An Empirical Model for Estimating the Probability of Electrical Short Circuits from Tin Whiskers – Part II

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- This presentation summarizes the research presented in the articles titled:

  Tin Whisker Electrical Short Circuit Characteristics—Part II, Courey, K. J.; Asfour, S. S.; Onar, A.; Bayliss, J. A.; Ludwig, L. L.; Zapata, M. C.; Electronics Packaging Manufacturing, IEEE Transactions on, Volume 32, Issue 1, Jan. 2009, Page(s): 41-48

  Tin Whisker Electrical Short Circuit Characteristics—Part I, Courey, K. J.; Asfour, S. S.; Bayliss, J. A.; Ludwig, L. L.; Zapata, M. C.; Electronics Packaging Manufacturing, IEEE Transactions on, Volume 31, Issue 1, Jan. 2008, Page(s): 32-40

Tin Whisker Characteristics

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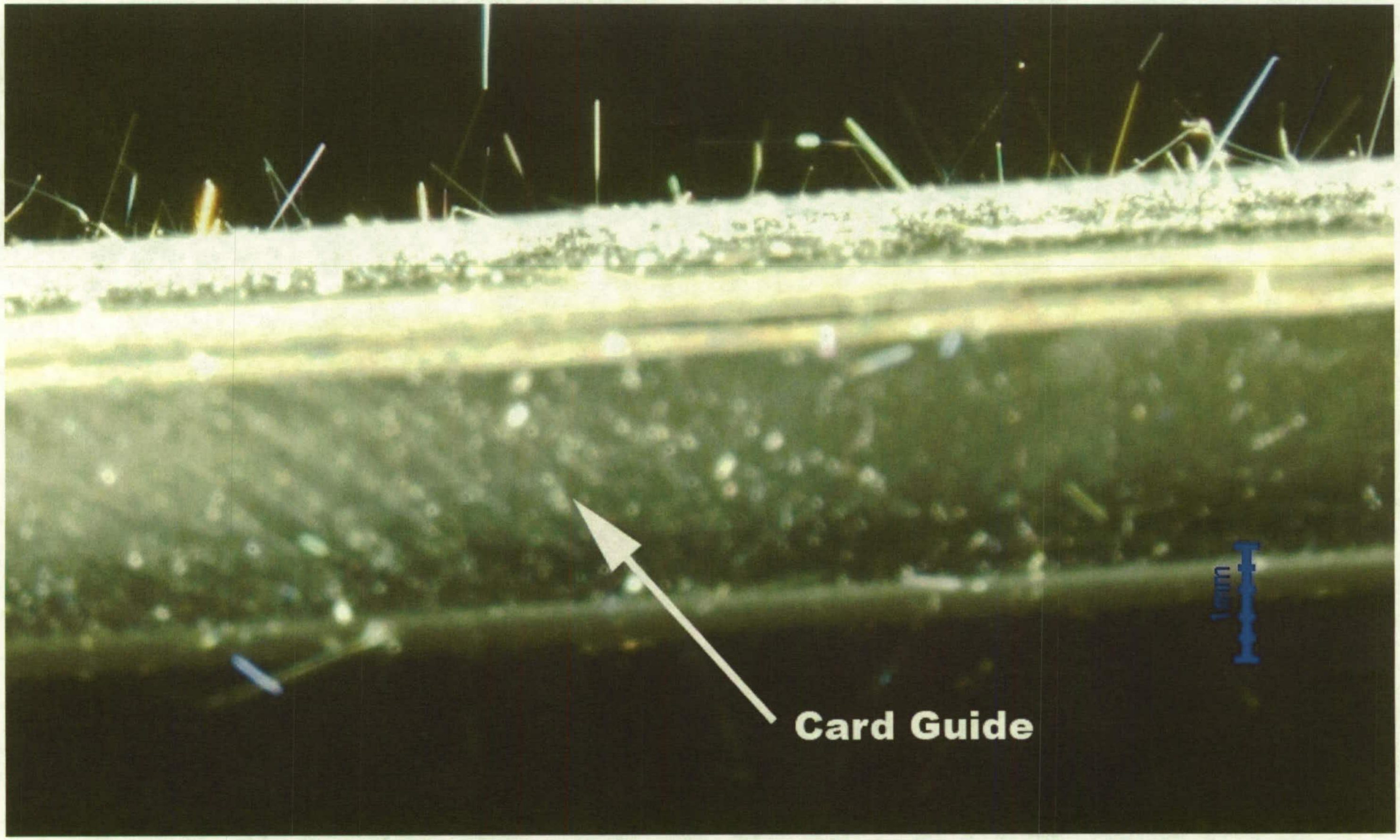
- Metal Whiskers are crystal structures that can grow from plated surfaces, most commonly Tin, Zinc or Cadmium [Leidecker & Brusse]
- Length - Typically Less Than 1mm, some longer than 10mm [Leidecker & Brusse]
- Diameter - Between 0.006µm and 10µm, typical ~ 1µm
- Shapes - Straight, Kinked, Curved [Leidecker & Brusse]
- Failure modes - Permanent and Temporary Electrical Short Circuits, Debris/Contamination, Metal Vapor Arcing [Leidecker & Brusse]

Card Guide 22 from Ascent Thrust Vector Controller (ATVC) 31



Current Assumption in Risk Models

- In the published simulations it is assumed that physical contact between a whisker and an exposed contact results in an electrical short
- This conservative assumption was made because the probability of an electrical short circuit from free tin whiskers had not yet been determined

Contact Resistance

- Contact resistance is the sum of the constriction resistance and the film resistance [R. Holm & Holm]
  - When two surfaces touch, only a small portion of the area actually makes contact due to unevenness in the surfaces [R. Holm & Holm]
    - Current flow is constricted through the smaller area resulting in a constriction resistance [R. Holm & Holm]
  - Film resistance is due to the build up of tarnish films (oxides, etc.) on the contact surfaces that act in a nearly insulating manner [R. Holm & Holm]

Objective

- To develop an empirical model to quantify the probability of occurrence of an electrical short circuit from tin whiskers bridging adjacent contacts as a function of voltage

Methodology

- To determine when a tin whisker's contact resistance breaks down, the voltage level at the transition to metallic conduction current must be recorded
- To determine the breakdown voltage of a tin whisker a micromanipulator probe was brought into contact with the side of the tin whisker growing from a tin-plated beryllium copper card guide

Methodology - Micromanipulator probe touching tin whisker growing from the card guide

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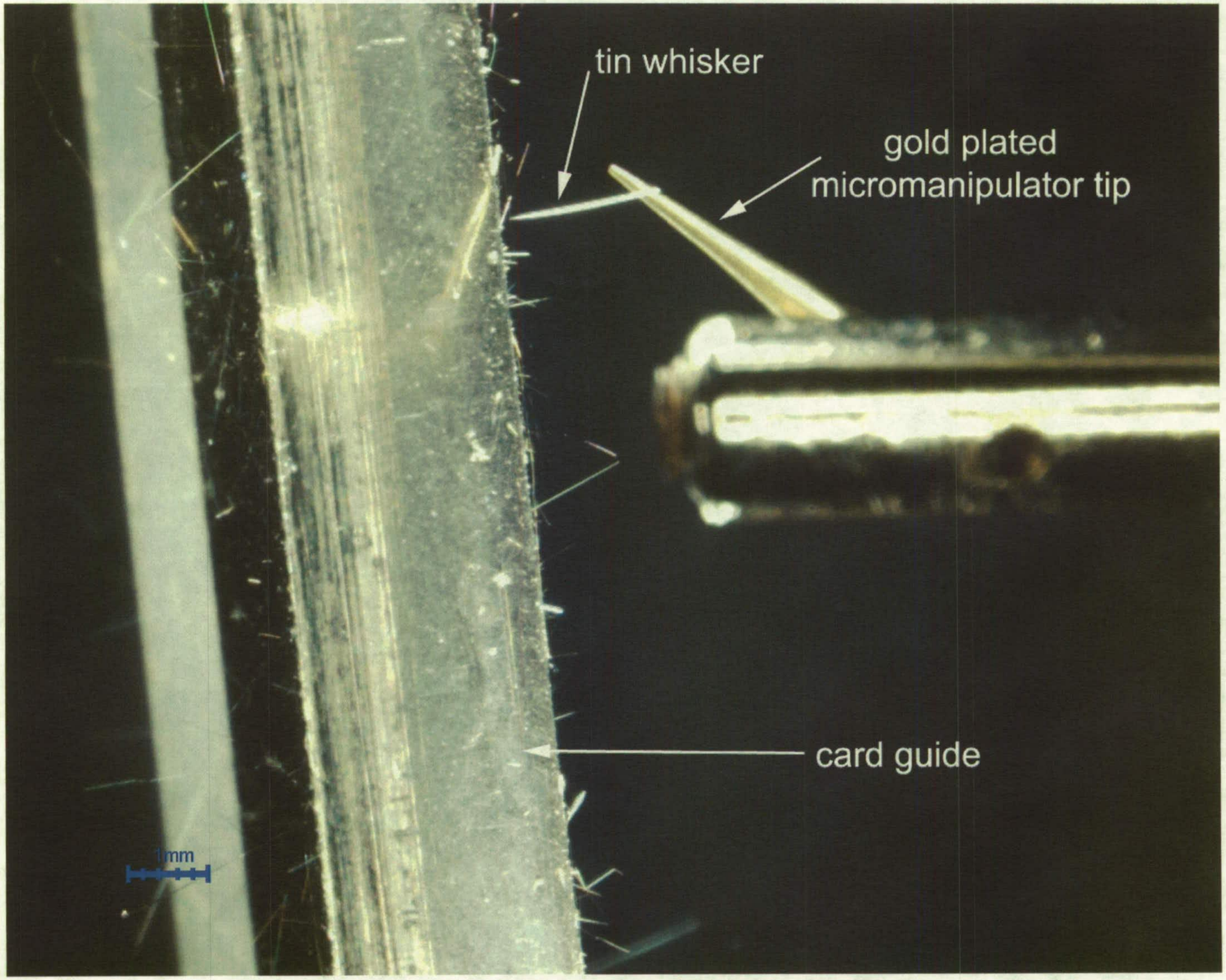
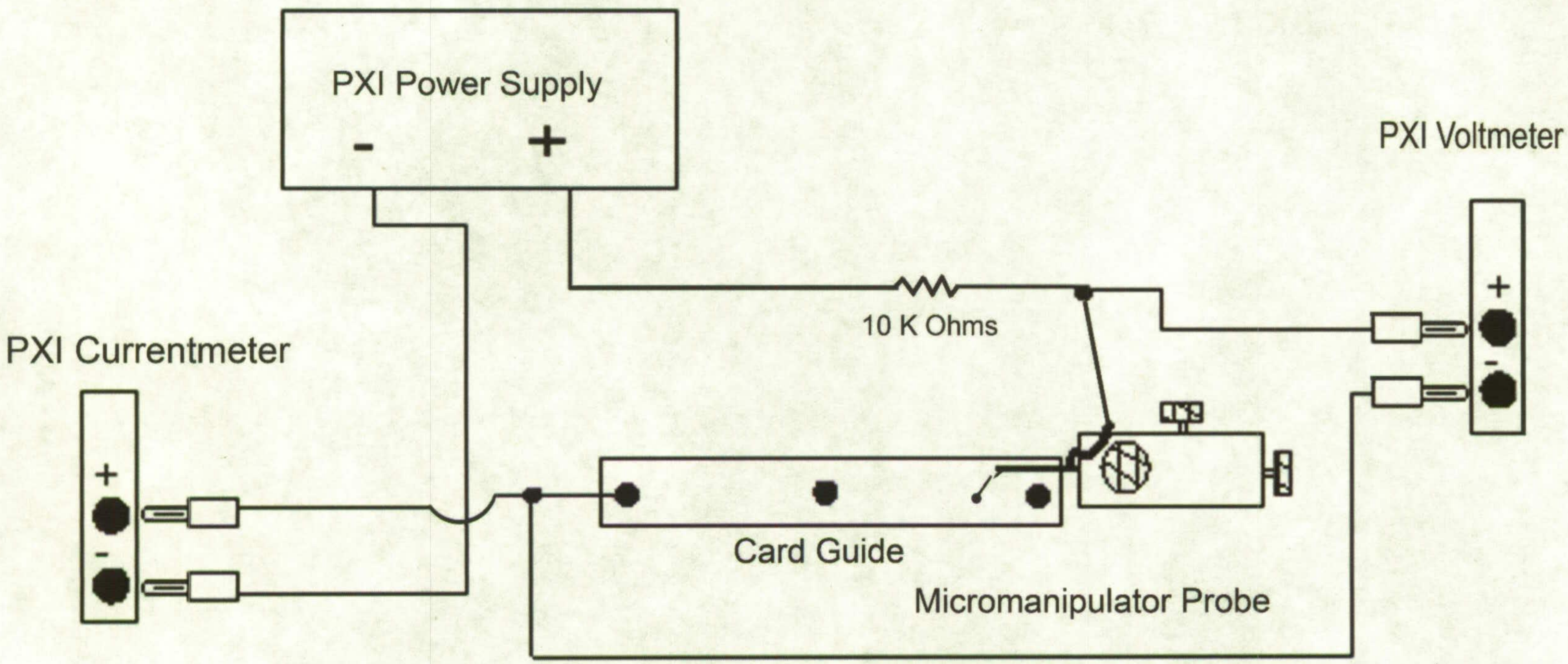


Methodology

- Data Acquisition (DAQ) software was written using LabVIEW® to automate both the incrementing of power supply voltage changes as well as the gathering and recording of the voltage and current data for each of the tin whiskers
- Once contact was established, as determined with an optical microscope, the power supply voltage was increased from 0 to 45 volts direct current (vdc) in 0.1 vdc increments
- Validation of the automated test station was performed by substituting a calibrated resistor decade box for the micromanipulator, whisker and card guide

Automated Tin Whisker Test Fixture

PXI Instrumentation Running a Labview Program



Methodology – Tin Whisker Test Station

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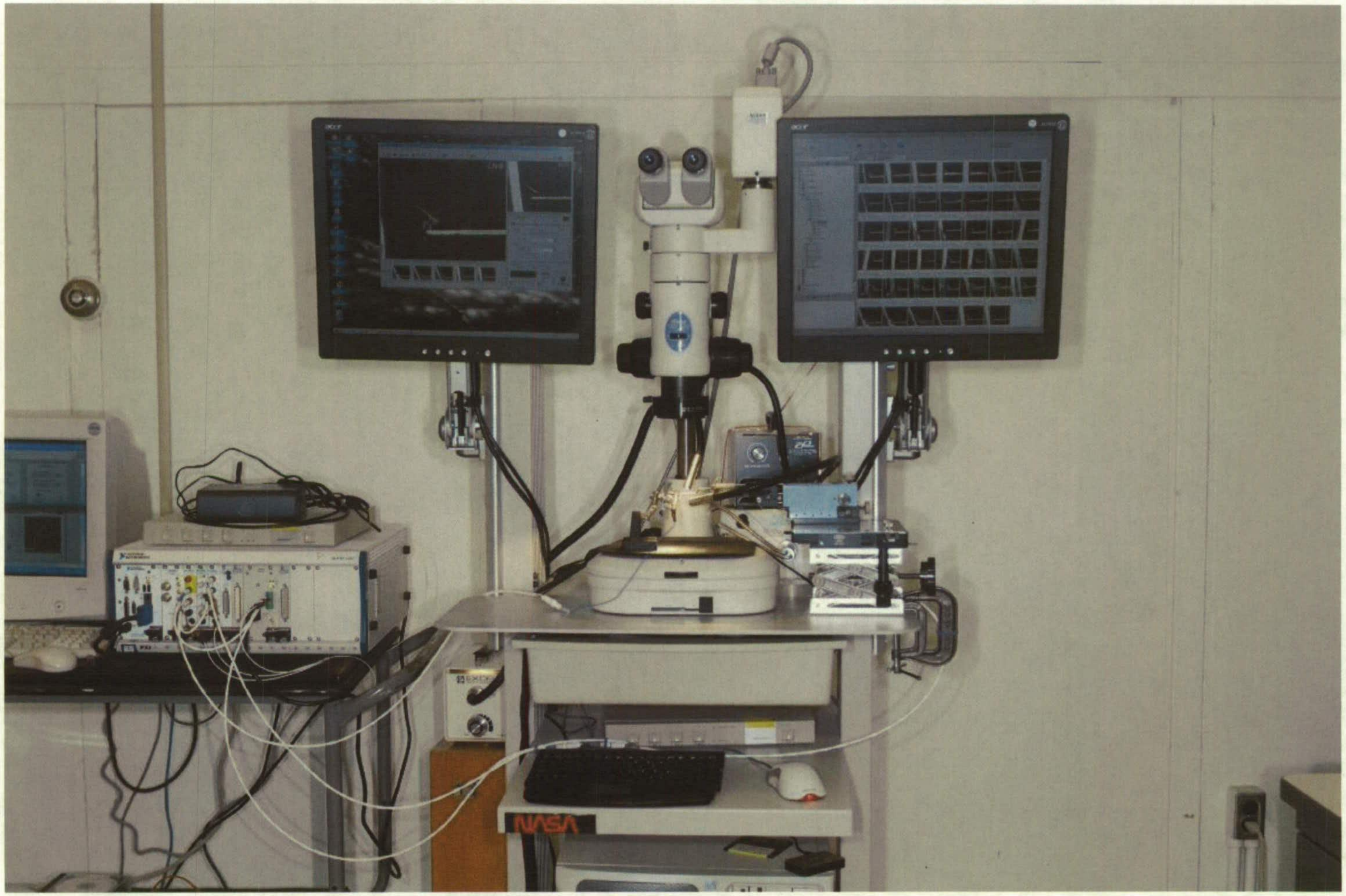
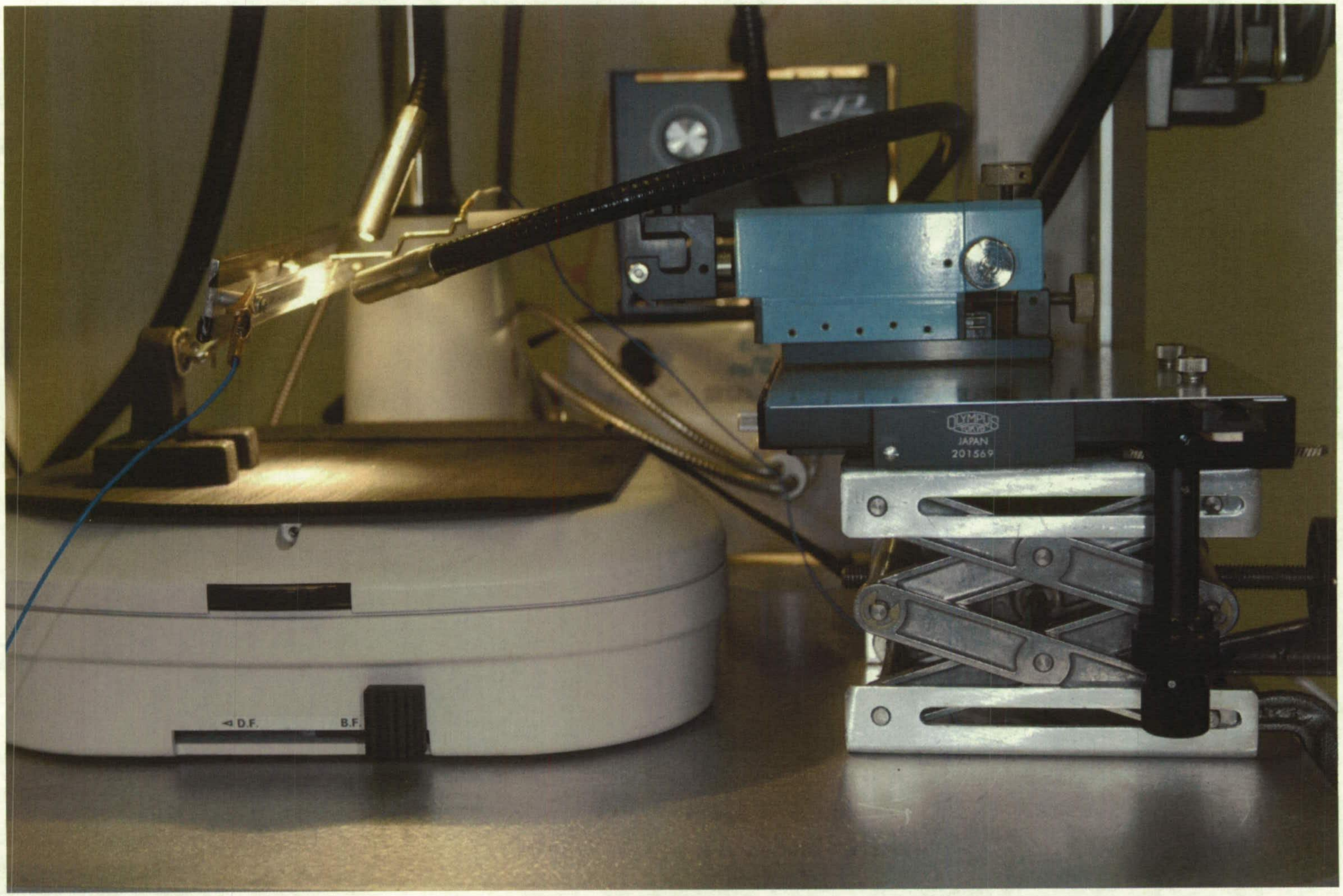


Methodology – Test Station Close Up



Methodology – Breakdown Voltage

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- The breakdown voltage for each whisker was determined from the graphs of recorded current and voltage data
- Although the software had originally been written to stop recording data after the film resistance broke down as determined by the change in whisker current, it was decided to run the whiskers to the full range of the test, 0 – 45 vdc, to observe their behavior
- An interesting benefit of running the test from 0 - 45 vdc for all of the whiskers was the opportunity to witness the difference in transitions
- There were three different transition categories: Single, Multiple, and Multiple with intermittent contact

Methodology – Whisker Current

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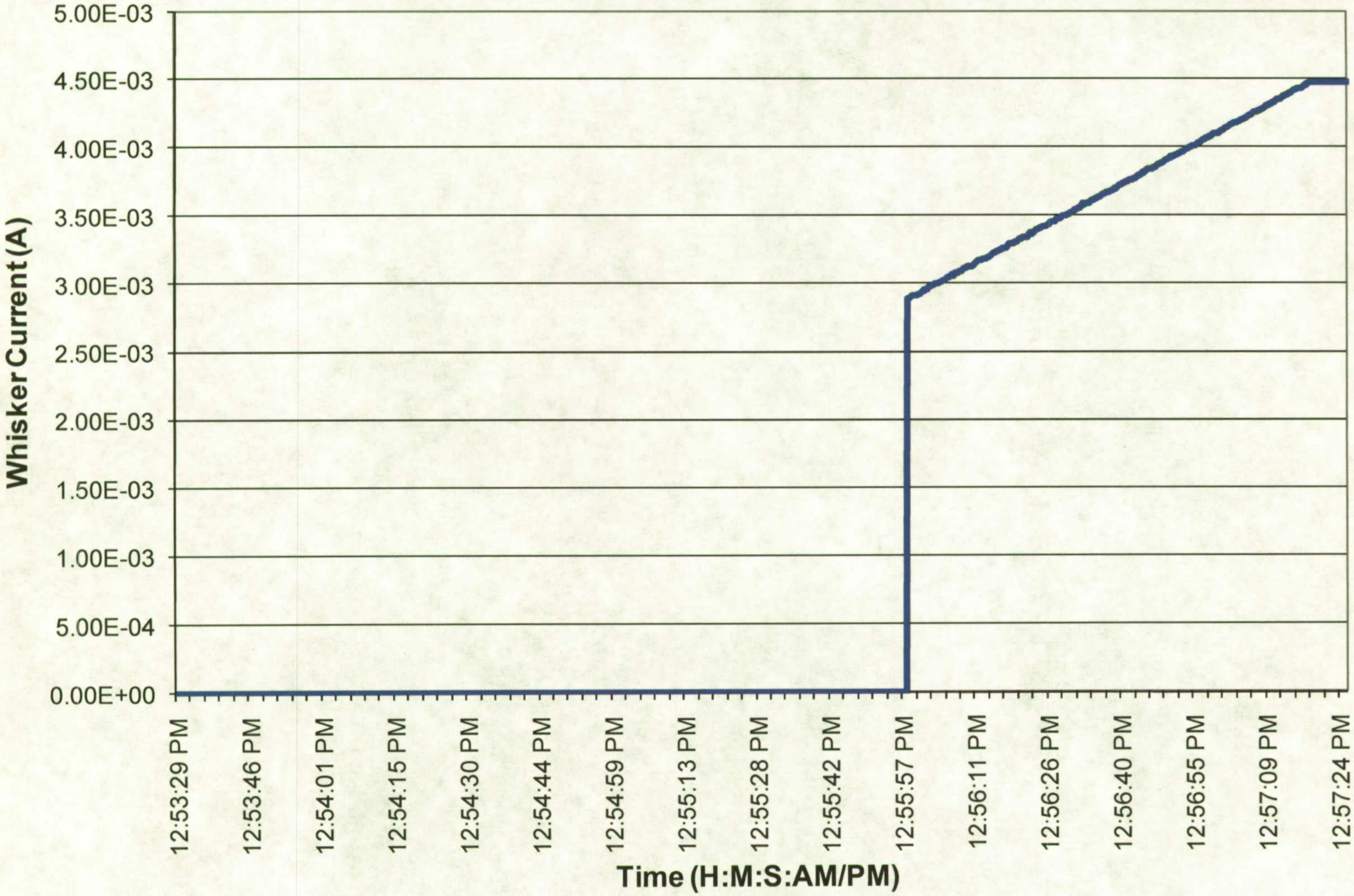
Tin Whisker No. 137 Graph of Current VS. Time (Single Transition)



Methodology – Whisker Voltage

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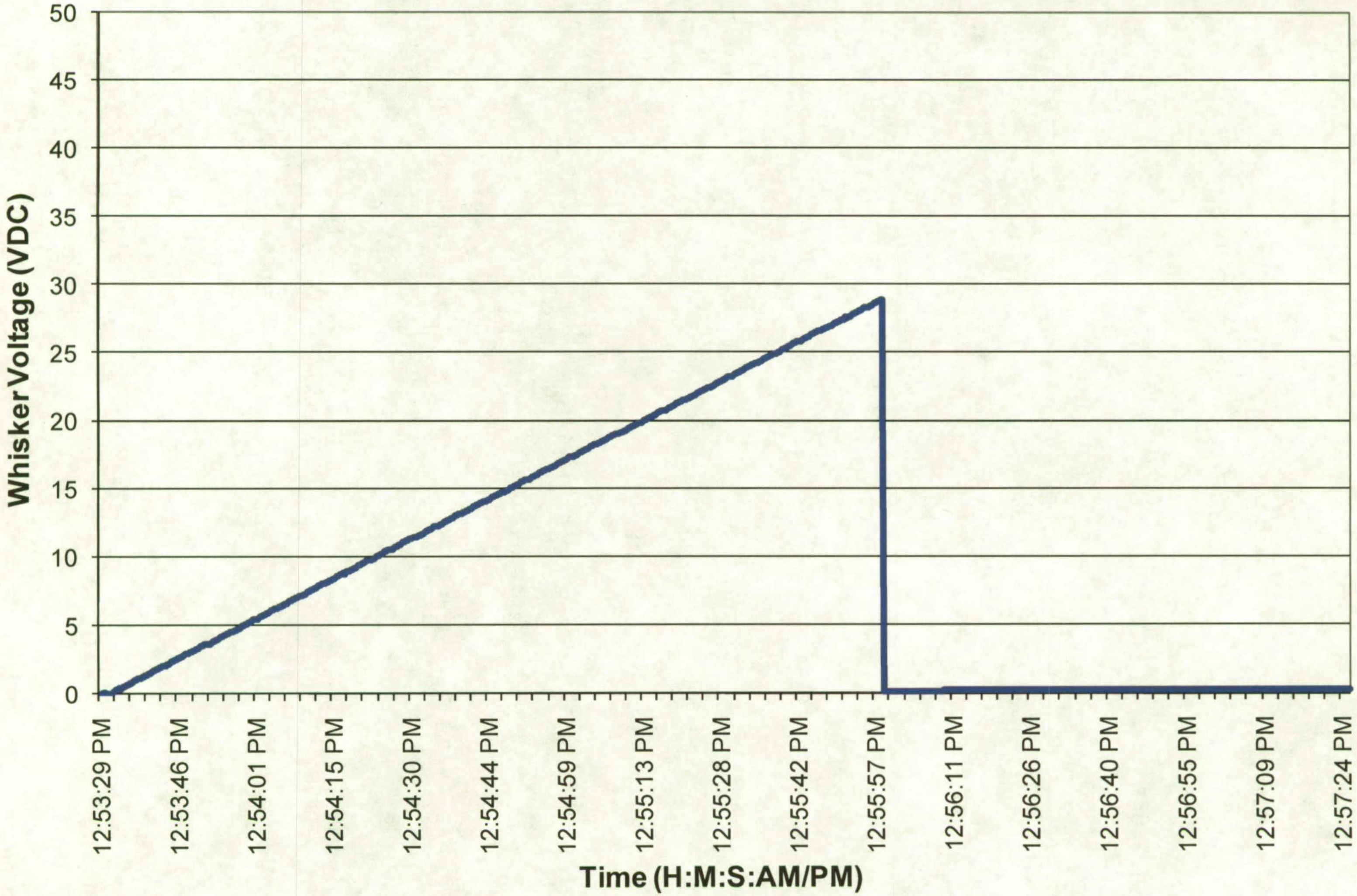
Tin Whisker No. 137 Graph of Voltage VS. Time (Single Transition)



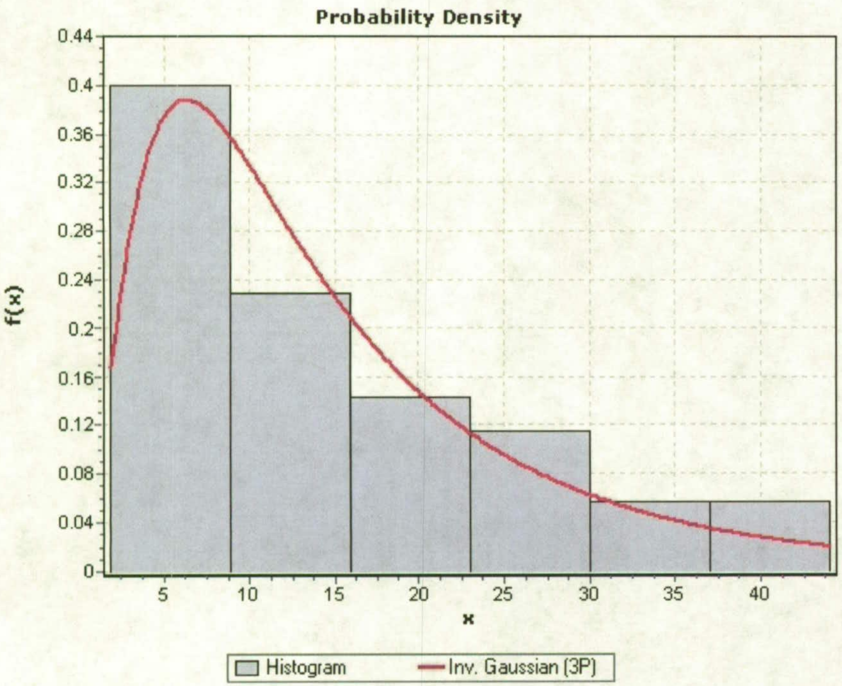
- The breakdown voltages for all 35 whiskers were recorded and analyzed
- Probability-Probability (P-P) plots were used to determine how well a specific model fits the observed data
- The Kolmogorov-Smirnov test was used to further analyze the best fit
- The EasyFit® distribution fitting software tested over 40 different distributions before the 3-Parameter Inverse Gaussian was selected as the best fit

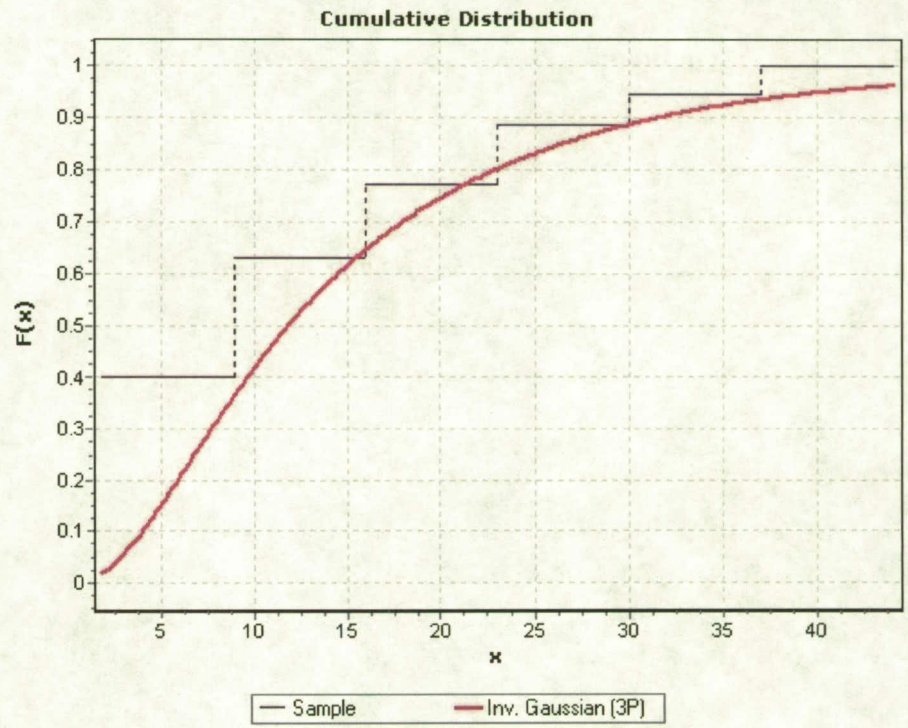
First Experiment - Three Parameter Inverse Gaussian Distribution

- The values for the Three Parameter Inverse Gaussian Distribution are $\lambda = 31.977$, $\mu = 17.571$, $\gamma = -1.9716$, and x = the applied voltage
- The Probability Density Function for the Three Parameter Inverse Gaussian Distribution is shown in the following equation:

$$f(x) = \sqrt{\frac{\lambda}{2\pi(x-\gamma)^3}} \exp\left(-\frac{\lambda(x-\gamma-\mu)^2}{2\mu^2(x-\gamma)}\right)$$

Probability Density Function and Cumulative Distribution Function for the Three Parameter Inverse Gaussian Distribution





X = applied voltage

Second Experiment - Improvements

- The following improvements were added to the second experiment :
  - •A larger sample size of 200 whiskers
  - •Random card guide selection
  - •Improved grounding
  - •Added shielding to wires
  - •Gold plated tungsten micromanipulator tips
  - •Software was written to select the breakdown voltages to ensure consistency
  - •Fabricated a card guide holder for solderer's helper

Second Experiment - Data Analysis

- The breakdown voltages for all 200 whiskers were recorded and analyzed
- Minitab was used instead of EasyFit because Minitab contained a feature to address censored data
- Probability-Probability (P-P) plots were used to determine how well a specific model fits the observed data
- The Anderson-Darling test and the Correlation Coefficient were used to further analyze the best fit
- The Minitab software tested 11 different distributions before the lognormal was selected as the best fit

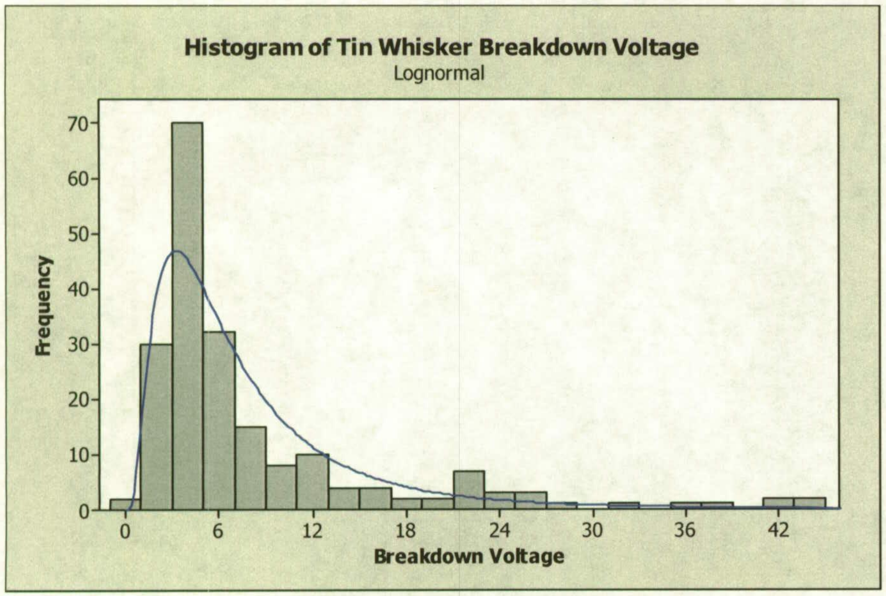
Second Experiment - Data Analysis

- The values for the Lognormal distribution are the location parameter = μ = 1.77895, and the scale parameter = σ = 0.776320, and x = the applied voltage
- The Probability Density Function for the Lognormal distribution is shown in the following equation:

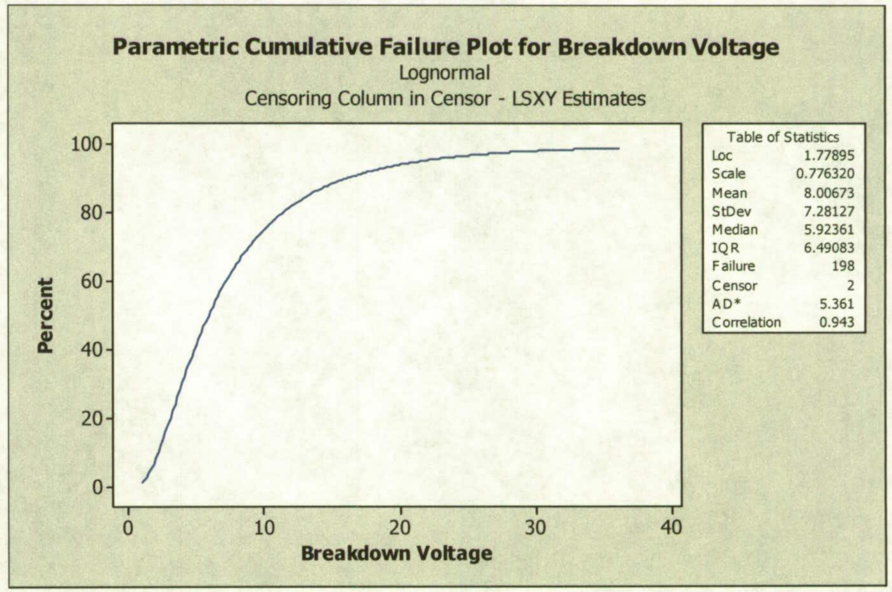
$$f(x) = \frac{1}{\sigma x \sqrt{2\pi}} \exp\left(-\frac{\left(\ln(x) - \mu\right)^2}{2\sigma^2} \right)$$

Probability Density Function and Cumulative Distribution Function for the Lognormal Distribution

Probability Density Function



Cumulative Distribution Function



Comparison of Results

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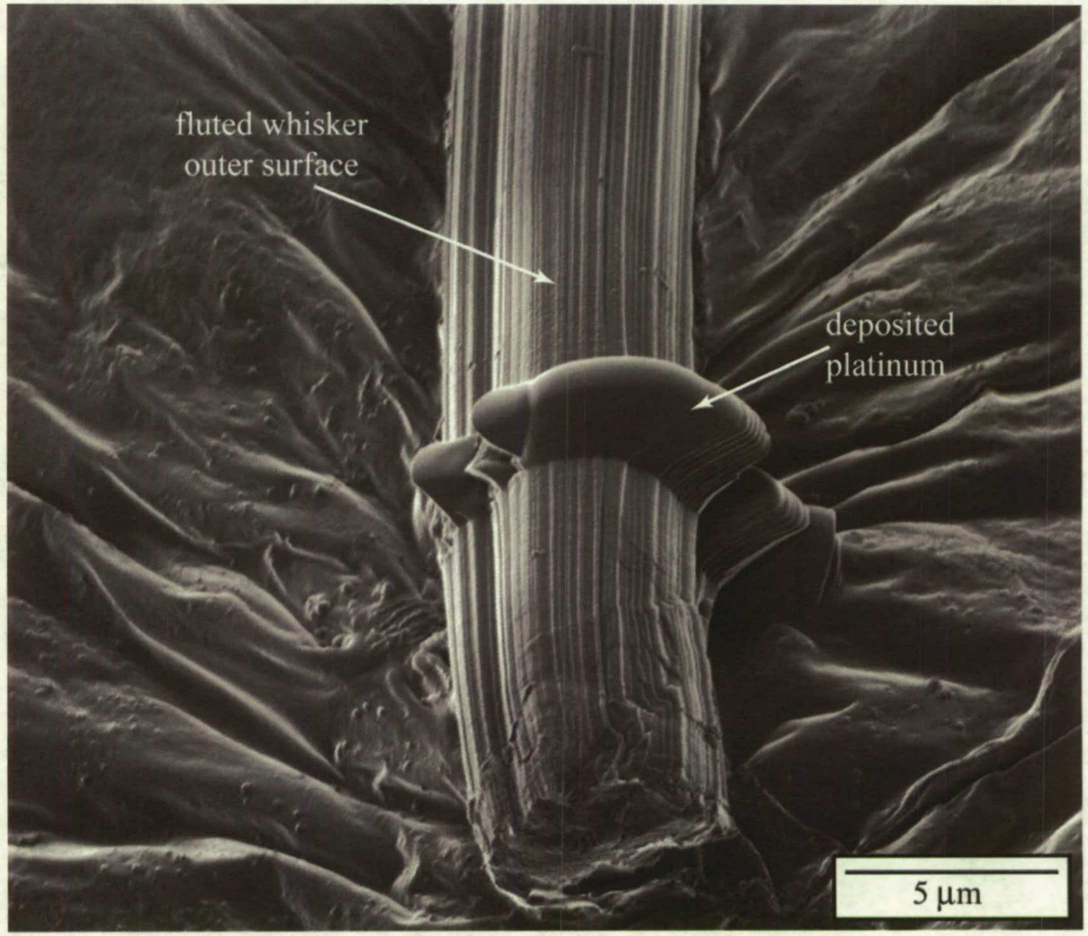
- First Experiment - mean voltage were a short will occur is 15.59 vdc
- Second Experiment - mean voltage were a short will occur is 8.01 vdc
- The shift in the mean can be explained partially by the change to a gold-plated probe tip in the second experiment, thus eliminating the effect of oxides on the probe tip
- Inverse Gaussian and lognormal are similar in shape
- Analyzed data from first experiment using Minitab and lognormal was best fit - both experiments are consistent
- First Experiment - 33 of the 35 tin whiskers tested (~94%) conducted up to 4.5 mA
- Second Experiment - 158 of the 200 tin whiskers tested (~79%) conducted up to 4.5 mA

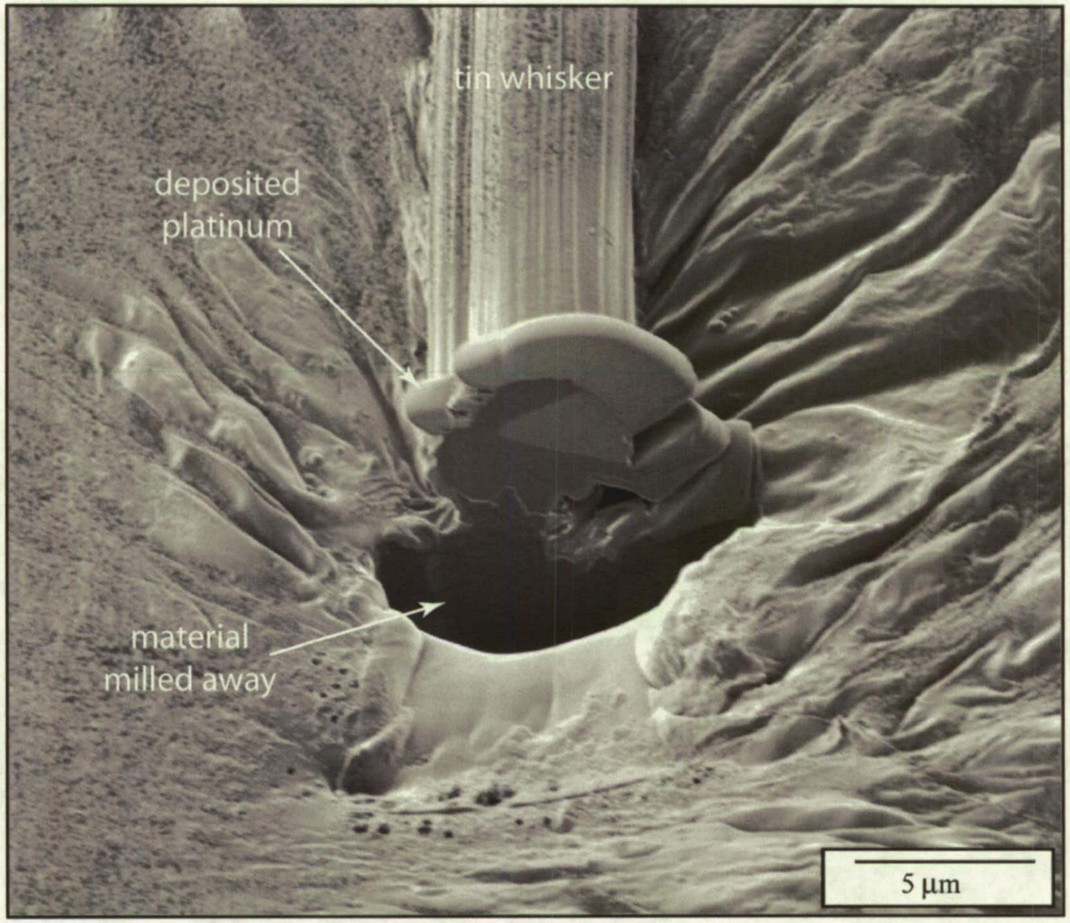
- One of the factors that contributes to film resistance is the oxide layer that forms on the tin whisker
- To study the oxide layer, it was necessary to section a few tin whiskers

- FIB image of tin whisker removed from card guide shows a fluted outer surface
- Platinum was deposited on the surface prior to sectioning in order to preserve the region of interest



FIB image (NASA/UCF)

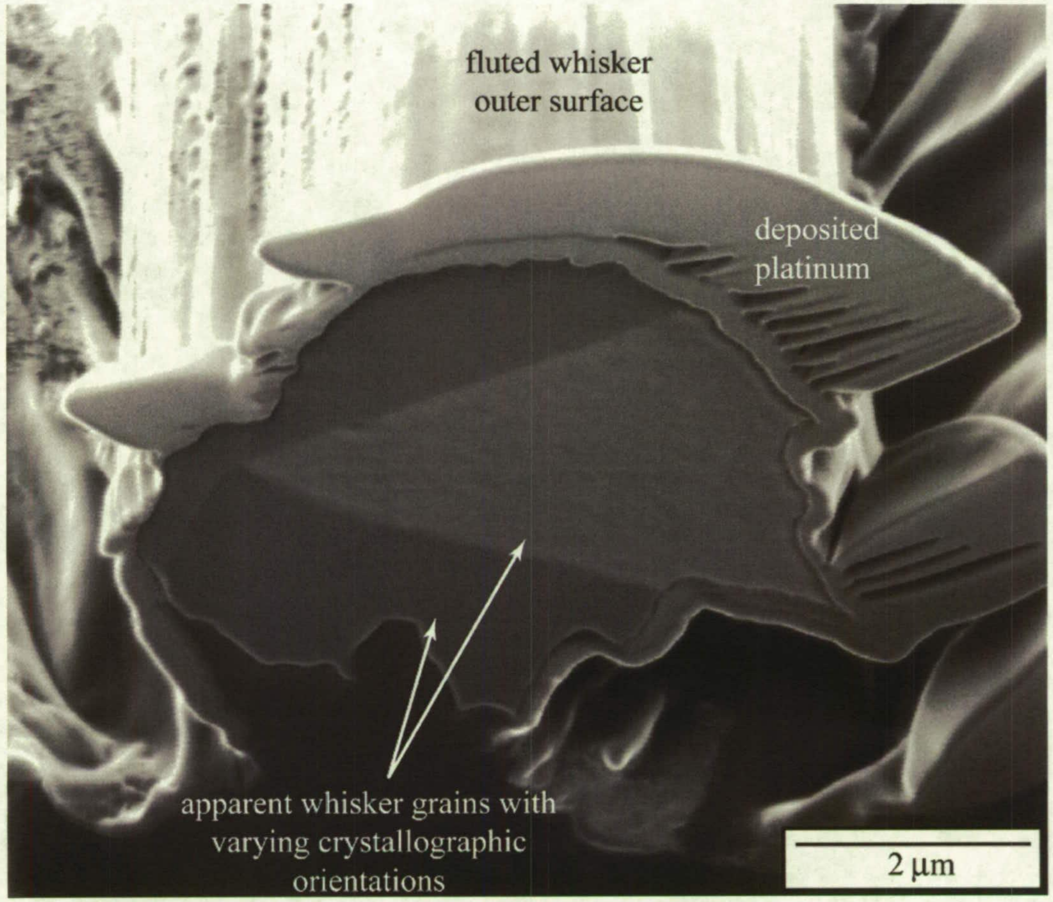
- The gallium ion beam was used to mill away sufficient whisker material to obtain a cross section normal to the whisker's growth direction
- The FIB cross section facilitated the examination of the crystallographic orientations



FIB image (NASA/UCF)

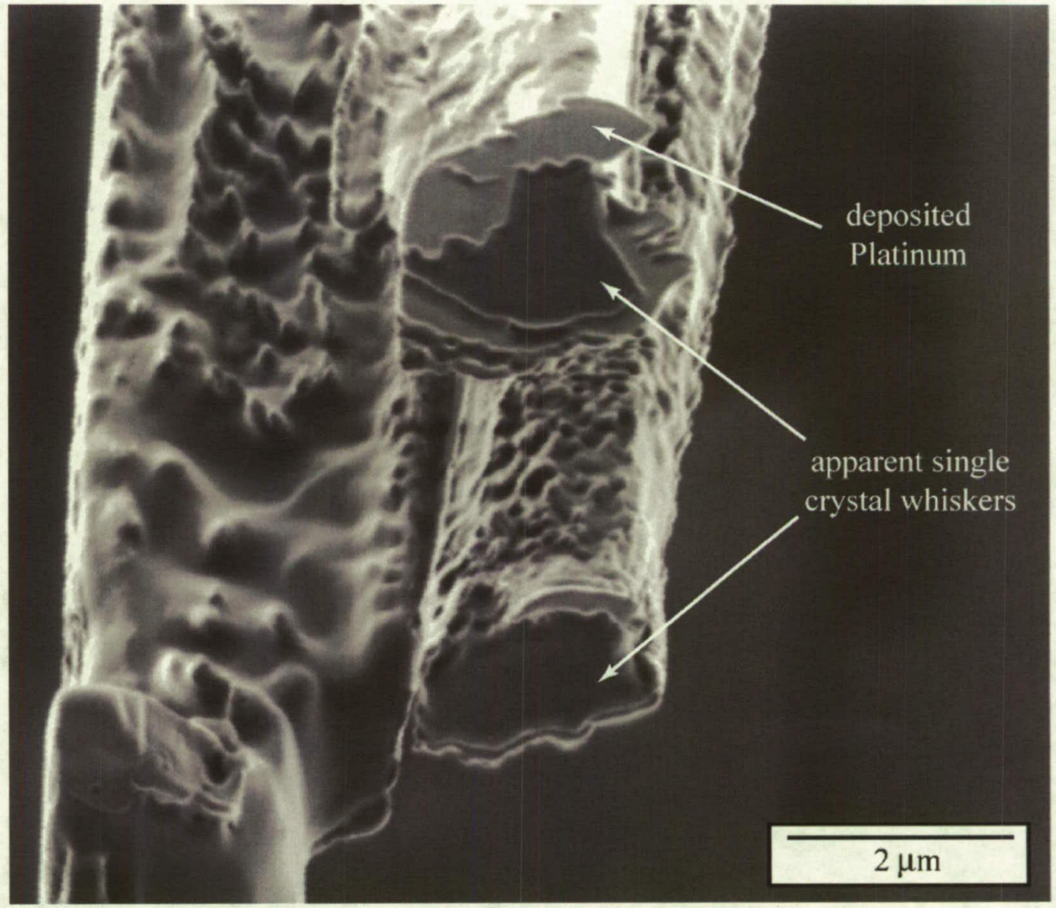
Materials Analysis - Focused Ion Beam (FIB) Analysis

- One of the three tin whiskers studied here was found with what appeared to be grains with varying crystallographic orientations
- While polycrystalline tin whiskers have been seen before, in the majority of literature tin whiskers were described as single crystals



FIB Image was taken 52º from horizontal
(NASA/UCF)

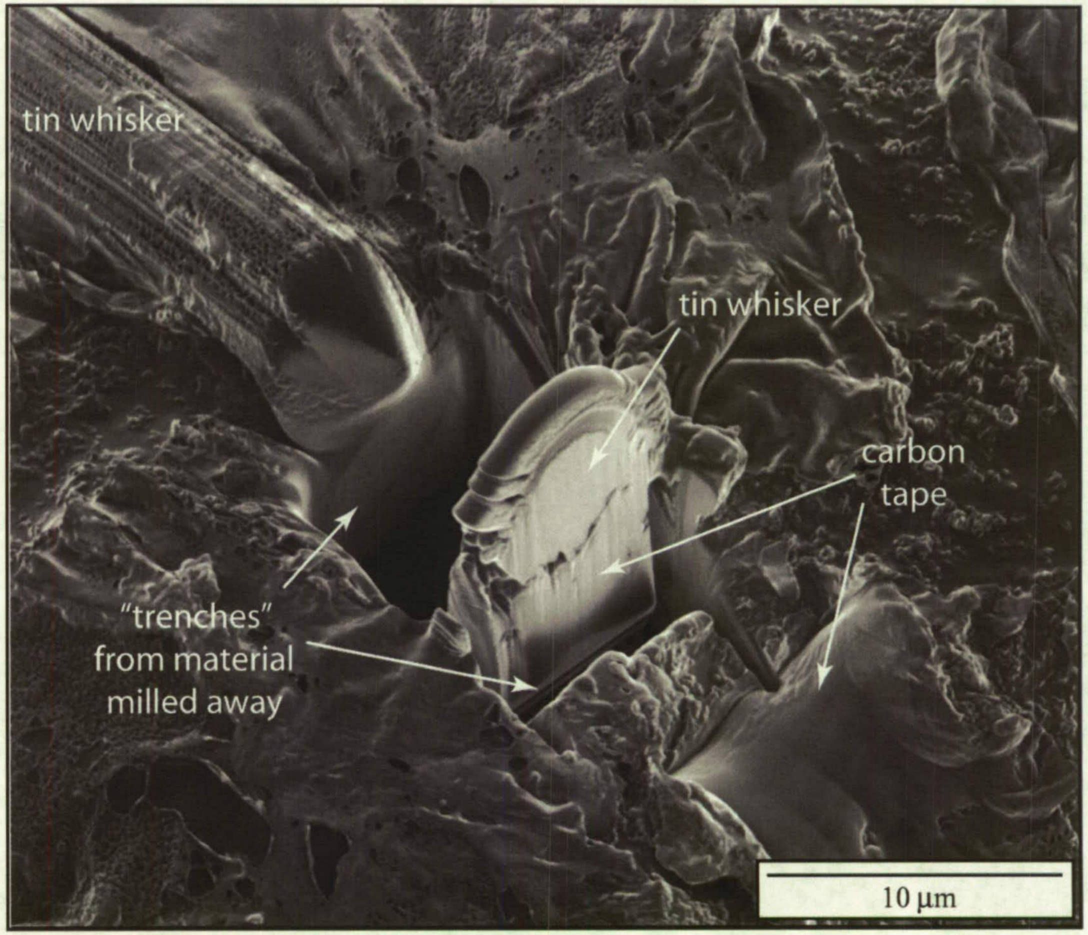
- FIB image of two as-sectioned tin whiskers that exhibited the expected single-crystal cross section.



FIB Image was taken 52º from horizontal (NASA/UCF)

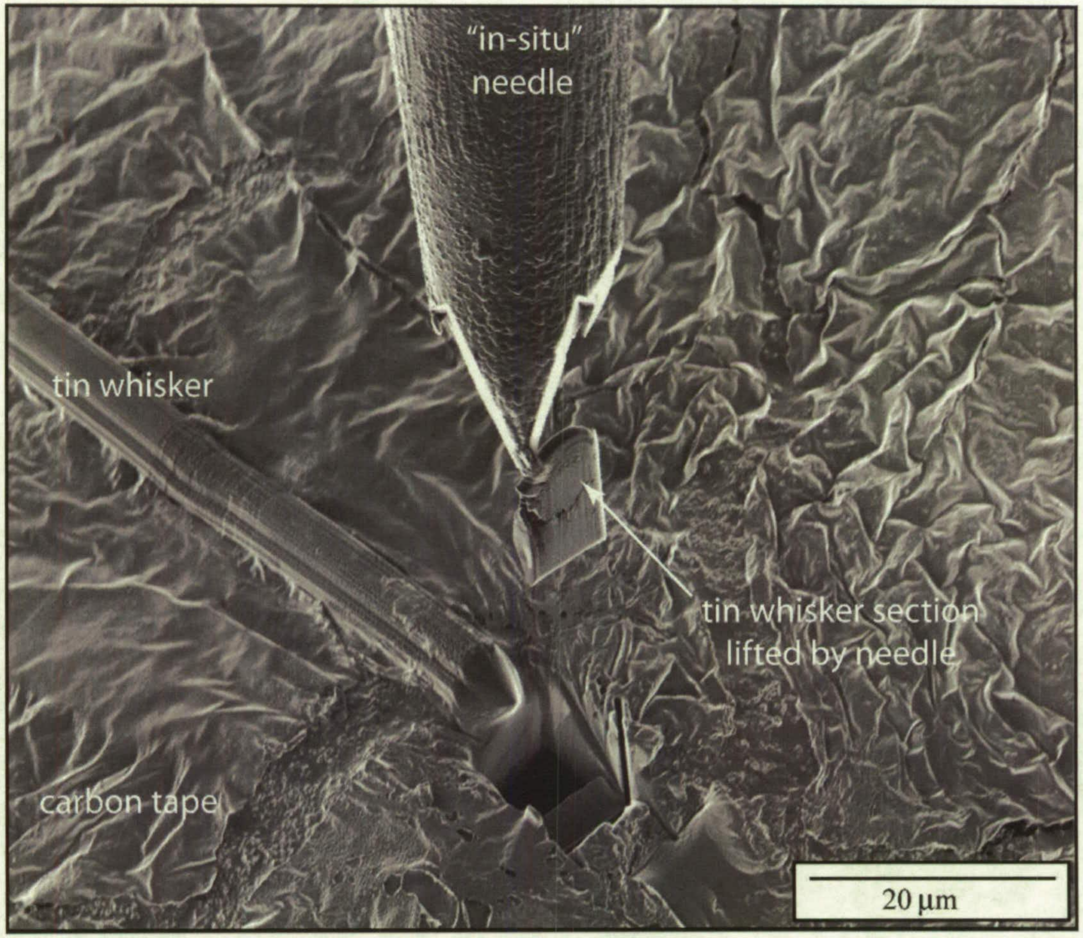
- A scanning electron microscope (SEM) was used for higher-magnification imaging and elemental analysis
- We were not able to identify the oxide layer as originally planned with the techniques and equipment that were used
- However, we were able to find what appeared to be a rare polycrystalline tin whisker
- A focused ion beam (FIB) was used to prepare a sample for Transmission Electron Microscopy (TEM) examination

- FIB image showing how the tin whisker is prepared by ion beam milling for TEM analysis



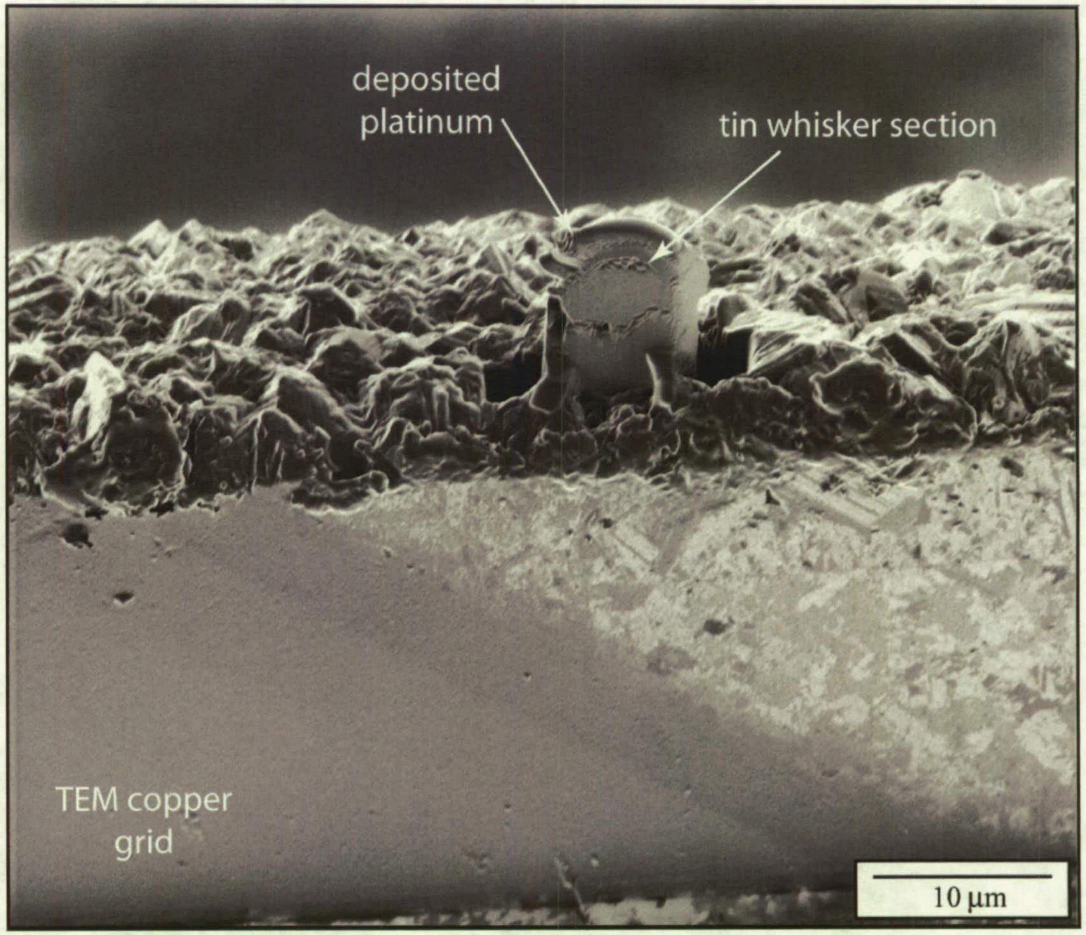
FIB image (NASA/UCF)

- FIB image showing removal of tin whisker section using the in-situ needle



FIB image of tin whisker (NASA/UCF)

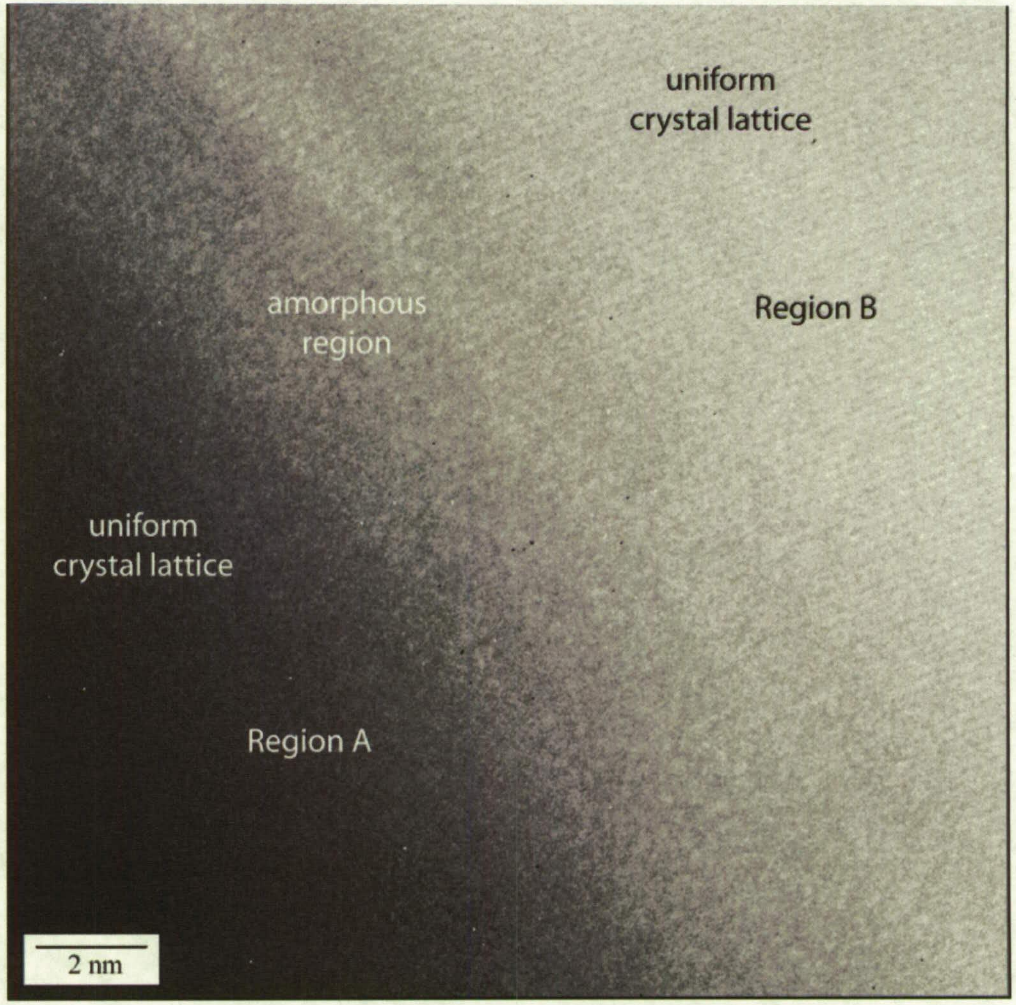
- FIB image of tin whisker section mounted on copper grid for TEM



FIB image (NASA/UCF)

Materials Analysis - High-resolution TEM image

- High-resolution TEM image of the amorphous region in the polycrystalline tin whisker between the uniform crystal lattices of regions A and B



TEM image (NASA/UCF)

Materials Analysis - Selected Area Diffraction Patterns (SADPs)

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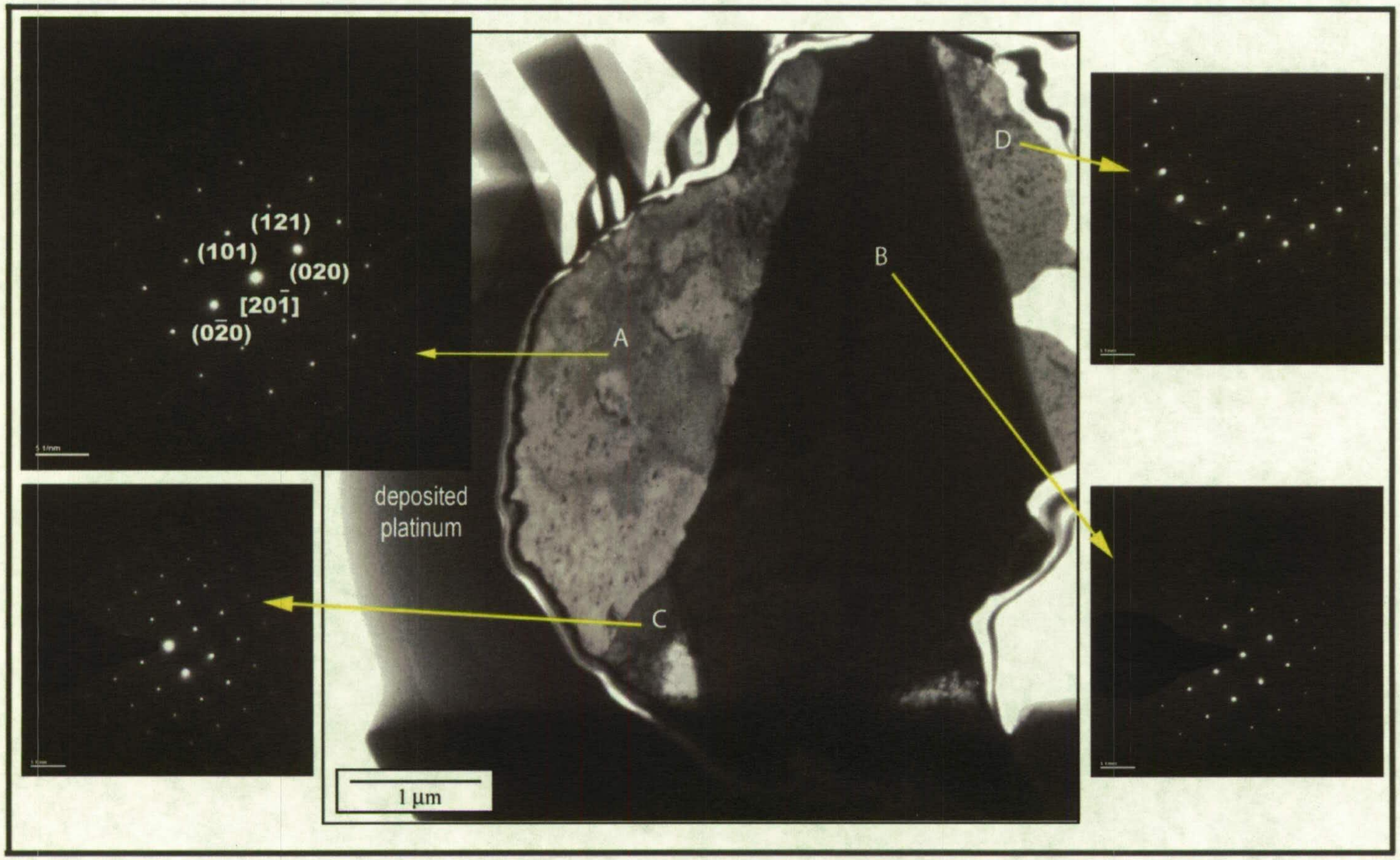
- The Selected Area Diffraction Patterns (SADPs) were taken at four site specific regions, labeled A, B, C and D as shown on the next page
- The SADPs obtained from regions A, B, C and D indexed to the tetragonal crystal structure of tin in the beam direction (refer to figure on the next page)
- Region D was misoriented approximately 2 degrees with respect to region A in the (121) direction
- Regions A, B and C were nearly identical with one another

Bright field TEM image of the polycrystalline tin whisker and nomenclature used to identify the various regions (A-D



TEM and SADP images (NASA/UCF)

- The polycrystalline structure of the studied whisker is shown by the contrast in regions A, B, C, and D in the bright field TEM image, the misorientation of region D with respect to region A shown in the SADPs, and the amorphous region between the uniform crystal lattices of regions A and B, which delineates a grain boundary between the crystals in the high-resolution TEM image

- The purpose of measuring the grain size was to quantitatively determine the finish of the tin plating. Large grain matte finish has been classified as having a grain size between 3-8 μm, fine grain matte finish as having a grain size between 1-2 μm, and bright finish as having a grain size < 1 μm [Shetty]
- Using a modified line-intercept method, the average grain size for the card guide from ATVC S/N 31 was estimated to be 0.350 μm (350 nm), and the average grain size for the card guide from ATVC S/N 33 was estimated to be 0.290 μm (290 nm)
- Based on the aforementioned criteria, the tin plating used in both ATVC S/N 31 and 33 can be classified as bright finish
- While tin finish was not a variable in this experiment, it is a point of interest because bright tin finishes have been associated with greater tin whisker growth than matte tin finishes [Smetana] [Osterman]

Materials Analysis - Card Guide FIB Cross-section

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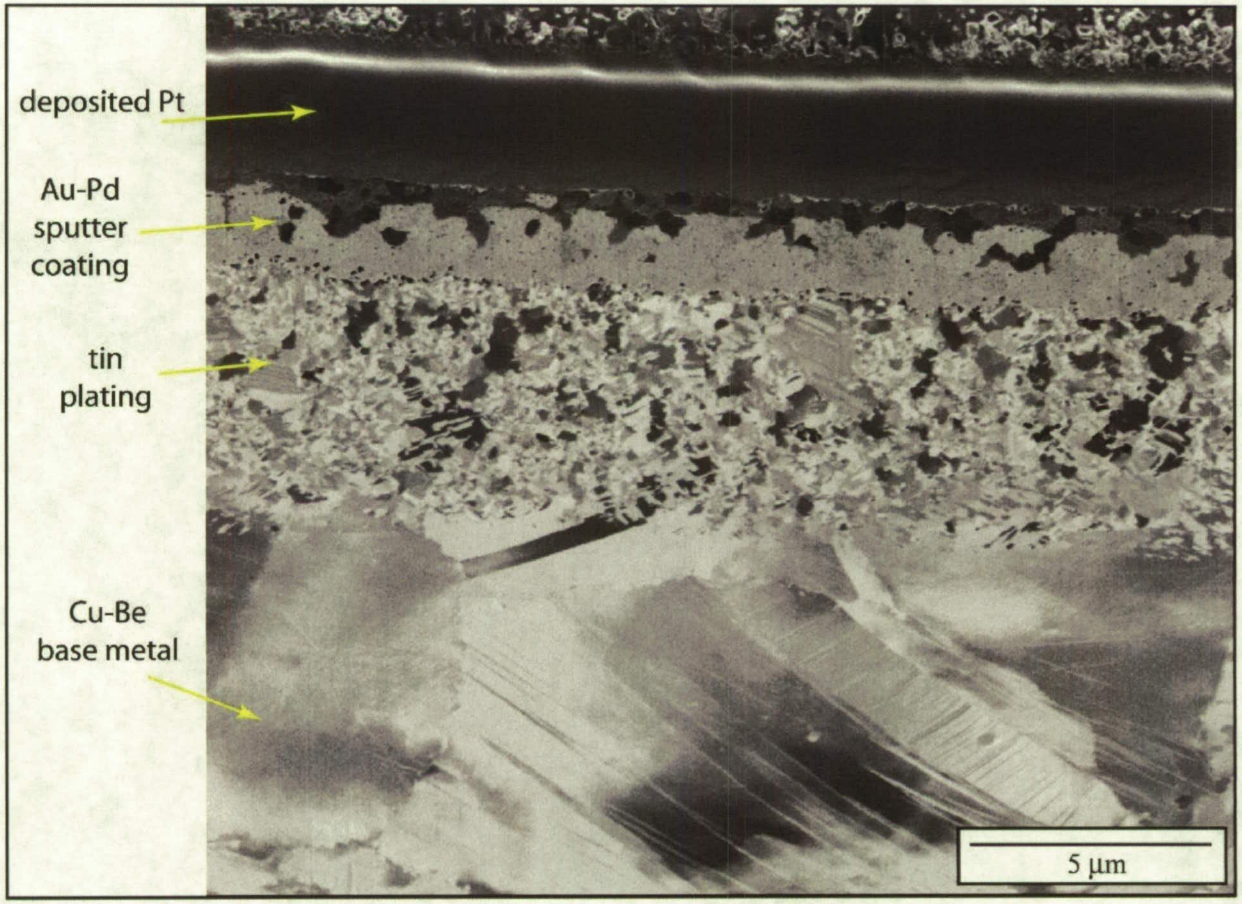
- FIB ion channeling image of card guide 16 (ATVC S/N 31) cross section showing the distinct layers studied



FIB image (NASA/UCF)

Limitations

- Limitations of the this experiment included:
  - The number of conducting surfaces
  - The difference and variation between force applied by gravity and the force applied by the micromanipulator probe
  - Power supply range 0-45 vdc
  - Sample size
  - Whisker characteristics (thickness, length, shape)
  - Oxide layer thickness
  - Contact area

Conclusion

- In this experiment, an empirical model to quantify the probability of occurrence of an electrical short circuit from tin whiskers as a function of voltage was developed
- This empirical model can be used to improve existing risk simulation models
- FIB and TEM images of a tin whisker confirm the rare polycrystalline structure on one of the three whiskers studied
- FIB cross-section of the card guides verified that the tin finish was bright tin

Future Work

- Effect of the following variables on tin whisker shorting:
  - Applied Pressure
  - Acceleration
  - Whisker Shape
  - Oxidation Layer Thickness
- Free Whisker Test
- Metal Vapor Arcing
- Fusing Current

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