounting (Mechanical)</td>
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<td>-Terminal Strip</td>
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<td>-Relay Mechanical Elements</td>
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<td>Cadmium or Zinc</td>
<td>Chassis/Structural Members</td>
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<td>MIL/Aerospace Program</td>
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<td>GALAXY VII (Side 1)</td>
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<td>SOLIDARIDAD I (Side 2)</td>
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<td>Space (Complete Loss)</td>
<td>Tin Whiskers Relays</td>
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<td>Power Mgmt Modules</td>
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<td>Telecom</td>
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<td>RF Enclosure</td>
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<td>Connectors</td>
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<td>Tin Whiskers</td>
<td>Waveguide</td>
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<td>2005</td>
<td>Communications</td>
<td>Radio (1960s vintage)</td>
<td>Tin Whiskers</td>
<td>Transistor TO Package</td>
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<td>2005</td>
<td>Millstone Nuclear Power Plant</td>
<td></td>
<td>Power</td>
<td>Tin Whiskers</td>
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These are ~10% of the Problems We Know About
Why Are Tin, Zinc, Cadmium Still Used?

- Not all Tin (or Zinc or Cadmium) surfaces grow whiskers!
  - Rough estimate: 3% to 30% do whisker.
- Not all metal whiskers cause shorts
  - Application matters: geometry, electrical potentials, circuit sensitivity to shorting
  - 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
"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."
Another Case for Whisker Mitigation Strategies?

*Metal Whiskers on External Case of Potentiometers*

- No electrically insulating materials were used on the metal cases
- Metal whiskers bridging between the cases or from case to adjacent components can cause circuit malfunction

Images Courtesy of T. Riccio (STPNOC)
Tin Whiskers Forming “Circus Tents” in Thin Uralane 5750 Conformal Coat - 9-Years of Office Ambient Storage

Coating Thickness < 0.5 Mil
NASA Goddard Whisker Mitigation Study
Whisker Puncture vs. Coating Thickness

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

Decreasing Coating Thickness

Whiskers punch through in this region where Coating thickness < ~0.2 mils

~2 mils of Uralane 5750
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!!!

These Long Whiskers Experienced Euler Buckling Before Penetrating a Distant Conformal Coated Surface

Tin Whisker “Buckling”

Tin Whiskers Growing from Non-Conformal Coated Card Rail

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

0.5-mm long tin whisker

Now You See It...

... Now You Don’t

“Slight” Change in Angle of Lighting Makes this Whisker Invisible to Optical Inspection

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
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
Derivation of Melting Current of a Metal Whisker in Vacuum

\[ \frac{du}{dt} + \Phi = \text{source} \]

**Derivation**

\[ u = C \cdot T \quad c = \frac{C}{V} \]
\[ u = \left( \frac{C}{V} \right) \cdot V \cdot T = c \cdot V \cdot T \]
\[ u = c \cdot \Delta L \cdot A \cdot T \]

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

**Source**

\[ \text{source} = I^2 \cdot R \]
\[ I = J_c \cdot A \quad R = \frac{\rho \cdot \Delta L}{A} \]
\[ \text{source} = \left( J_c^2 \cdot A^2 \right) \cdot \left( \frac{\rho \cdot \Delta L}{A} \right) \]

**Heat Loss**

Assume both ends of Whisker are thermally grounded to \( T_o \)

\[ \text{Convection loss} = 0 \text{ for vacuum} \]

\[ \text{Neglect radiation loss} \]

Conduction loss:

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

\[ J = -k_t \cdot \frac{\partial T}{\partial x} \quad \frac{\partial J}{\partial x} = -k_t \cdot \frac{\partial^2 T}{\partial x^2} \]

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

\[ k_t = \frac{L_z \cdot T}{\rho} \]

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

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

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

**Melting Current**

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