FAILURE ANALYSIS WHEN TIN WHISKERS ARE SUSPECTED

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https://nepp.nasa.gov/whisker

To be presented virtually by Lyudmyla Ochs during IPC Pb-Free Bootcamp on July 13-15, 2021

Acronyms

Acronym	Meaning
CALCE	Center for Advanced Life Cycle Engineering
CTE	Coefficient of Thermal Expansion
DOA	Dead On Arrival
DPA	Destructive Physical Analysis
EDS	Energy Dispersive Xray Spectroscopy
EEE	Electronic, Electrical and Electromechanical
ETH	Elevated Temperature and Humidity
GSFC	Goddard Space Flight Center
IEC	International Electrotechnical Commission
IPC	Institute for Interconnecting and Packaging Electronic Circuits
JEDEC	Joint Electron Device Engineering Council
JESD	JEDEC Standards
NASA	National Aeronautics and Space Administration

Acronym	Meaning
NEPP	NASA Electronic Parts and Packaging Program
PWB	Printed Wiring Board
RH	Relative Humidity
SEM	Scanning Electron Microscope
SSAI	Science Systems and Applications Inc.
TC	Temperature Cycling
XRF	Xray Fluorescence Spectroscopy
BSE	Backscattered Electrons
SE	Sencondary Electrons
ICESat	Ice, Cloud and land Elevation Satellite
2D	Two Dimensional
3D	Three Dimensional

Outline

- Whisker Basics
  - What is a whisker
  - Failure modes caused by whiskers
- Electrical verification when whisker is suspected
  - Range of resistances expected for whisker shorts
  - Unintentional whisker removal during electrical testing
  - Build a better whisker meter
- Identifying and imaging whiskers
  - Things that are not whiskers
  - Tips on imaging whiskers
- Examples of failure analyses that included whiskers

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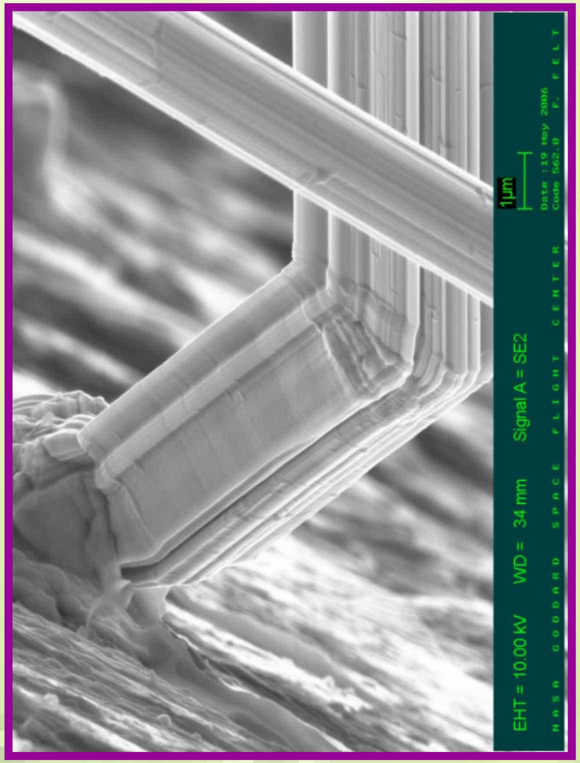
What are Metal Whiskers?

- Hair-like metal structures that erupt outward from a grain or several grains on a metal surface
  - May be straight, kinked, or odd-shaped eruptions

- Coatings of *Tin*, *Zinc* *and* *Cadmium* are especially able to develop whiskers; but, whiskers have been seen on Indium, Gold, Silver, Lead, and other metals too

Source Material	→	atoms from the metal itself
Transport Mechanism	→	primarily grain boundary diffusion
Transformation	→	diffusing atoms aggregate at the root (NOT the tip) of the forming whisker



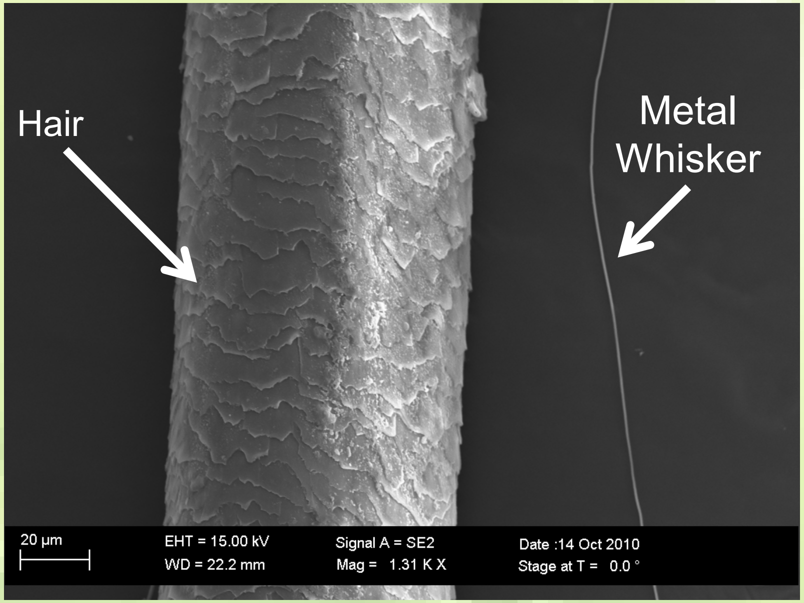
Tin Whiskers on Tin-Plated Electromagnetic Relay Terminals

Human Hair vs. Metal Whisker

Metal Whiskers are commonly
1/10 to <1/100 the thickness of a human hair

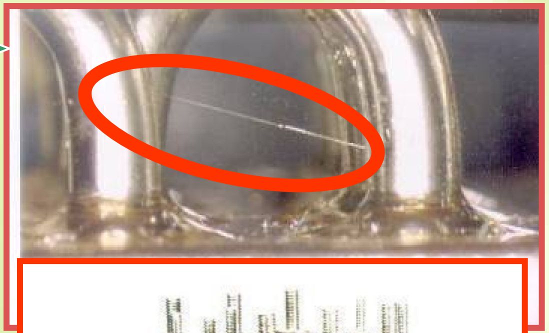
OPTICAL COMPARISON OF
HUMAN HAIR VS. TIN WHISKER

SEM COMPARISON OF
HUMAN HAIR VS. METAL WHISKER



Failure Modes Caused By Metal Whiskers

1. Electrical Short Circuits



$$R = \frac{\rho \cdot L}{A}$$

Where
R = resistance of whisker
ρ = resistivity; L = length;
A = cross sectional area

- **Continuous short if current** $I_{whisker} < I_{melt}$
- **Intermittent short if** $I_{whisker} > I_{melt}$

2. Metal Vapor Arc
Up to HUNDREDS of AMPERES can be Sustained!!!

3. 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

Jay Brusse, Michael Sampson, Zinc Whiskers: Hidden Cause of Equipment Failure, Published by the IEEE Computer Society, 2004.

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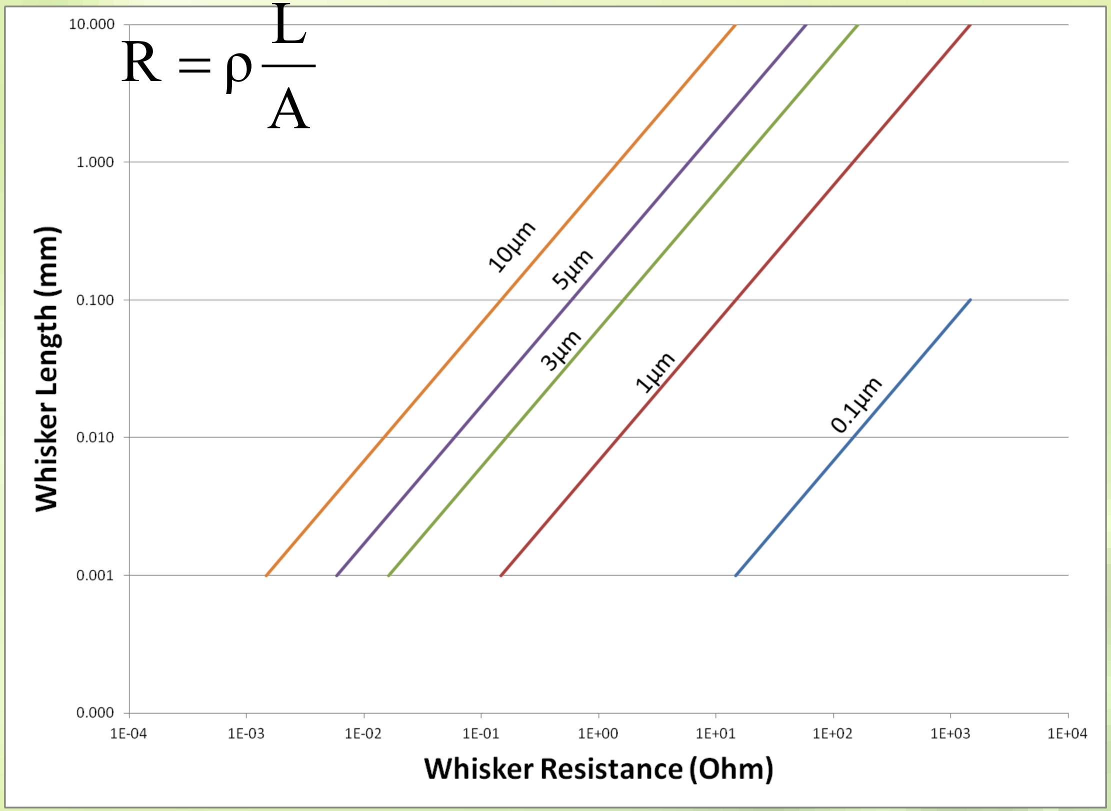
Electrical Behavior of Whiskers

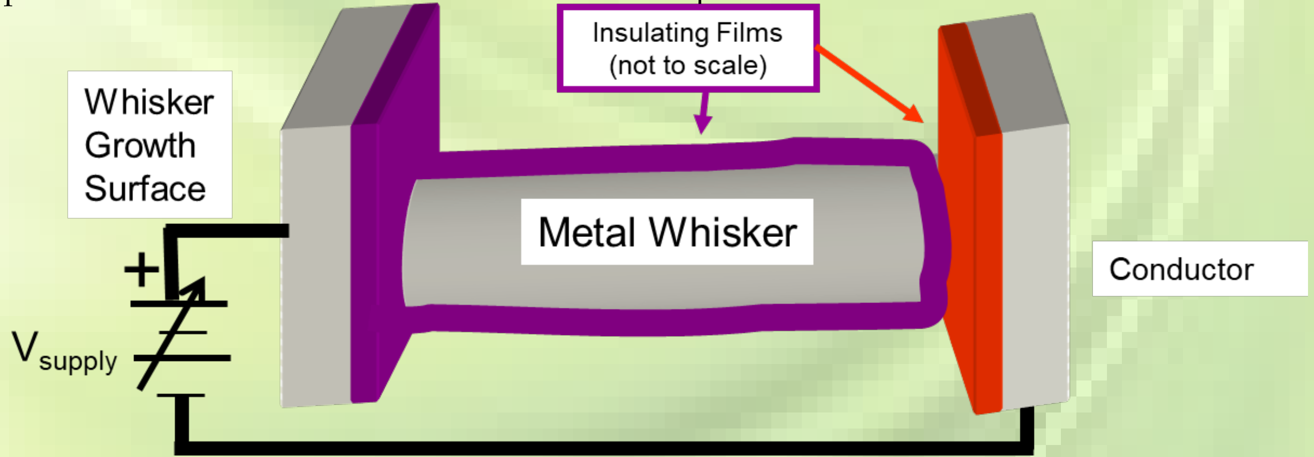
- Variations expected in whisker resistance
  - $$R = \rho\frac{L}{A} = \rho\frac{L}{\pi(d/2)^2}$$
  - ρ is metal resistivity, L is whisker length, d is whisker thickness
  - Since both length and thickness vary, so does resistance
- Whiskers are coated with insulative oxide layers
  - Mechanical contact with a whisker does not mean electrical contact
  - Dielectric breakdown of insulative layers required for conduction to occur
- Whiskers will melt with enough current through them!
  - How to protect circuits under failure analysis from burning out a whisker?

Tin Whisker Resistance at Room Temperature for Different Lengths and Thicknesses



Metal Whiskers and Adjacent Conductors Grow Insulating Films

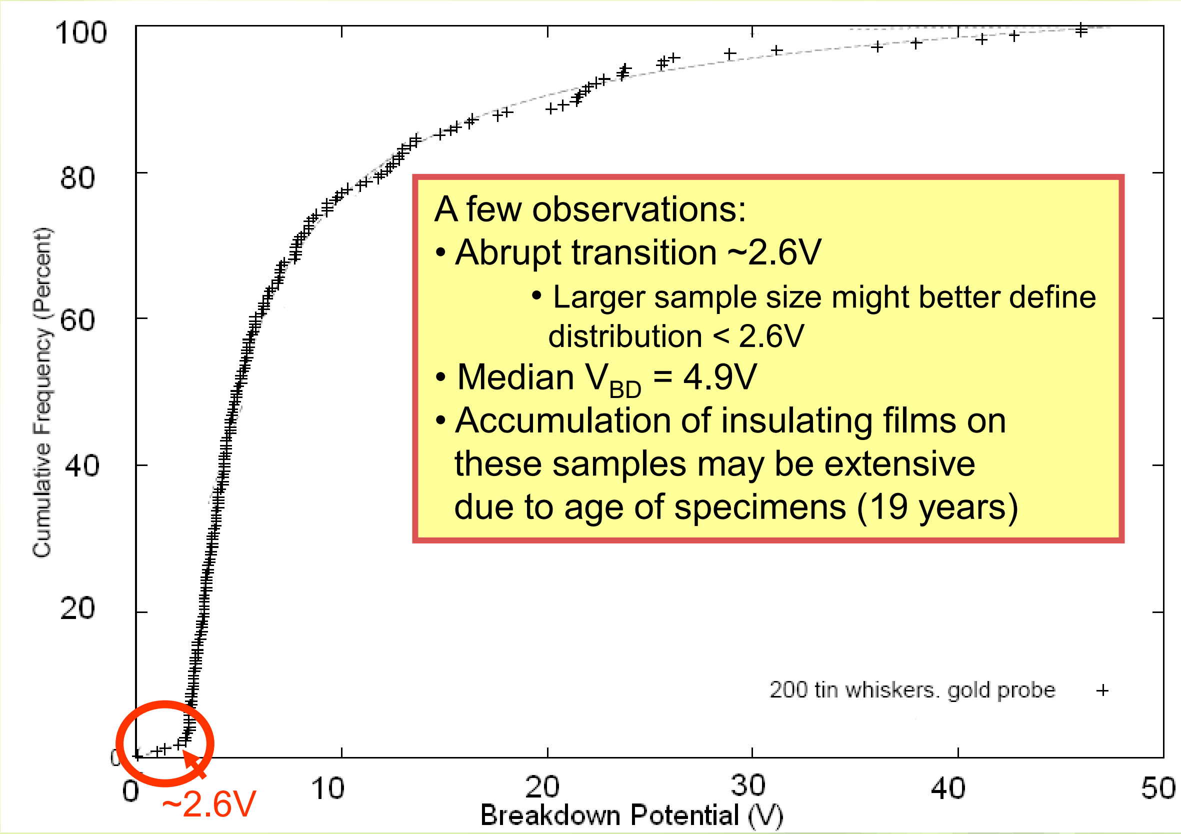
- Electrically insulating films form within hours on metal whiskers and adjacent conductors
  - Oxides, sulphides, sulphates, chlorides, hydrides, etc.
- These films act as barriers to electrical current flow UNLESS applied voltage exceeds "dielectric breakdown" strength of the combined films
  - Direct **MECHANICAL** contact does NOT guarantee **ELECTRICAL** contact
  - Courey (NASA), among others, have measured the breakdown voltage of films on tin whiskers
    - V_{BD} fit a probability distribution with a wide range (~60mV to >45Volts)
  - Insulating effects of these films are important to recognize
    - Has fooled failure analysts when bench testing (e.g., Ohm-meter) to detect shorts
    - Can explain survival of some electronics in the field despite whisker infestation



Pb-free Electronics Risk Management PERM

Breakdown Potential of Insulating Films

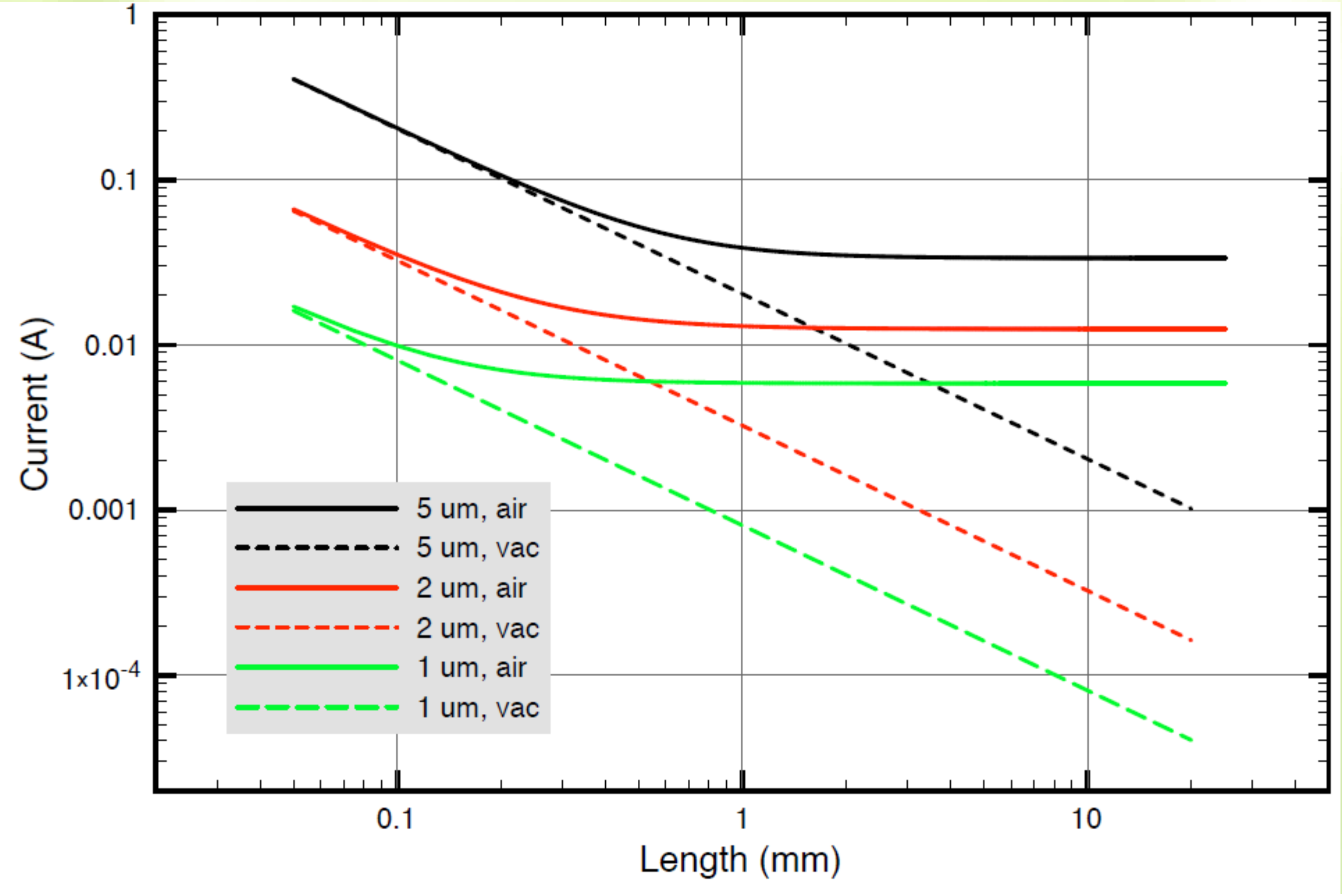
on 200 Tin Whiskers from ~19 Year Old Space Shuttle Hardware
when probed using gold-plated probe



Analysis of Data from PhD Dissertation of
Courey, K., "An Investigation of the Electrical Short Circuit Characteristics of Tin Whiskers", 2008-03-04
https://scholarship.miami.edu/discovery/delivery?vid=01UOML_INST:ResearchRepository&repId=12355285760002976#13355492690002976

Melting Current vs. Length for Selected Whisker Diameters

J.H. Richardson, and B.R. Lasley, "Tin Whisker Initiated Vacuum Metal Arcing in Spacecraft Electronics," *1992 Government Microcircuit Applications Conference*, Vol. XVIII, pp. 119 - 122, November 10 - 12, 1992.



Whisker Melting Currents can range three orders of magnitude: 0.1mA to 0.5A

Whisker Melting Current and Voltage (in Vacuum)

Pb-free Electronics Risk Management PERM

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

$$V_{melt,vac} = 2\sqrt{Lz}\sqrt{T_{melt}^2 - T_{amb}^2}$$

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

Material	T_{melt}	$I_{melt,\ vac}$ for To = Tamb =293.15K	$V_{melt,\ vac}$ for Tamb =293.15K
Tin	505.1K	87.3 mV / R_0	129 mV
Cadmium	594.2K	96.8 mV / R_0	162 mV
Zinc	692.7K	104.1 mV / R_0	196 mV

If $V_{whisker} > V_{melt}$

Then the Whisker will Fuse Open

The Killing of a Whisker

- Sn whisker is probed with a Au tip, and its resistance is measured using a hand-held ohm-meter.
- No protective resistor is in series.
- Ohm-meter reading ~200Ω.
- During range switching, whisker is burnt out

Beware of Ohm-Meter Limitations

- Published research shows that ohm-meters detect less than 10% of the bridging whiskers, and sometimes less than 1%
- The investigator may conclude "No Fault Found"
  - Ohm-meter may supply $V_{out} < V_{breakdown}$ for the insulating films (oxides, moisture) that form on a metal whisker. No Current will flow – the whisker remains undetected during the few seconds of examination. **"No Fault Found"**
  - Ohm-meter may supply $V_{out} > V_{melt}$. Current Will Flow, the whisker melts in less than 1 ms -- no detection happens. There is no longer a bridging whisker to detect. **"No Fault Found"**
- Range switching can have the ability to deliver whisker-killing impulses

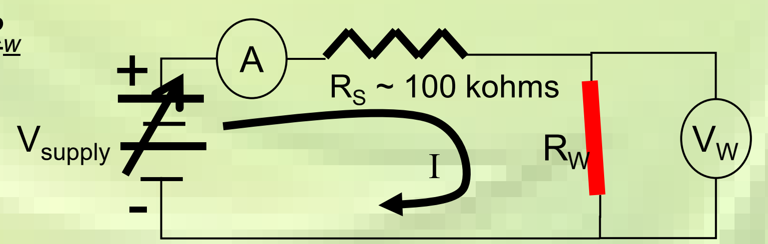
Build Your Own Better Whisker Detector!

- Use a variable power supply (V_{supply}) and a protective resistor in series (R_S) with the whisker to be detected
  - Choose R_S ~ 100kΩ
  - Adjust $V_{supply} > V_{breakdown}$ of insulating films on whisker and conductor being bridged
  - When $V_{supply} > V_{breakdown}$, R_S quickly drops $V_{whisker} < V_{melt}$

Circuit to measure R_w

$$R_W = \frac{V_W}{I}$$

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



WARNING: "DO NO HARM" principle should be applied:

- The use of this circuit may be damaging to active parts or powered circuits under test
- A high impedance voltage meter should be used for measurements made across a whisker

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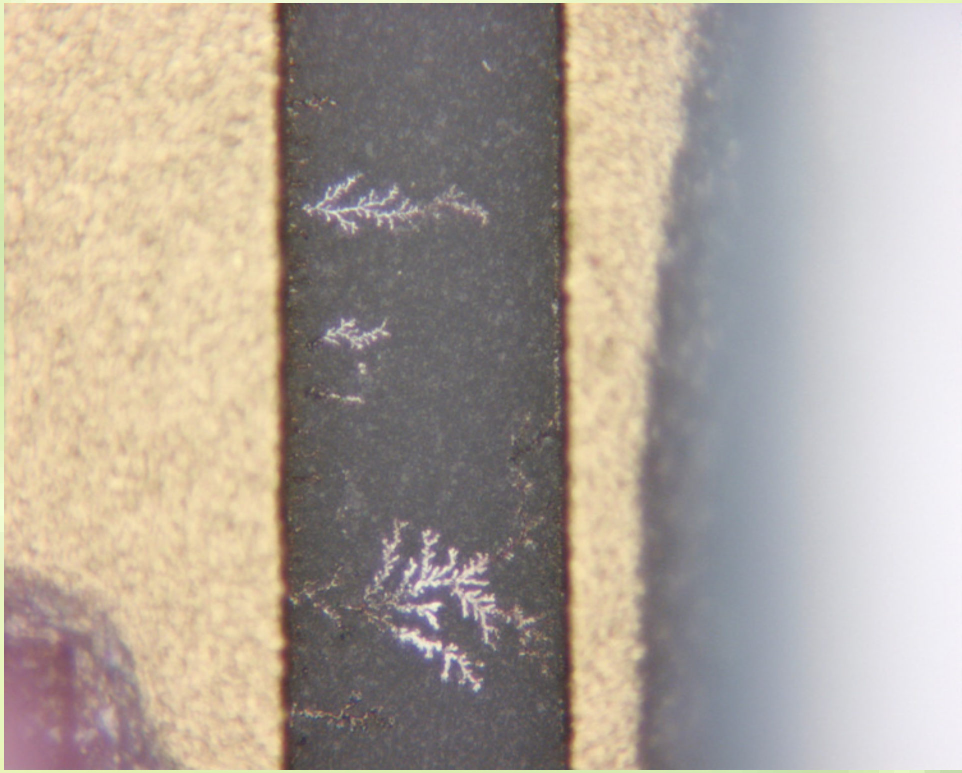
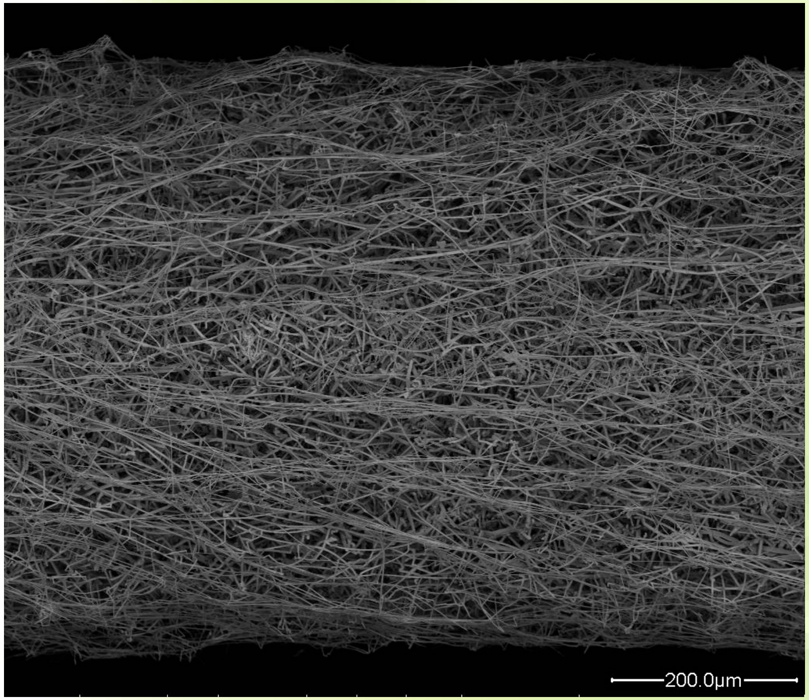
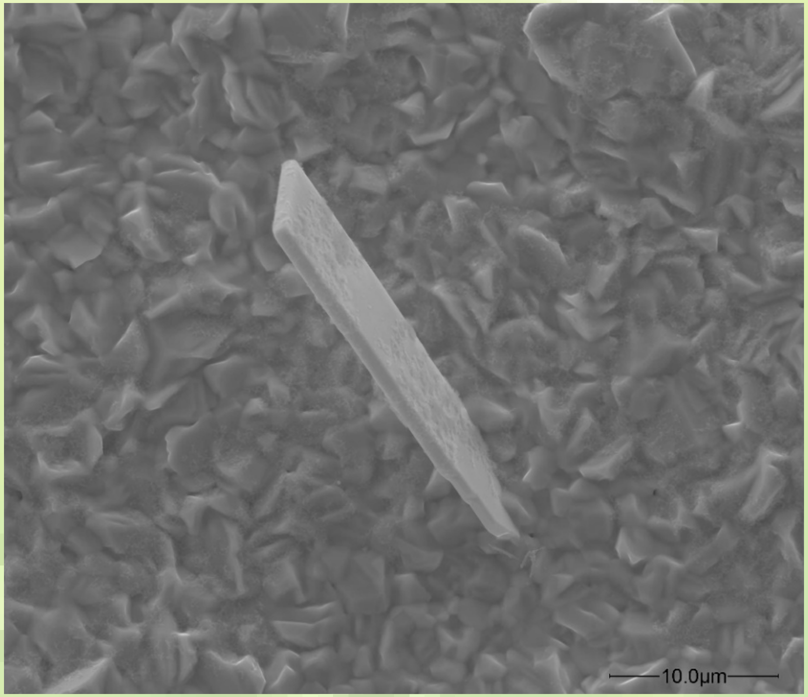
NOT Whiskers:
Electrochemical Migration Dendrites



Unlike whiskers, require presence of ionic medium and voltage bias to grow.
These are 2D structures, while whiskers are 3D.

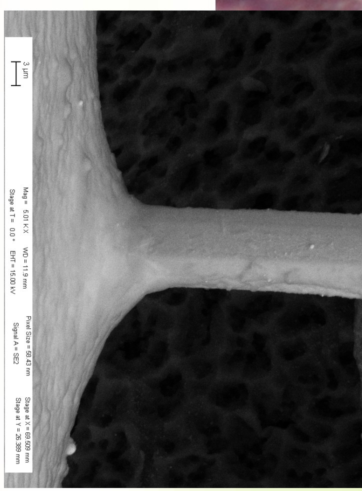
NOT Whiskers: Plating Dendrites

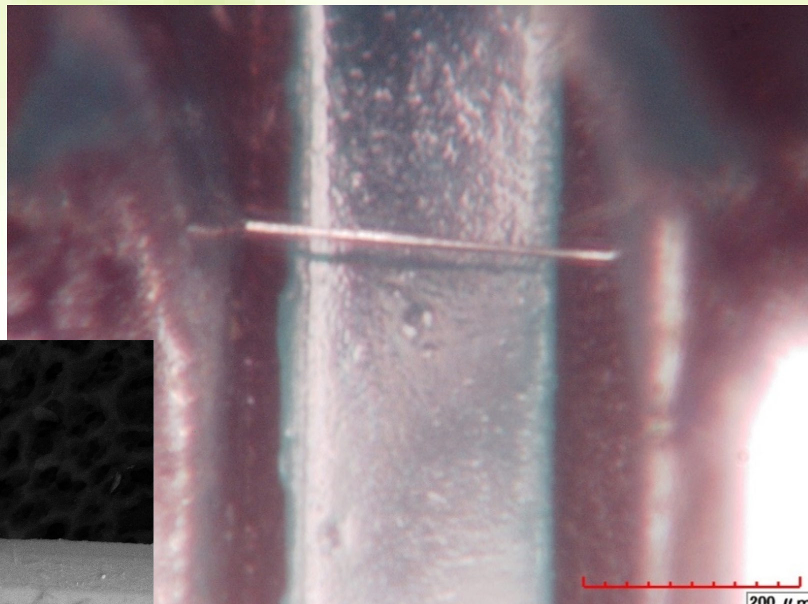




Unlike whiskers, form during electroplating only and do not grow longer with time.
Do not contain characteristic ridges along the length.

NOT Whiskers: Cu-Sn Intermetallic Needles





Result of excess Cu in Sn-based solder. Will develop only during soldering or rework – when the solder is molten. Unlike whiskers, do not grow over time.

A Real Phone Call We Received Circa 2006:

Electronics Technician working in the Aerospace Industry:

"Hi. Today my boss gave me a 3x hand lens and instructed me to look inside a bunch of avionics boxes to see if we have a tin whisker problem.

Will I be able to see any tin whiskers this way?"

Our response went something like:

"Houston, we have a problem!"

Disclaimer

- The material herein is presented "for guidance only".
- The optical inspection techniques described are NOT guaranteed to detect all metal whiskers. Optical detection of metal whiskers can be hindered by many factors including but not limited to:
  - Operator experience working with actual metal whiskers
  - Dimensions (especially whisker thicknesses) are extremely small and difficult to illuminate
  - Inadequate lighting technique, angle of inspection or magnification
  - Objects adjacent to whiskers may block line of sight and illumination
  - Excessive glare from reflective surfaces can obfuscate whiskers
  - Conformal coatings can produce reflections or haloing
  - Whiskers may be growing INSIDE of packaged devices requiring destructive analysis
  - Operator fatigue from excessive inspection times

Detecting Metal Whiskers: Optical Inspection Tips and Techniques

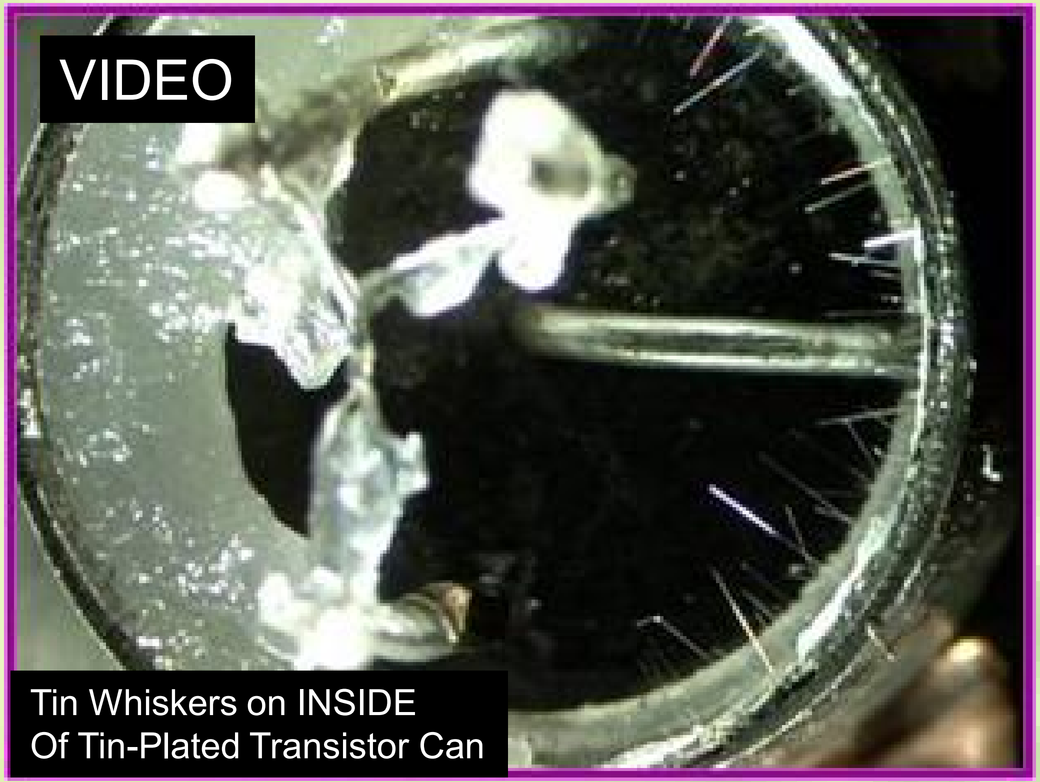
Generally, there are Three Types of People:

- **Type 1: "The Whisker-Naïve" ← ~50% of population**
  "Wait a minute! Are you telling me that I can actually ***SEE*** metal whiskers without using a Scanning Electron Microscope (SEM)?"

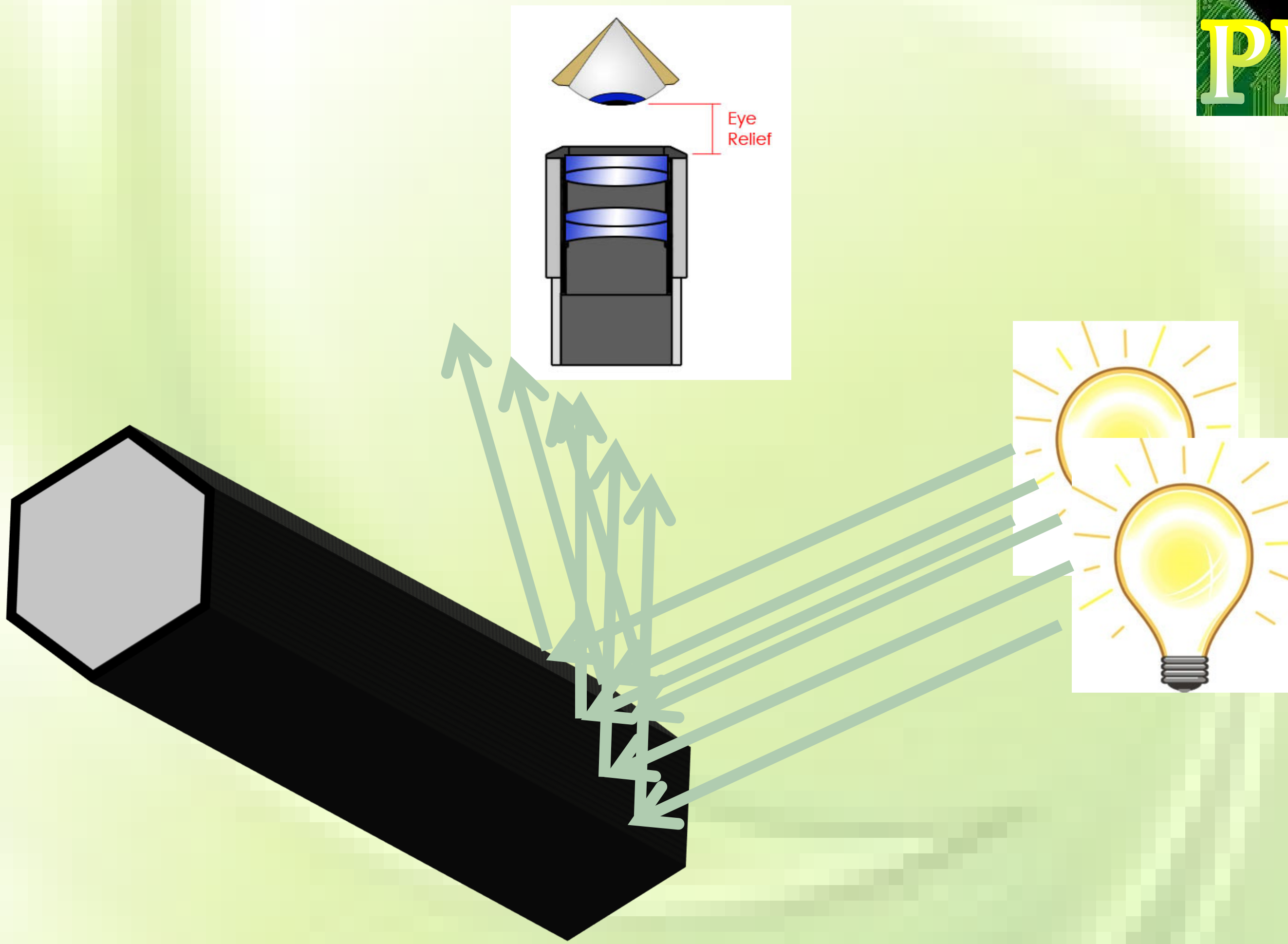
- **Type 2: "The Whisker-Arrogant" ← ~50% of population**
  "Hey, I'm a professional. You don't need to tell me how to use a microscope to see metal whiskers! I could do it blind-folded"

- **Type 3: "The Whisker-Respectful" ← ~0.1% of population**
  "Wow.. Those little buggers are really tough to see! However, with lots of practice on actual whiskering specimens using a variety of lighting techniques, varying the angle of inspection, working with low and high magnification, etc., I now at least have a better chance of seeing SOME ALBEIT NOT ALL of the whiskers."

It's Not Always THIS BAD! Nor This Easy to See



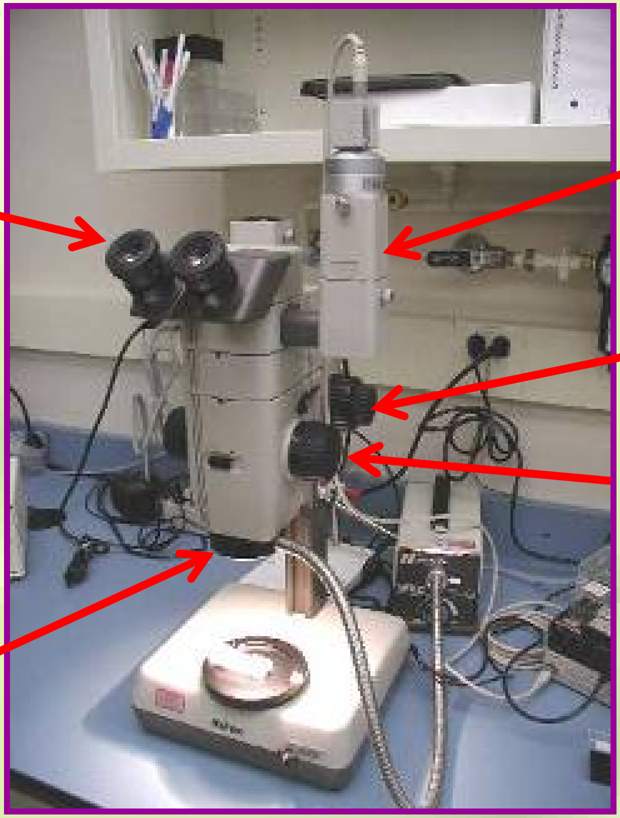
Tin Whiskers on INSIDE
Of Tin-Plated Transistor Can


Eye
Relief

Desirable Capabilities for Optical Inspection for Metal Whiskers

- Microscope
  - Stereo microscope is preferred ← enables better 3D perception
  - Magnification
    - 3x to 100x is a good working range ← Start with low mag, then work to high
    - >100x may be needed for extremely short whiskers (<50 microns)
- Sample Manipulation
  - Ability to tilt the sample (3-axes) to view from various angles
    - Some microscopes come with adapters to enable oblique view and 360° rotation around the axis of the objective lens!
  - Color and reflectivity of the background can enhance/inhibit whisker detection
- Illumination
  - Preferably use FLEXIBLE Lamps NOT Ring Lights
    - Flex light enables varying the angle of illumination which is critical to illuminating the whisker facets at an angle to can be deflected towards the observer's eye
    - Ring lights can make whiskers utterly invisible!!!
  - LED or Fiber Optic lighting is preferable over incandescent lamps
    - Provides lighting without shadows from the lamp filament
  - Ability to vary the intensity of light source
    - Can be too bright or too dim

One Example of a Stereo Microscope



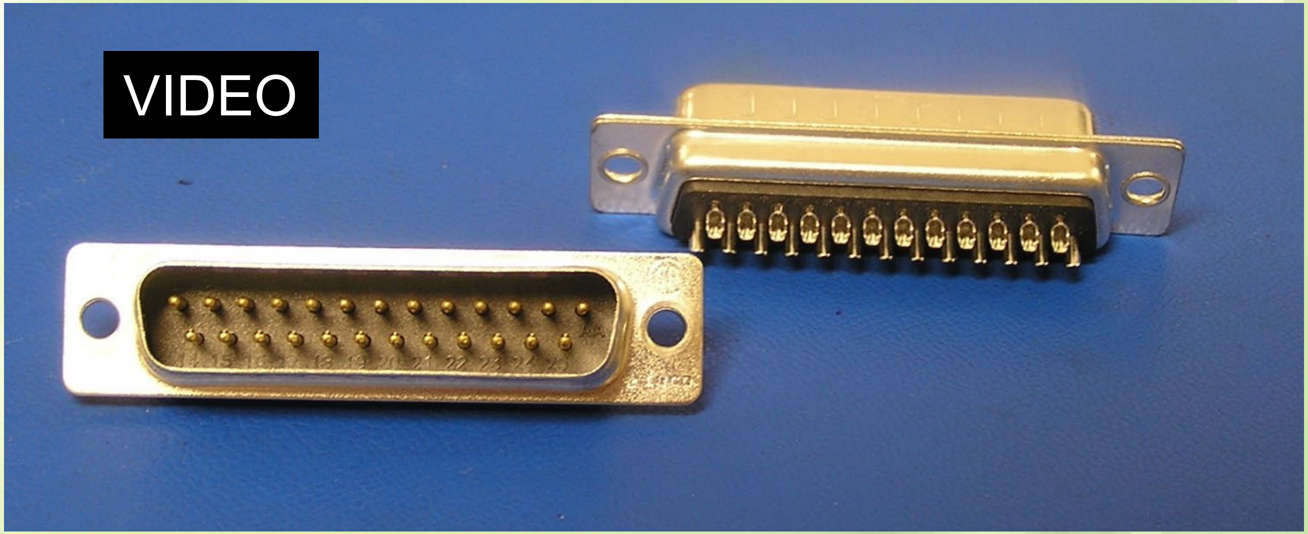
Comparison of Some Lighting Options

FLEXIBLE LIGHTING IS GENERALLY BEST
OFFERS ABILITY TO VARY ANGLE OF ILLUMINATION

RING LIGHTING CAN BE HORRIBLE CHOICE
BUT MOST ELECTRONICS LABS USE THIS TYPE OF LIGHTING BECAUSE IT OFFERS UNIFORM LIGHTING TO PRODUCE SHADOWLESS PICTURES, BUT THIS OFTEN RESULTS IN FAILURE TO "SEE" METAL WHISKERS

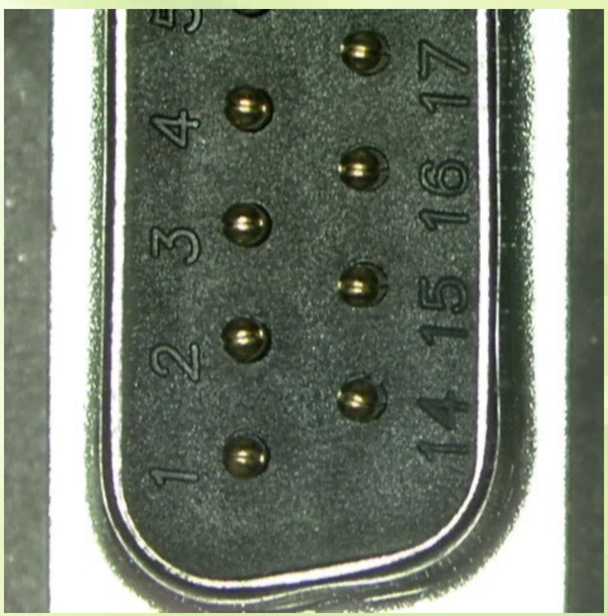
Demo of Optical Inspection Techniques for Tin Whiskers

Test Specimen: Connector, Plug, Size 3, 25 pin, solder cup
Connector Shell: Tin-plated steel
Contacts: Gold-plated brass
Date of Mfr: Dec. 2004

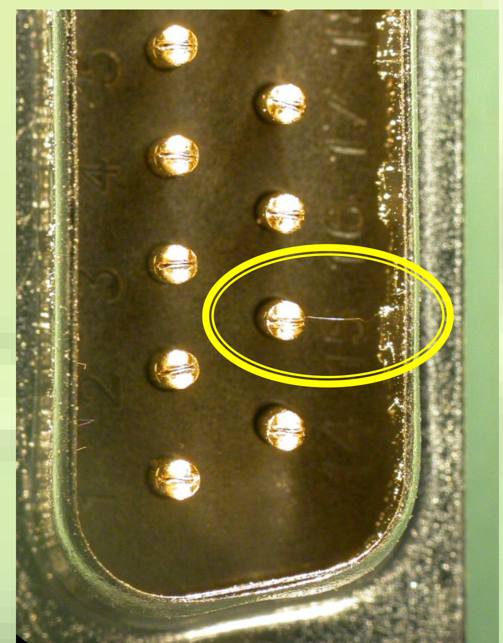


Absence of Evidence DOES NOT Equal *Evidence of Absence!!!*

WHERE ARE THE WHISKERS?
TOP DOWN LIGHTING



THERE'S ONE!
LOW ANGLE LIGHTING



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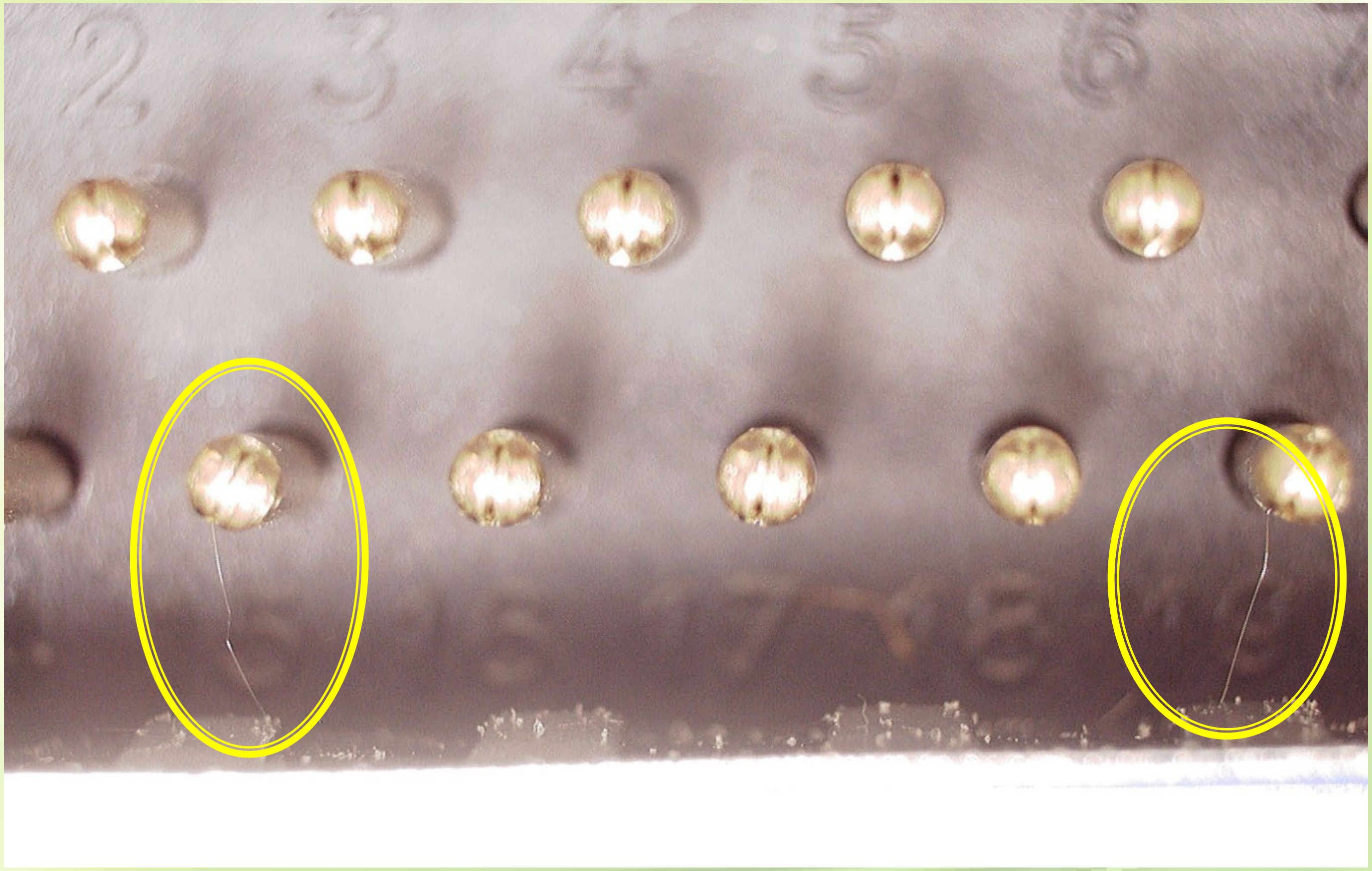
And There are Actually TWO Different Tin Whiskers Bridging From Shell to Pin 15 and Pin 19



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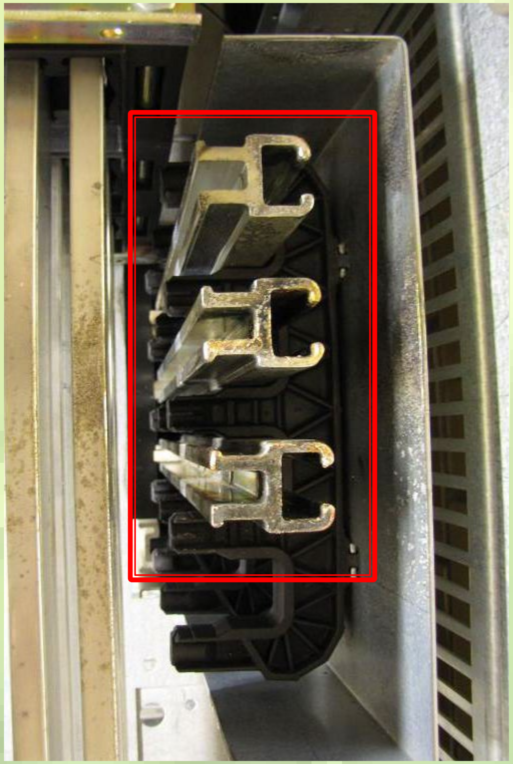
Carnage and Chaos in Swedish Paper Mill
Tin Whisker-Induced ***<u>Metal Vapor Arcing</u>***

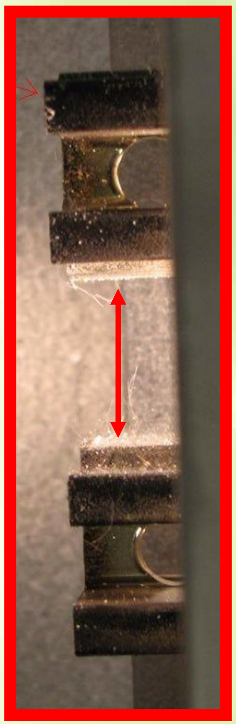
Problem in power supplied cabinet (500V AC) resulting in molten bus bars on three different occasions (1997, 2000, and 2009)

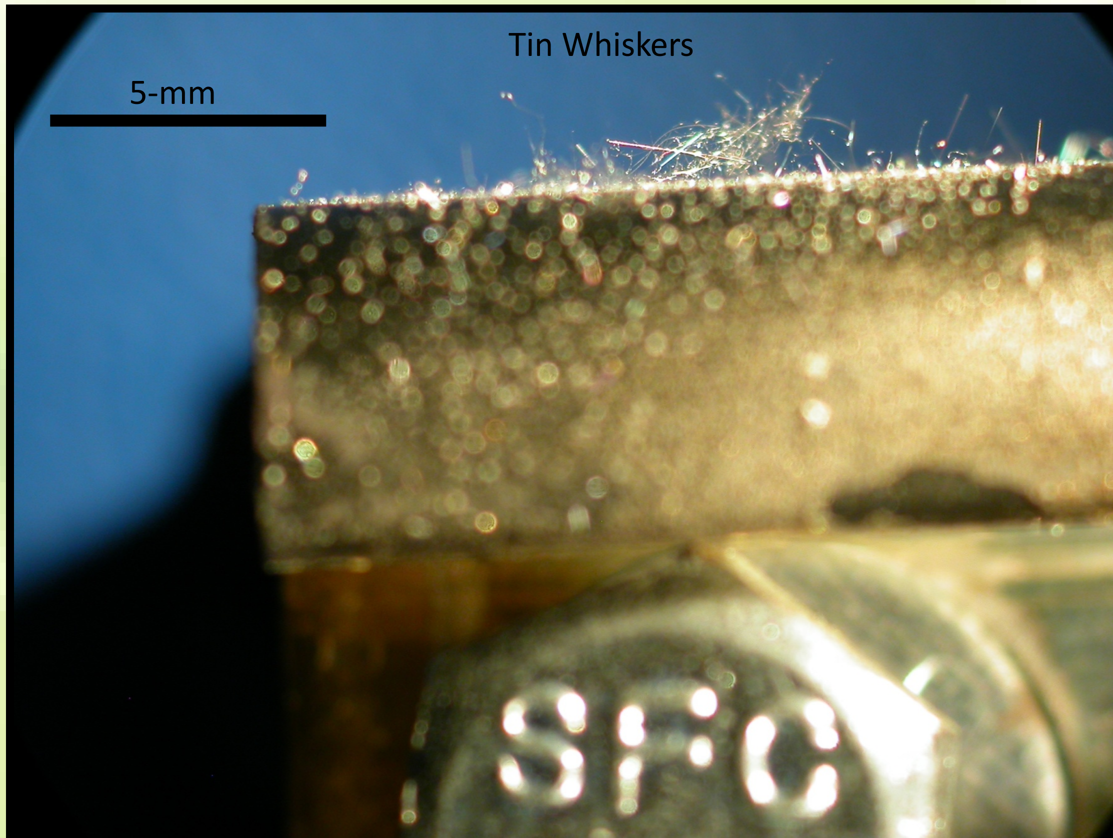


More information at http://nepp.nasa.gov/whisker/anecdote/2009busbar/2009-brusse-bus-bar-tin-whiskers-sweden.pdf

Tin Whiskers Responsible for Metal Vapor Arcing in Swedish Paper Mill

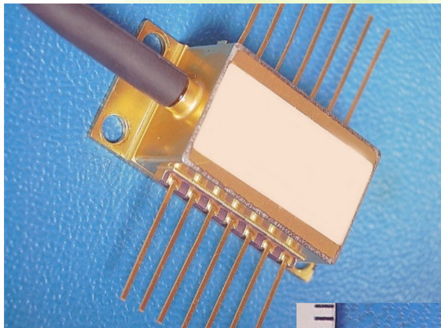
Distance between bars
Is ~20-mm

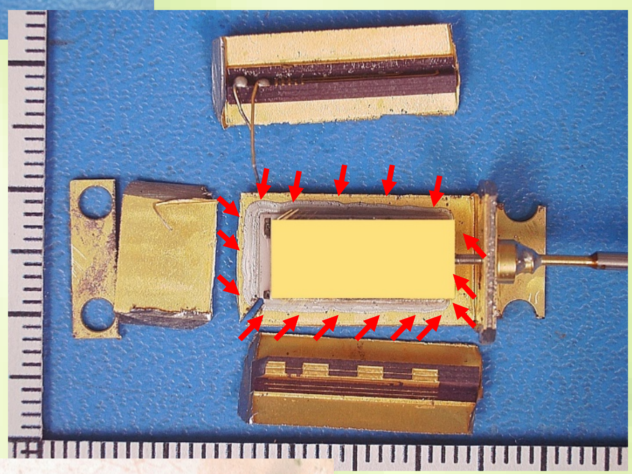


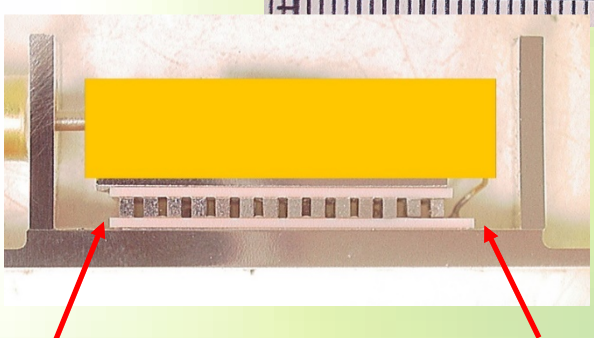


More information at http://nepp.nasa.gov/whisker/anecdote/2009busbar/2009-brusse-bus-bar-tin-whiskers-sweden.pdf

Butterfly Package with an Internal Short



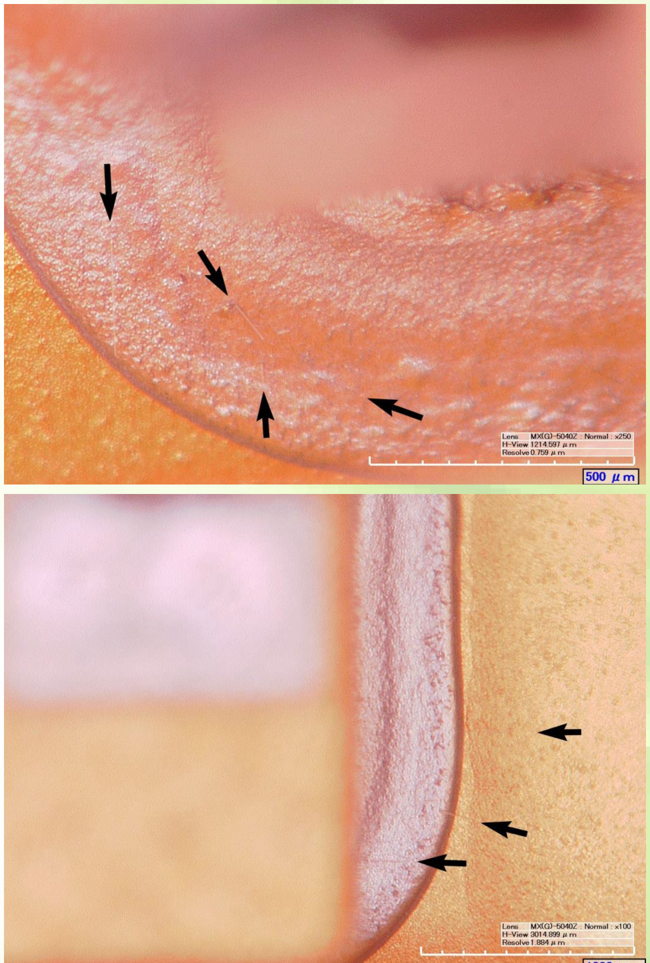




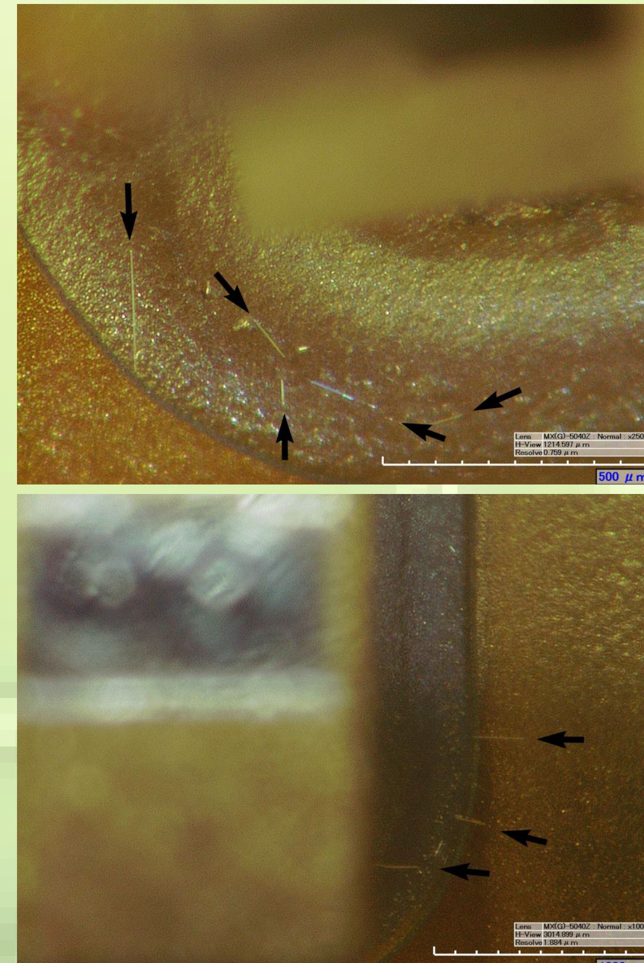
- Internal short between package body and columns of the thermo-electric cooler (TEC)
- Resistive short is due to tin whiskers growing from the Sn77.2-In20-Ag2.8 solder used for attaching TEC to the Au-plated package
  - Resistive shorts in 100-400Ω range
  - Normally the connection is electrically open
  - Tin whiskers bridged ~1.3mm gap
- Device background:
  - Underwent initial electrical check-out post-manufacturing
  - 2 years of non-operational storage
  - Hermetically sealed in nitrogen
  - Au-plated Cu-W package

L. Panashchenko "Tin Whisker Growth on Sn77.2-In20-Ag2.8 Solder" Presented at CMSE , Los Angeles, CA May 7-8, 2018
Available at: https://nepp.nasa.gov/whisker/reference/tech_papers/2018-Panashchenko-Tin-Whiskers-SnInAg-solder.pdf#v16

Effect of Optical Illumination



Change in Illumination



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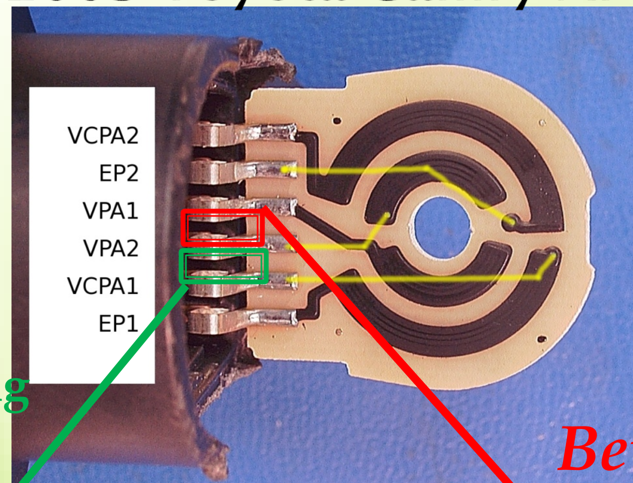
Electrical Tests on 2003 Camry APP Sensor

- Resistance measurements between all combinations of external APP sensor connector pins detected an intermittent resistive short between VPA1 and VPA2
  - Measurements made using lab-grade digital ohm-meter
  - Initially, ~3.5MΩ, dropping to ~5kΩ, and then remaining between 238Ω to 250Ω, until the pedal assembly was mechanically shocked
  - Mechanical shock to the pedal assembly returned the resistance to ~3.5MΩ and further pedal actuations dropped the resistance again to ~5kΩ and finally to the range between 238Ω to 250Ω
  - This shorting resistance remained unchanged throughout the entire range of travel of the pedal, except when mechanical shocks were delivered

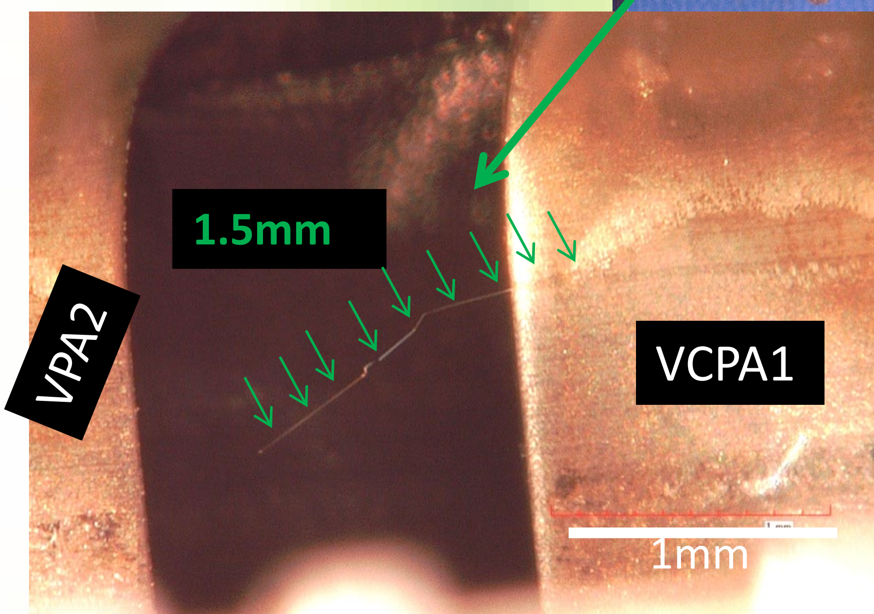
Source: H. Leidecker, L. Panashchenko, J. Brusse, "Electrical Failure of an Accelerator Pedal Position Sensor Caused by a Tin Whisker and Investigative Techniques Used for Whisker Detection", 5th International Tin Whisker Symposium, Sept. 2011. Available https://nepp.nasa.gov/whisker/reference/tech_papers/2011-NASA-GSFC-whisker-failure-app-sensor.pdf

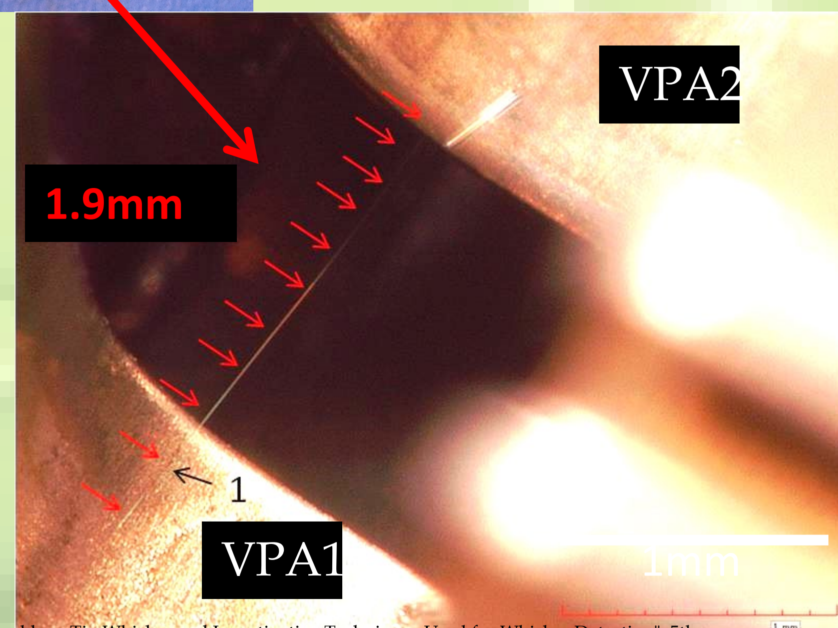
The Two Longest Tin Whiskers Observed in Faulty 2003 Toyota Camry APP Sensor



Tin Whisker Almost Bridging Between VPA2 and VCPA1

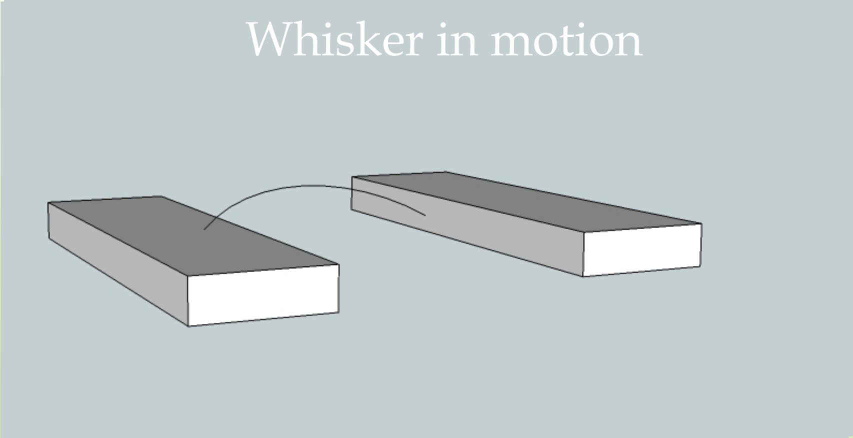
Tin Whisker Shorting Between VPA1 and VPA2





Source: H. Leidecker, L. Panashchenko, J. Brusse, "Electrical Failure of an Accelerator Pedal Position Sensor Caused by a Tin Whisker and Investigative Techniques Used for Whisker Detection", 5th International Tin Whisker Symposium, Sept. 2011. Available https://nepp.nasa.gov/whisker/reference/tech_papers/2011-NASA-GSFC-whisker-failure-app-sensor.pdf

Illustration of How a Whisker may Snag



- Long, thin whiskers are ductile. Without breaking they can bend, flex through very large angles under the influence of air, vibration, shock, electrostatic forces
- After significant movement, whisker tip may be caught by the irregular surface of the tin plating on an adjacent conductor
  - Mechanical shock or air movement may dislodge the whisker tip
- Insulating films may prevent immediate electrical continuity