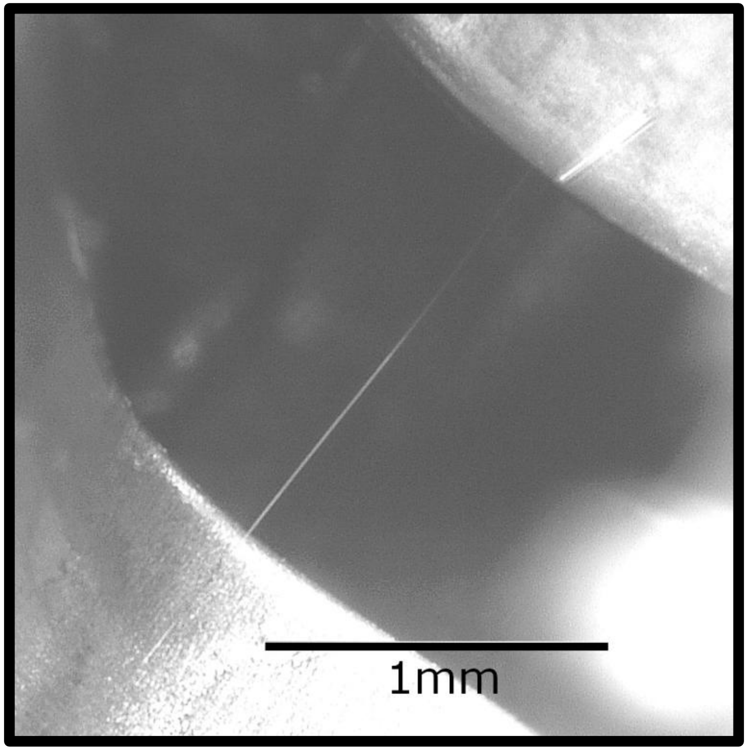
Electrical Failure of an Accelerator Pedal Position Sensor Caused by a Tin Whisker and Discussion of Investigative Techniques Used for Whisker Detection



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Outline

- About Us
- Investigation of a failed Accelerator Pedal Position (APP) Sensor due to a Tin Whisker
- Important Guidelines for Troubleshooters of Anomalies Related to Metal Whiskers

About Us

- Metal Whisker Investigation Team at NASA Goddard Space Flight Center
  - H. Leidecker, M. Sampson, L. Panashchenko, J. Brusse, J. Kim
- Widely recognized for our Metal Whisker WWW site
  - http://nepp.nasa.gov/whisker
- Published study of 11+ year evaluation of conformal coating for whisker mitigation
- Numerous other publications on metal whiskers (tin and zinc whiskers)
- >10 years experience with anomalies related to metal whiskers
  - Aerospace: Satellites and Space Shuttle
  - Military: Missile Systems, Ordinance Fuzes
  - Industrial: Nuclear and other Power Plants, Paper Mills, Non-interruptable Power Supplies
  - Automotive: Speedometers and other gauges, "DOA" cars
  - Others
- Supporting members of the NESC Toyota Investigation Team

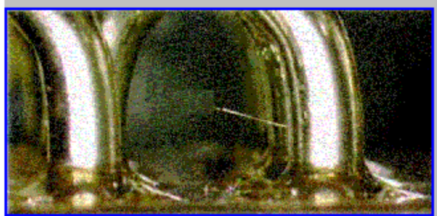
https://nepp.nasa.gov/whisker

NASA
Tin Whisker (and Other Metal Whisker) Homepage

Home | Basic Info/FAQ | Other Metal Whiskers | Literature References | Whisker Failures | Whisker Anecdotes | Photo Gallery | Video Gallery | GSFC Experiments

Related Links | What's New | Contact Us

Tin Whisker Growing from Pure Tin Plated Relay Terminal



Motion depicted in this image is for simulation purposes only

Photo of the Month

April 2004:
Limitations of "Hot Solder Dip" for Tin Whisker Mitigation

Hot Topics

August 2011
- "**Lead-Free Electronics Reliability - An Update**", A. Kostic, GEOINT Development Office, Aerospace Corporation, August 2011

January 2011
- "**Long Term Investigation of Urethane Conformal Coating Against Tin Whisker Growth**", L. Panashchenko, IPC Tin Whisker Conference, Dec. 2010

December 2010
- "**Examples of Lognormal Distributions of Tin Whisker Lengths and Thicknesses**", extracted from master's thesis of L. Panashchenko, 2009 (full dissertation link)

November 2010
- **"How do whiskers and hillocks grow in Pb-free Sn coatings?** *Fundamental mechanisms controlling stress evolution and whisker growth", E. Chason/Brown University*
  - *Powerpoint File (with embedded animation/movies)*
  - *Adobe PDF file (No Animation)*

May 2010
- **Videos: "Real-Time Growth Videos of Whiskers and Hillocks in Tin Over Copper Structures", Brown University**

March 2010
- **Whisker Photo Gallery Updated**
- **Whisker Anecdotes Added**

February 2010
- "Evaluation of Environmental Tests for Tin Whisker Assessment", L. Panashchenko, Univ. of Maryland Thesis, Dec. 2009

September 2009
- "Examination of Nickel Underlayer as a Tin Whisker Mitigator", L. Panashchenko, M. Osterman, ECTC, May 2009
  - Presentation *(modified for tin whisker telecon)*

August 2009
- "Examination of Nickel Underlayer as a Tin Whisker Mitigator", L. Panashchenko, M. Osterman, ECTC, May 2009
  - Paper
  - Presentation

Focus of this Presentation

- Describe the failure of a Accelerator Pedal Position (APP) sensor caused by a ***TIN WHISKER****
- Describe the failure analysis methods used to identify ***TIN WHISKERS*** as the root cause of failure
- Convey guidance to failure analysts/troubleshooters for improved techniques to electrically detect metal whisker-induced short circuits

(*) VOQ# 10304368, Available on: http://www-odi.nhtsa.dot.gov/complaints/

Source of APP Sensor

- In March 2010, Dept. of Transportation (DoT) contacted the NASA Engineering & Safety Center (NESC – HQ in Langley, VA) for support
- In February 2011, the DoT published the 200+ page NESC report entitled:

  Technical Support to the National Highway Traffic Safety Administration (NHTSA) on the Reported Toyota Motor Corporation (TMC) Unintended Acceleration (UA) Investigation

  http://www.nhtsa.gov/UA

  http://www.nhtsa.gov/staticfiles/nvs/pdf/NASA-UA_report.pdf

Extract from NASA Findings

- Destructive physical analysis of a failed pedal assembly from a consumer vehicle with a diagnostic trouble code found a tin whisker had formed a 248 ohm resistive short between VPA1 and VPA2
- A second tin whisker of similar length was growing from a 5 volt source terminal adjacent to a pedal signal output terminal, but had not made contact with any other terminals. Inspection of “non-failed” potentiometer pedals revealed tin whiskers present in similar locations as the failed pedal

Extract from NASA Findings

- Vehicle testing of a MY 2005 Toyota Camry demonstrated that a 248 ohm short between VPA1 and VPA2 results in different vehicle responses depending on the sequence of operations following the fault
  - *If the pedal is depressed quickly, then throttle is limited to 15 degrees*
  - *If the pedal is depressed slowly, then throttle can jump to 15 degrees, and further pedal application can achieve wide open throttle*
- In all cases, releasing the accelerator pedal closes the throttle, and brakes are fully operational
  - *Although the vehicle would operate, we did not consider it to be driveable*

Event Sequence Chart

This chart is not self-contained, but requires the materials in the section 6.6.2.3.1 of the NESC Technical Assessment Report

Technical Support to the National Highway Traffic Safety Administration (NHTSA) on the Reported Toyota Motor Corporation (TMC) Unintended Acceleration (UA) Investigation , February 2011. Page 115, Figure 6.6.2.3-2
http://www.nhtsa.gov/UA
http://www.nhtsa.gov/staticfiles/nvs/pdf/NASA-UA_report.pdf

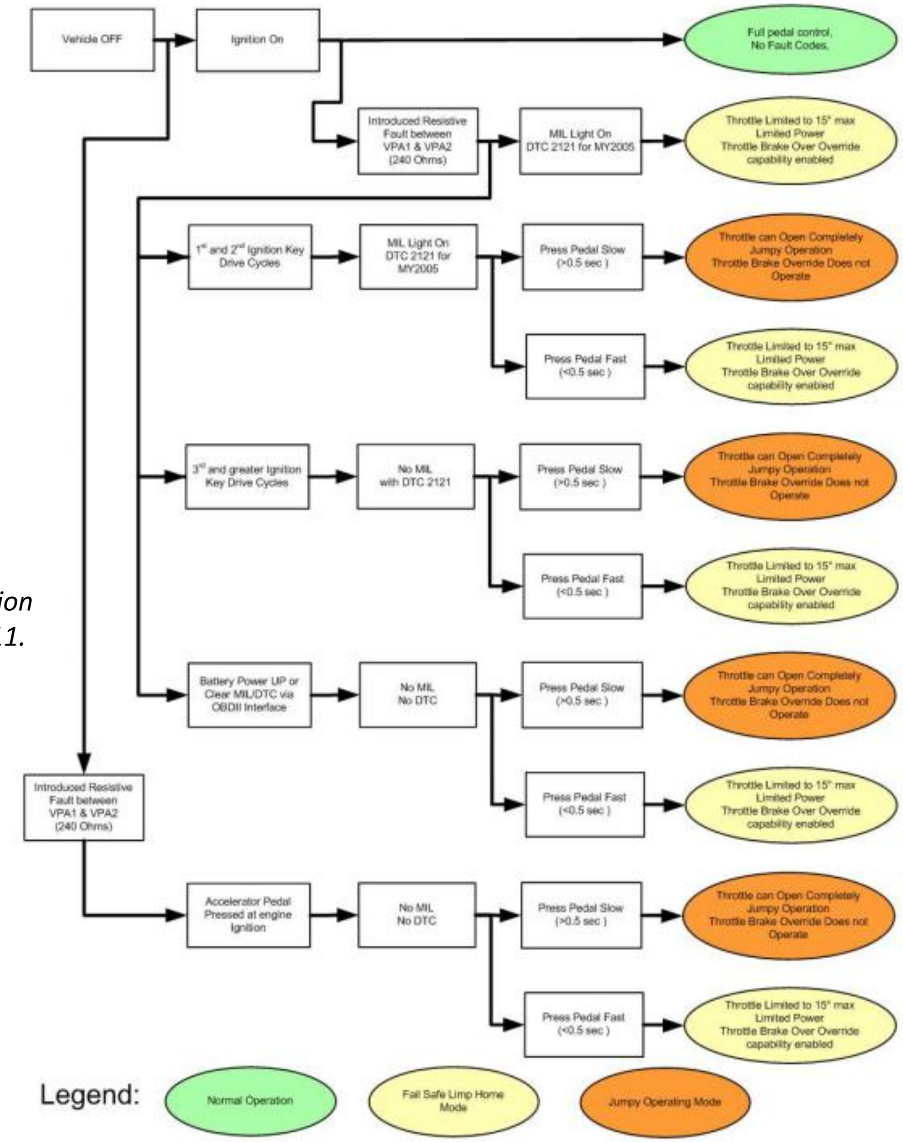
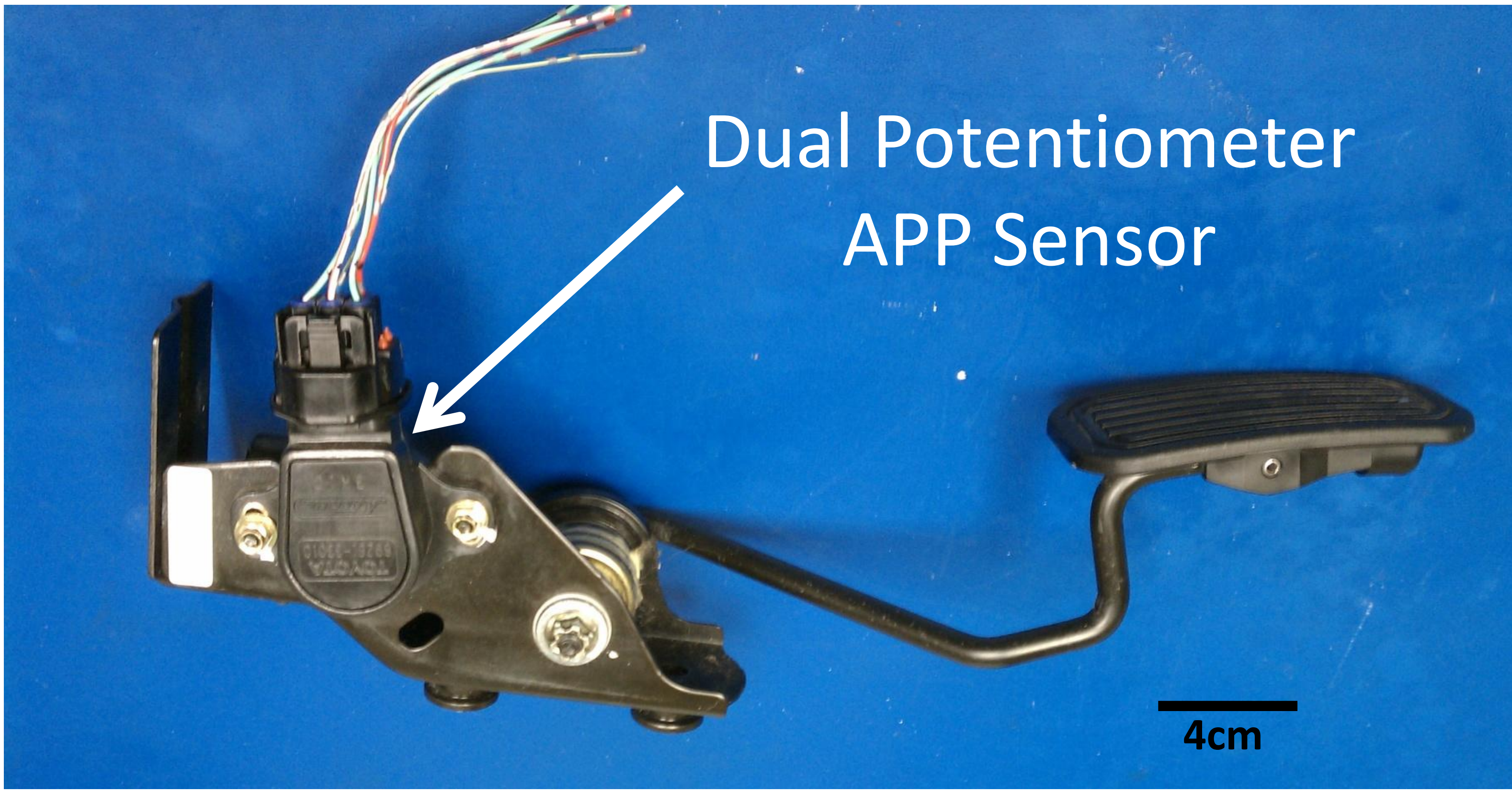


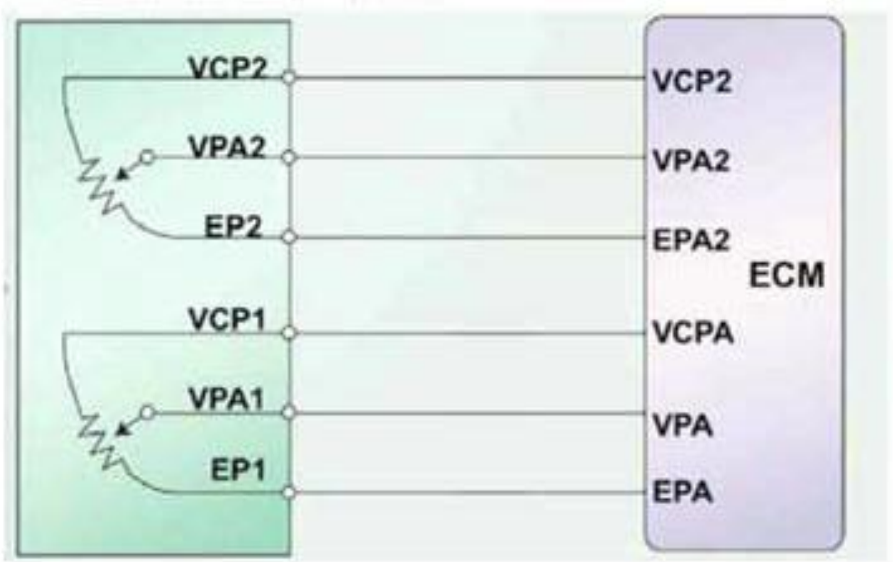
Figure 6.6.2.3-2. Pedal Resistive Fault Event Sequence Diagram

Accelerator Pedal Assembly with Dual Potentiometer Accelerator Pedal Position (APP) Sensor



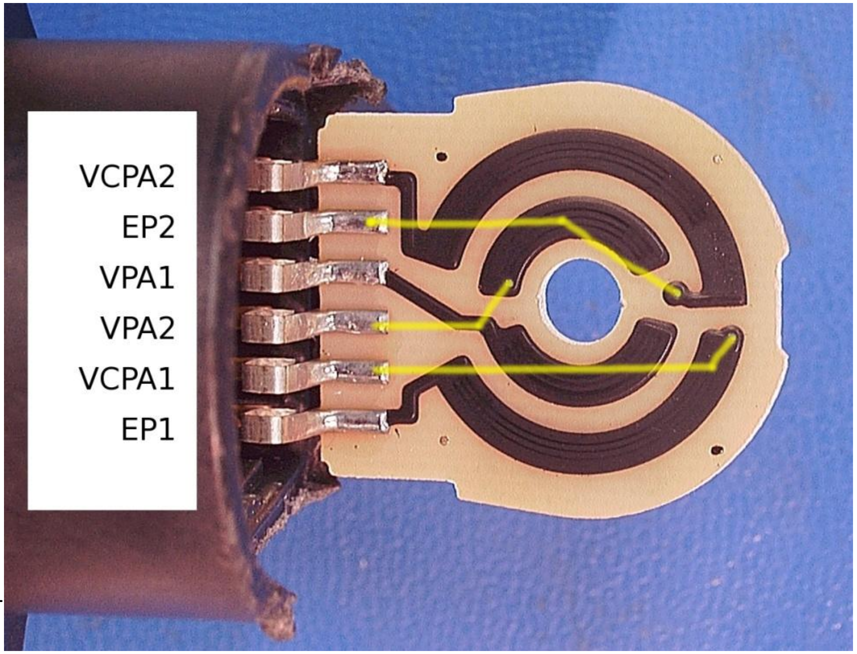
Overview of a Dual Potentiometer-Based APP Sensor

Architecture Dual Potentiometer APP Sensor For Camry MY 2002 - 2006



Source: NESC "NHTSA Toyota UA Investigation", January 18, 2011 Figure 6.4.1.3-1

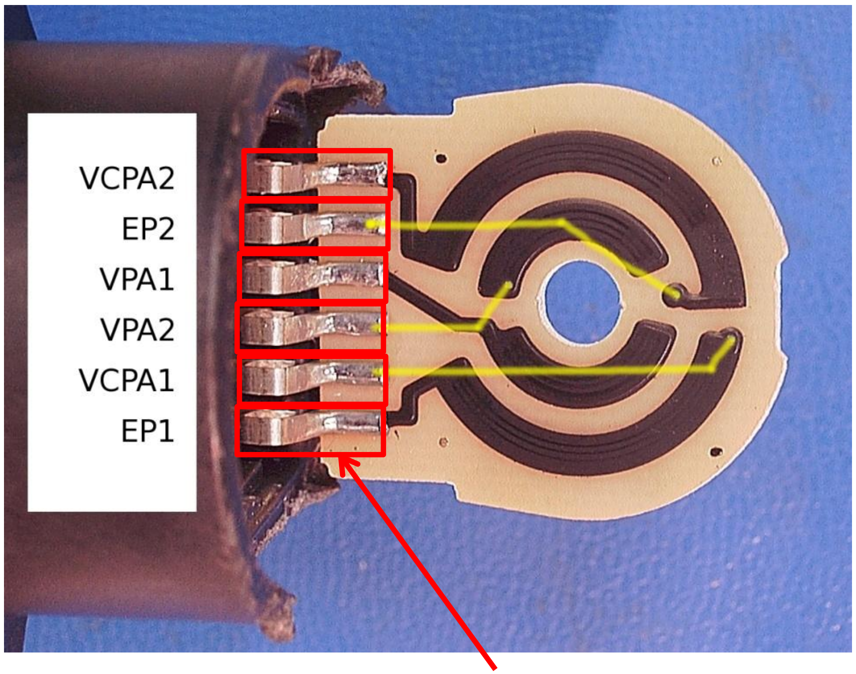
Actual Dual Potentiometer APP Sensor (partially disassembled)



Signal Line Labels:

- VCP1, VCP2 = voltage supply fixed at 5.0 volts for potentiometers 1 and 2, respectively
- VPA1, VPA2 = sliding tap, producing a voltage between VCP1, VCP2 (respectively) that is linear with pedal displacement – these are the voltage signals sent to the engine control module to control the throttle position
- EP1, EP2 = system ground at 0.0 volts for potentiometers 1 and 2, respectively ("E" = "Earth")

Partially Disassembled Dual Potentiometer-Based APP Sensor



Tin-plated Cu alloy

- Ribbon Leads are a Copper Alloy Coated with 2 μm of Pure Tin
  - Confirmed by XRF & EDS
- No other coatings present on Ribbon Leads (i.e., no conformal coating over them, no intermediate plating layers)
- Separation between adjacent terminals varied from 1000 to 1500 μm
- Dual potentiometers produce independent electrical signals based upon pedal depression angle (VPA1 and VPA2)

Source of Accelerator Pedal Assembly Provided to NASA Metal Whisker Team

http://www-odi.nhtsa.dot.gov/complaints/

- Make : TOYOTA Model : CAMRY **Year : 2003**
- Manufacturer : TOYOTA MOTOR CORPORATION Crash : No
- Fire : No Number of Injuries: 0
- ODI ID Number : 10304368 Number of Deaths: 0
- **Date of Failure: November 11, 2009**
- Component: VEHICLE SPEED CONTROL: ACCELERATOR PEDAL
- Failure Mileage: 81,957 *(information courtesy of DOT)*
- Summary:
  I HAVE A 2003 CAMRY. ON NOV. 8, 2009 I HAD A VERY BIG PROBLEM WITH THE ACCELERATOR. WHEN STEPPING ON THE GAS PEDAL I COULDN'T GET ANY GAS, AND THEN THE CAR WOULD JERK FORWARD AT A RAPID RATE SO THAT I HAD TO APPLY THE BRAKES. IT WAS TOTALLY UNDRIVABLE.

  THE MECHANIC REPLACED THE GAS PEDAL ASSEMBLY, AND I HAVE THE OLD PART IN MY POSSESSION. THE PART WAS $428.01 PLUS THE LABOR COST. MY OLD CAMRY I DROVE FOR 12 YEARS WITHOUT ANY PROBLEMS.

  I FEEL THE PART WAS DEFECTIVE AND THAT TOYOTA SHOULD REIMBURSE ME FOR THE COST OF REPLACEMENT. WOULD YOUR AGENCY PLEASE LOOK INTO THIS FOR ME?

NOTE: NHTSA report states warranty analyses identified at least two additional failures due to tin whiskers in similarly designed APP sensors

Failure Analysis of 2003 Camry APP Sensor

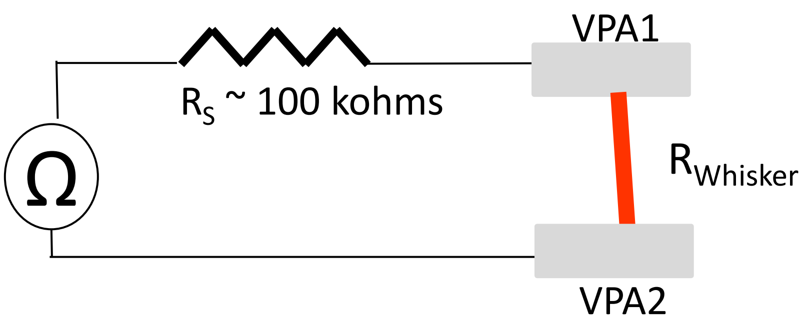
- Electrical Tests on Receipt by NESC at Goddard
  - The presence of a short was explored by using four different ohm-meters, testing on two vehicles and a vehicle simulator
  - Each method found a short
- Physical Analysis of Internal Components
  - Optical Microscopy & Scanning Electron Microscopy (SEM) to inspect for the cause of the short
  - X-Ray Fluorescence (XRF) Spectroscopy to determine material composition: elements and thickness of layers

Electrical Tests on 2003 Camry APP Sensor

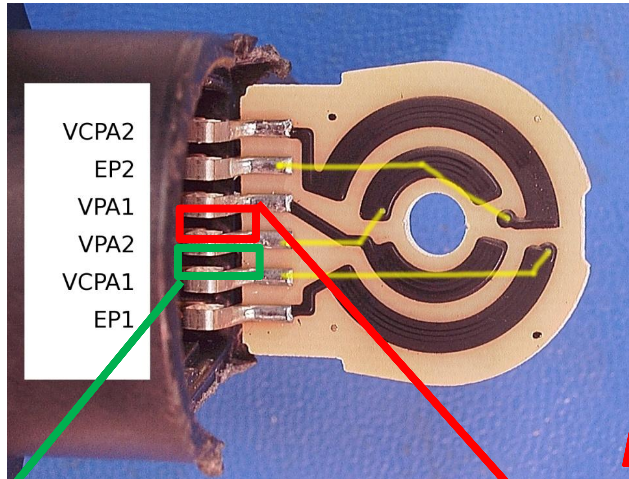
- Resistance measurements between all combinations of external APP sensor connector pins detected an intermittent resistive short between VPA1 and VPA2
  - Measurements made using multiple multimeters
  - Initially, ~3.5MΩ, dropping to ~5kΩ, and then remaining between 238Ω to 250Ω, until the pedal assembly 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

NASA GSFC Parts Analysis Lab

- APP sensor brought into the parts analysis lab at Goddard for further analysis
  - Intermittent resistance behavior confirmed
- Disassembly methods chosen to preserve evidence of conductive debris
  - Plastic housing removed without delivering shocks or introducing debris
  - Shorting resistance was continually monitored using a Fluke 87V multimeter in series with a 100kΩ protection resistor, and shown to remain at 238Ω throughout disassembly, except for several excursions to "open circuit" (>50MΩ) followed by return to about 238Ω

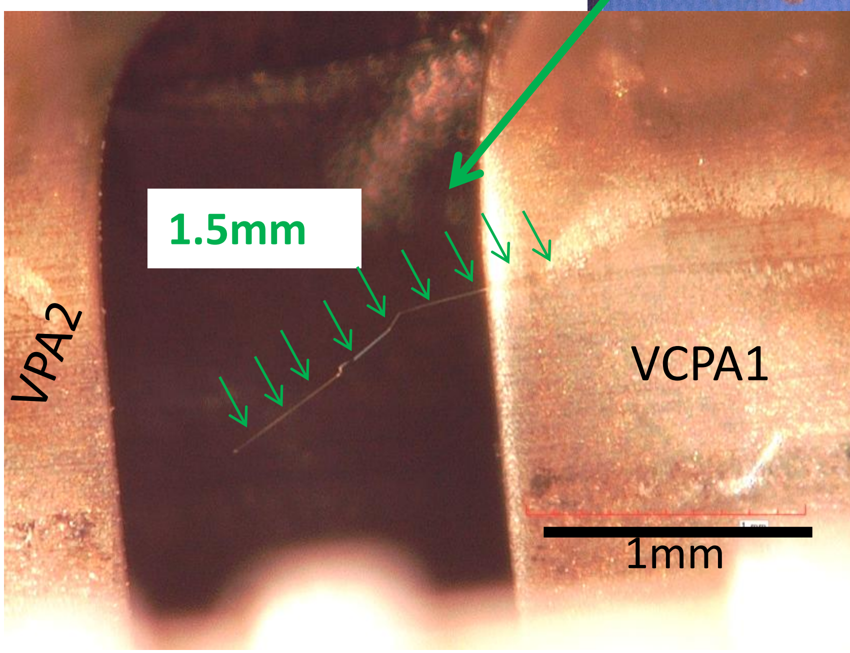


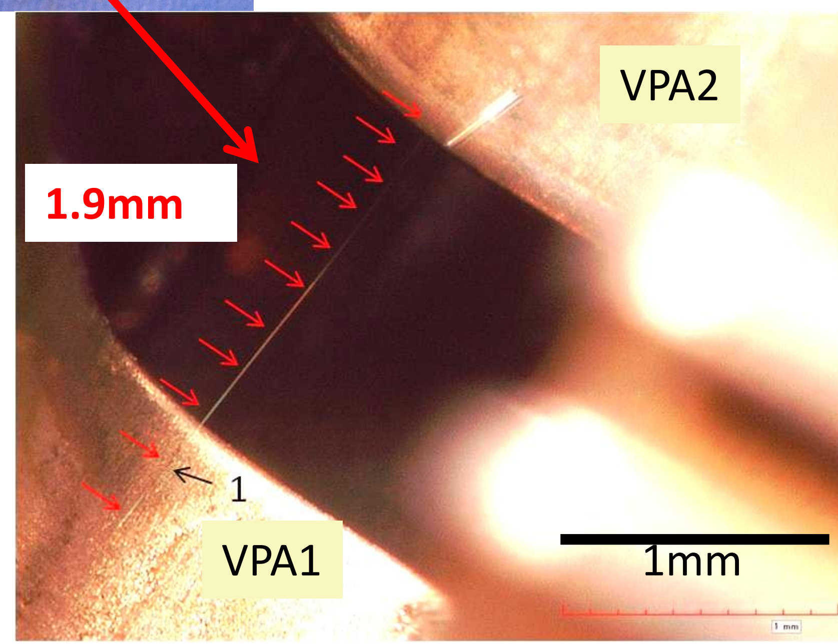
The Two Longest Tin Whiskers Observed in Faulty 2003 Toyota Camry APP Sensor



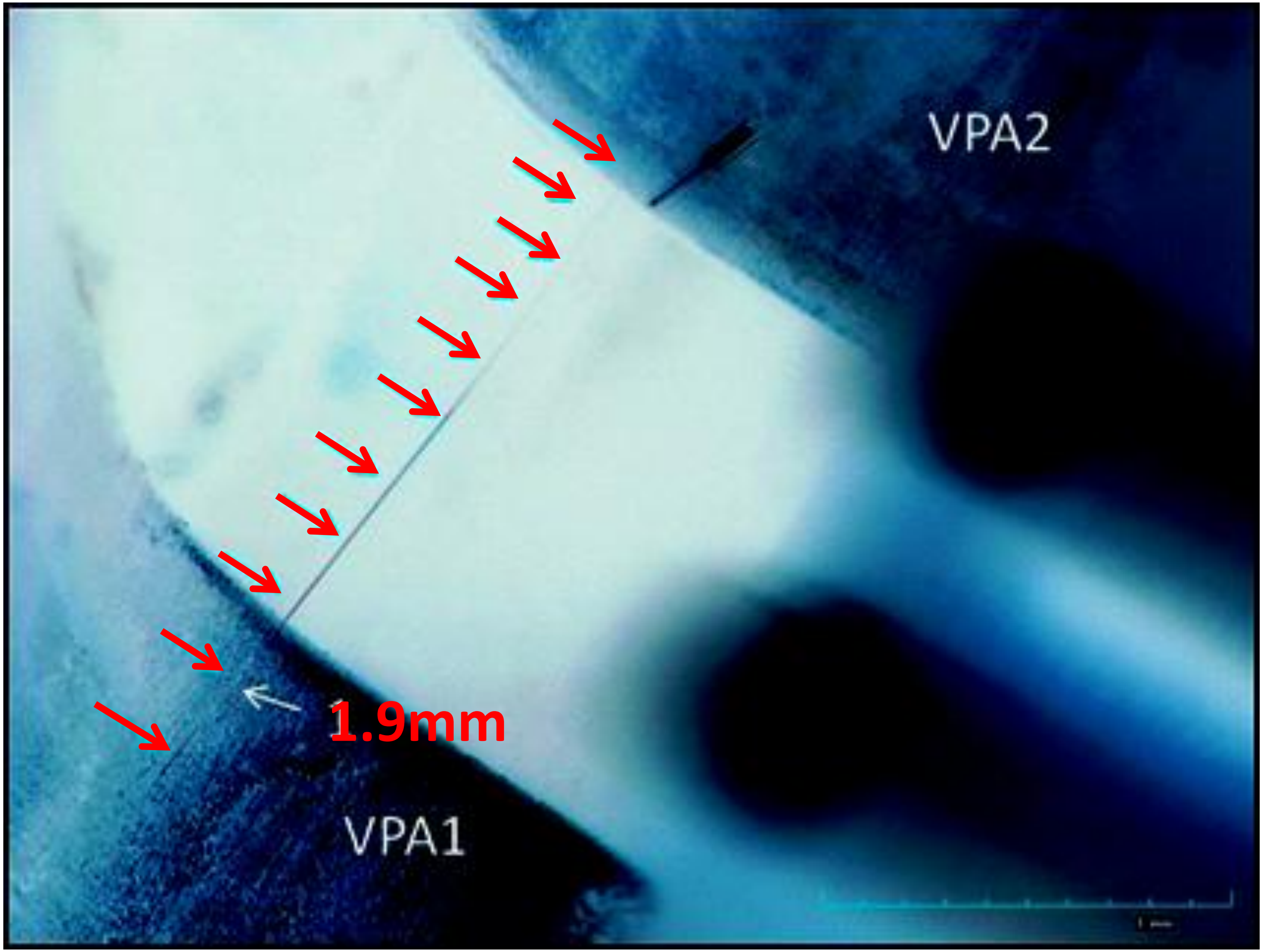
Tin Whisker Almost Bridging Between VPA2 and VCPA1

Tin Whisker Shorting Between VPA1 and VPA2





Whiskers in Faulty 2003 Toyota Camry APP Sensor

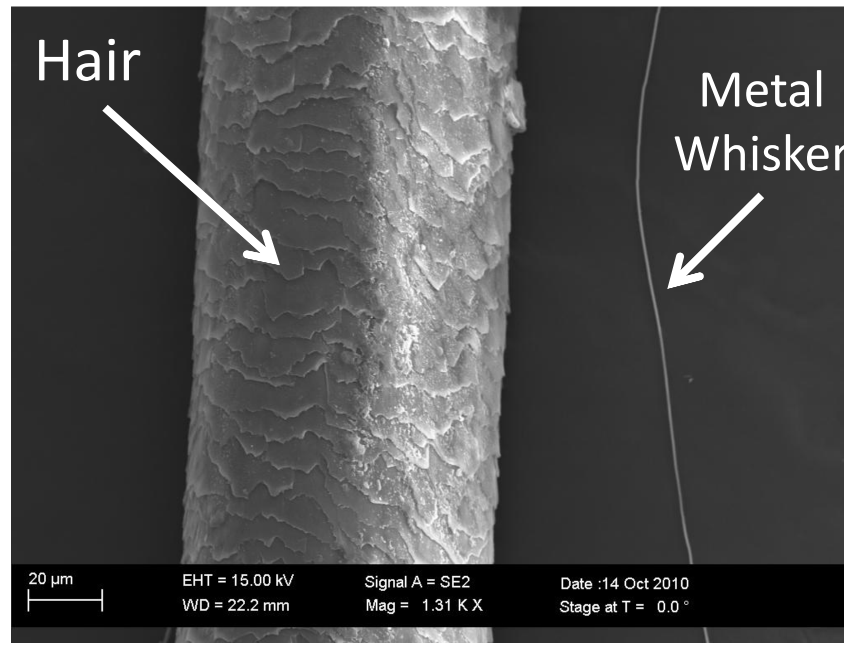


Human Hair vs. Metal Whisker

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



Calculation of Thickness of the Bridging Whisker from Measured Resistance and Length

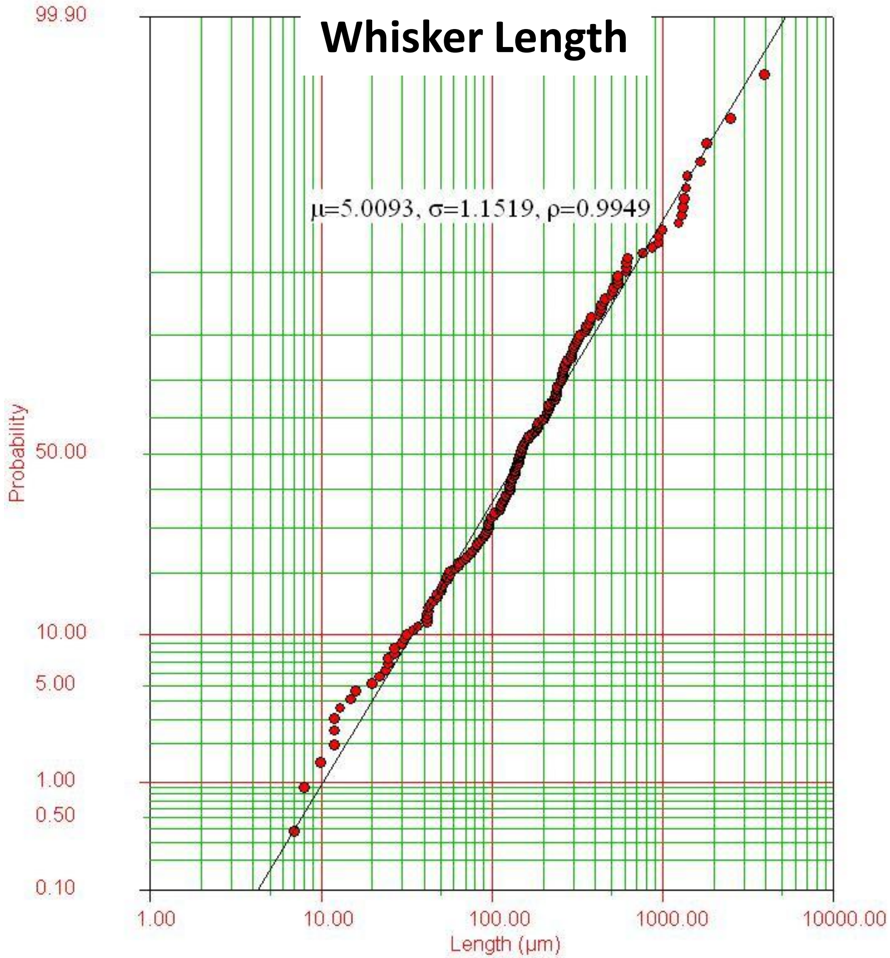
$$R = \rho \frac{L}{A}$$

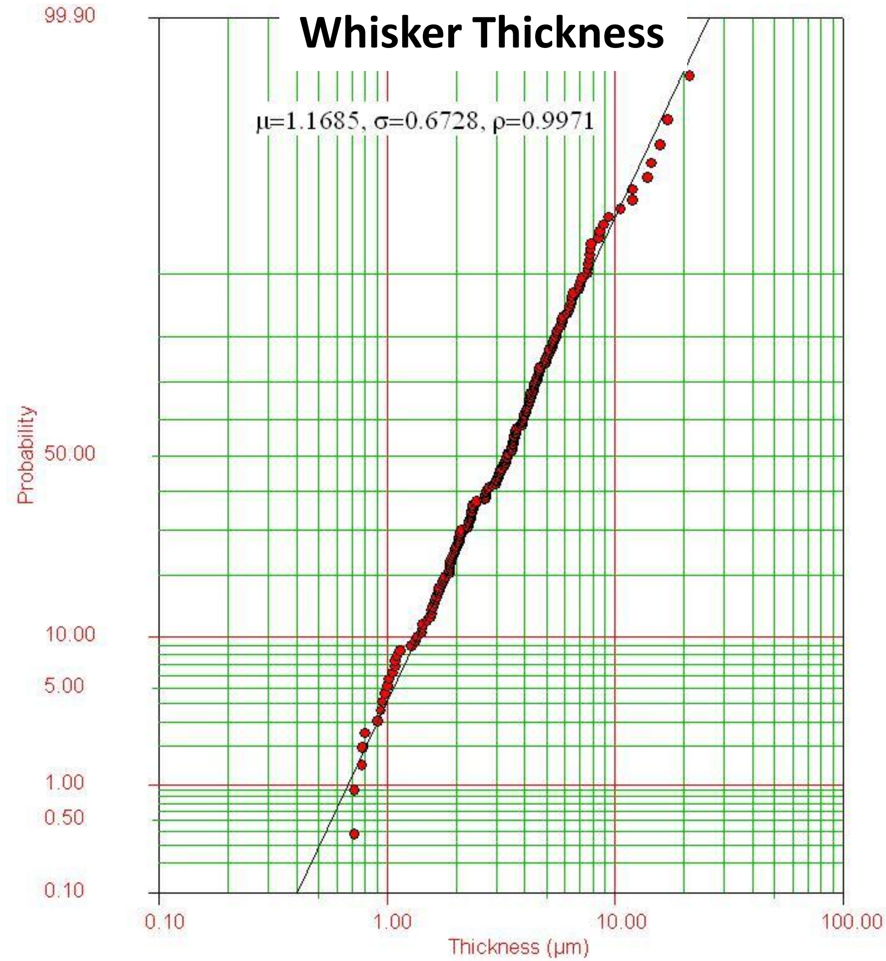
- Where ρ = resistivity of Sn ~ 11.5$\mu\Omega$ cm;
- L = length of whisker;
- A = cross sectional area of whisker = $\pi \frac{d^2}{4}$
  where d = diameter of whisker (approximating thickness of whisker)

- Therefore, since L= 1900 μm, R = 238Ω, then d ~ 1.1 μm
  - This is in line with typical thicknesses of tin whiskers

Example of Tin Whisker Length and Thickness Distributions

Collected for 187 whiskers on tin-plated brass that grew over 11 years of ambient storage

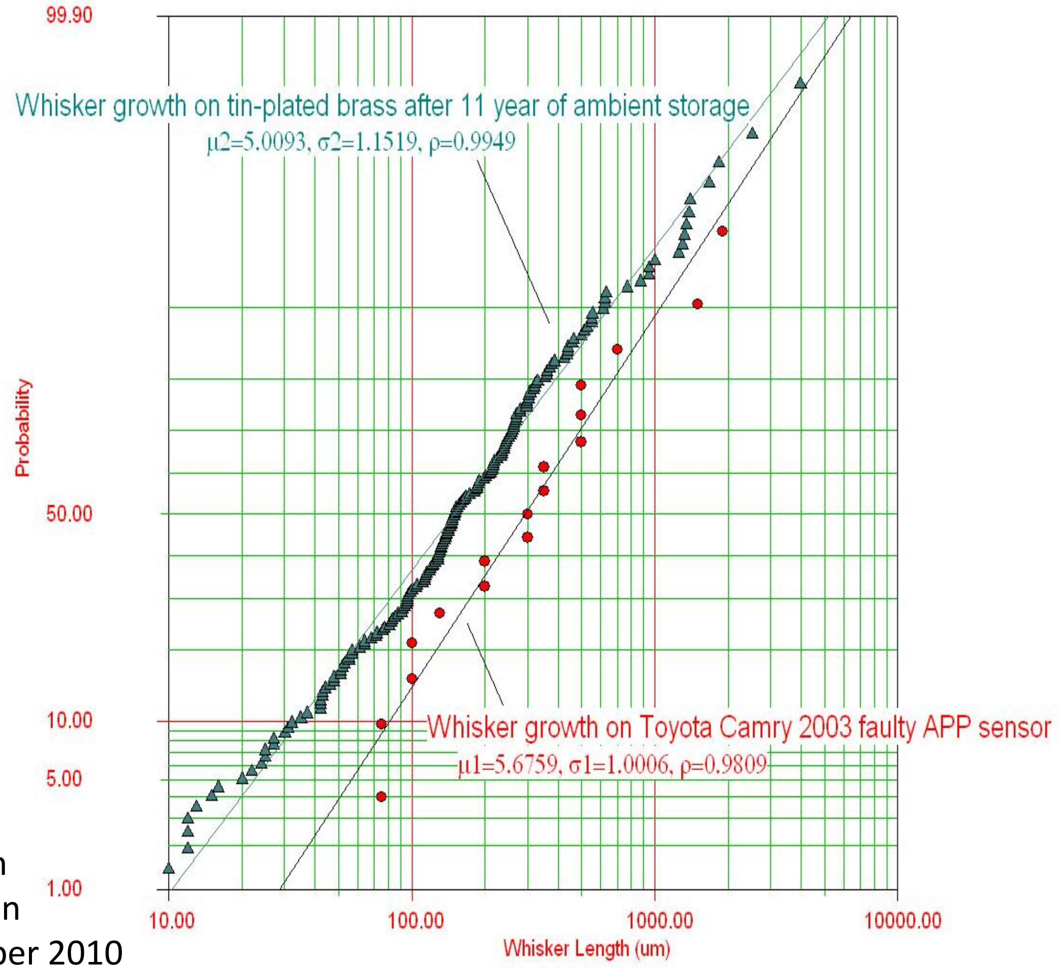




Source: L. Panashchenko "Evaluation of Environmental Tests for Tin Whisker Assessment", MS Thesis, University of MD, December 2009. Figures 59-60

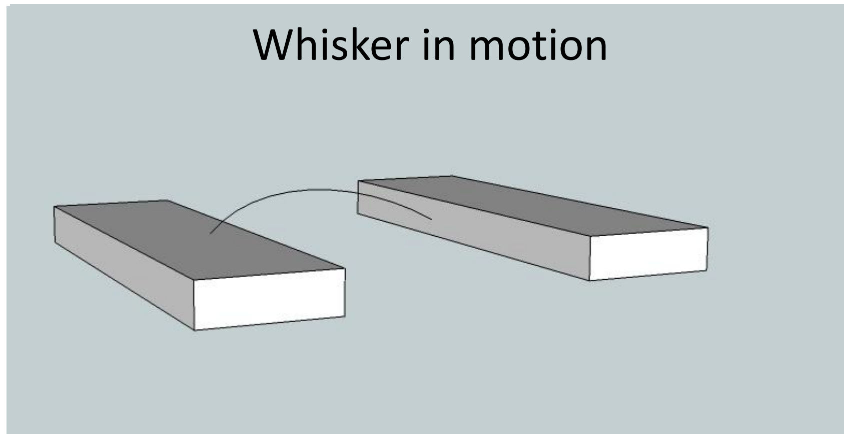
Whiskers >50μm in Length found on the Faulty 2003 Camry APP Sensor

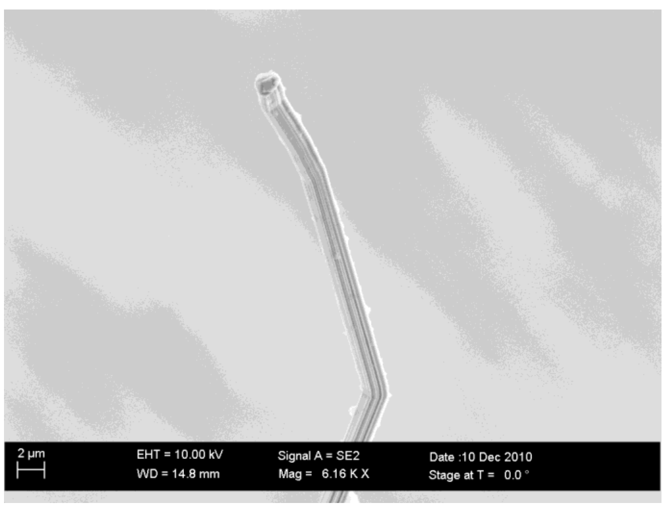
- 17 whiskers with lengths >50μm were observed on the faulty 2003 Camry APP sensor
  - Whisker lengths on APP sensor may actually be longer than shown due to measurement technique
- Whisker growth seen on faulty APP sensor is not 'out of family'
  - Compare to whisker length data collected for tin-plated brass after 11 years of ambient storage*



(*) L. Panashchenko, J. Brusse, H. Leidecker, "Long Term Investigation of Urethane Conformal Coating Against Tin Whisker Growth", IPC Tin Whisker Symposium, December 2010

Illustration of How a Whisker may Snag

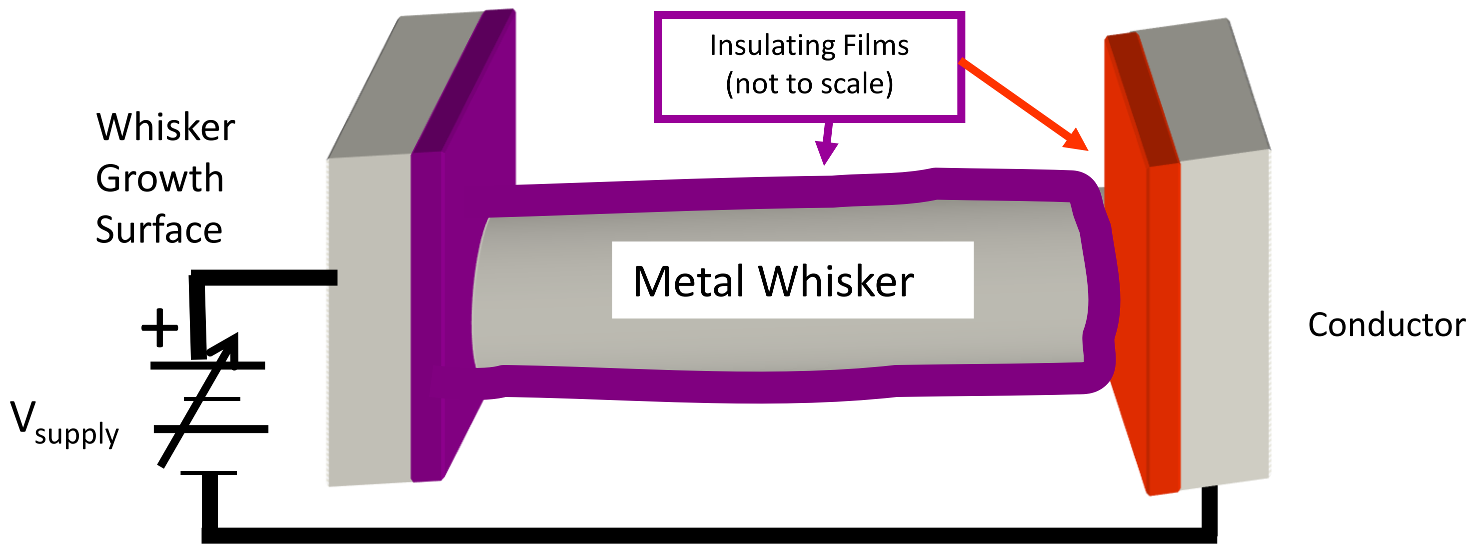




- Long, thin whiskers are ductile. Without breaking they can bend, flex through very large angles under the influence of air, vibration, shock, electrostatic forces
- After significant movement, whisker tip may be caught by the irregular surface of the tin plating on an adjacent conductor
  - Mechanical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

Metal Whiskers and Adjacent Conductors Grow Insulating Films

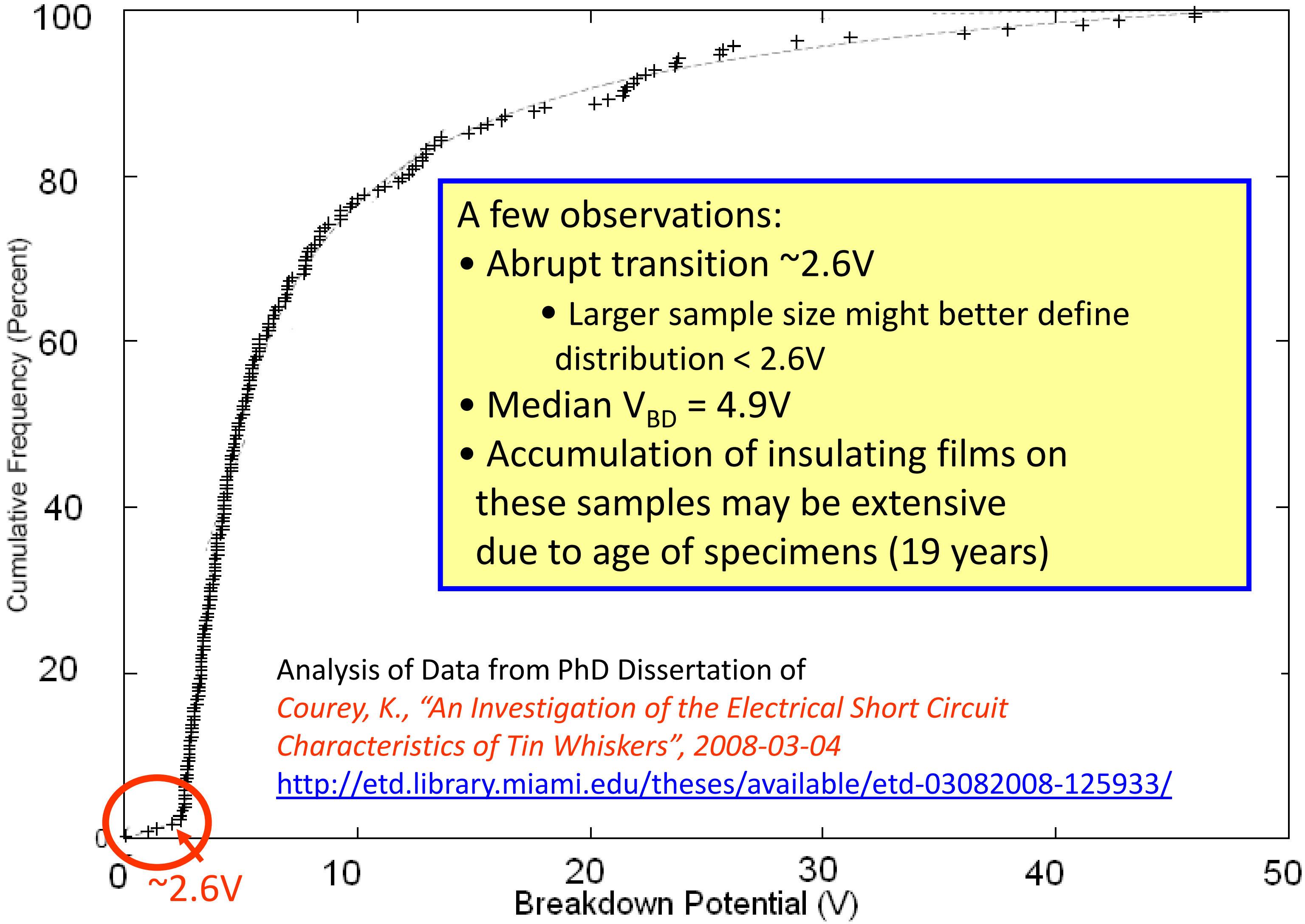
- Electrically insulating films form within hours on metal whiskers and adjacent conductors
  - Oxides, sulphides, sulphates, chlorides, hydrides, etc.
- These films act as barriers to electrical current flow UNLESS applied voltage exceeds "dielectric breakdown" strength of the combined films
  - Direct **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



Breakdown Potential of Insulating Films

on 200 Tin Whiskers from ~19 Year Old Space Shuttle Hardware

when probed using gold-plated probe



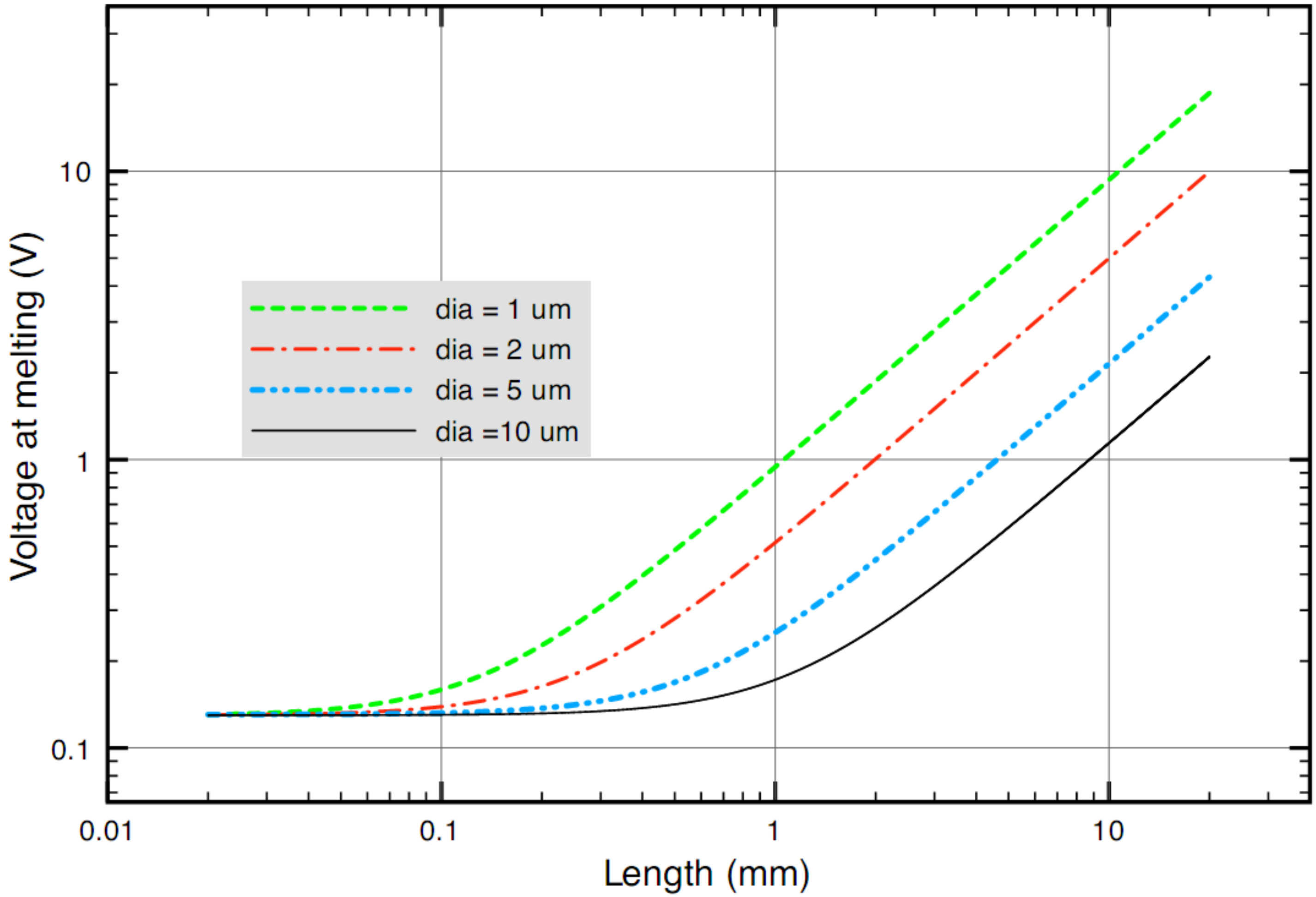
A few observations:

- 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/

Melting Voltage vs. Length for Selected Whisker Diameters

Based on: 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.



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

Charybdis and Scylla:
Electrical Detection of Whisker Short
Melting Whisker vs. Insulating Film Interference

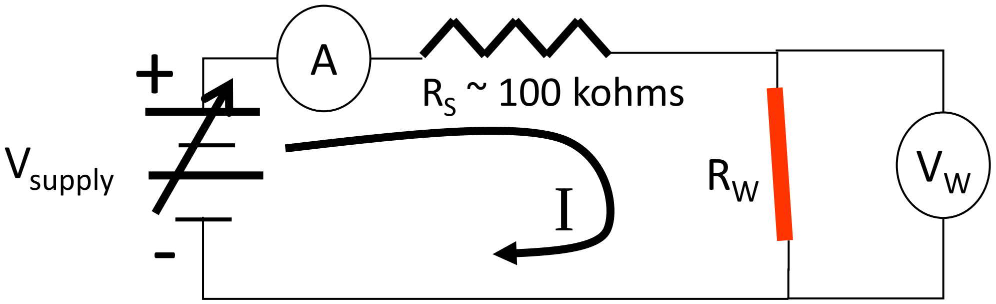
Build Your Own Better Whisker Detector!

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

<u>Circuit to measure *R_w*</u>

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

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



<u>WARNING</u>: "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

Summary

- A tin whisker induced short was responsible for the failure of a 2003 Toyota Camry Accelerator Pedal Position (APP) Sensor based on a Dual Potentiometer Design
  - NHTSA report states warranty analyses identified at least two additional failures due to tin whiskers in similarly designed APP sensors
- Use of pure tin coating can result in the formation of tin whiskers
  - Tin whiskers are to be expected in other dual potentiometer APP sensors that use tin coatings
- Based on published literature, applying less than 2.6V to detect shorting will detect fewer than 2% of bridging whiskers, and most ohm-meters apply less voltage and do not excite a short during the time of investigation
  - This also applies to many other circuits: they survive whiskers by failing to break down the oxide
- Use of an alternate circuit described herein increases the probability to detect and preserve the tin whisker short
  - Care should be taken not to damage the circuit or part under test with the measurement technique