NORTHROP GRUMMAN
DEFINING THE FUTURE

Current Understanding of the Quality and Reliability of Lead-free Tin

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Andrew D. Kostic, Ph. D.
Fellow
Northrop Grumman Corporation

Lead-Free Movement Background

- **In 1985, the Swedish government enacted the Chemical Products Act based on the "Precautionary Principle"**
  – Precautionary Principle: "When an activity raises threats of harm to human health or the environment, precautionary measures should be taken *even if some cause-and-effect relationships are not fully established scientifically."*

WEEE and RoHS Legislation in the EU

- **Fears over *perceived* harm from lead resulted in legislative action in Europe**
- **The European Union (EU) has issued two directives that have caused turmoil in the electronics industry**
  - WEEE (Waste Electrical and Electronic Equipment) mandates recycling
  - RoHS (Restrictions on Hazardous Substances) prohibits certain substances in specific categories of electronic equipment sold in EU member nations
    - Prohibited materials are lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE)
  - Each member state required to issue legislation supporting the directives
- **Laws supporting the directives take effect on July 1, 2006:**
- **Legislation applies to products put on the market in EU countries**
  - Country of origin is irrelevant
  - Exemption for strictly military applications

Expected Lead Reduction

- **A very large (~ $10B) electronics component manufacturer that sells millions of devices all over the world estimates that complete conversion to lead-free products will result in an annual worldwide lead reduction equivalent to only ten automobile batteries.**

Transition Cost

"Intel's ($34.2B) efforts to remove lead from its chips have so far cost the company more than $100 million and there is no clear end in sight to the project's mounting costs"

"the company hopes to be completely lead-free within five years"

Source: http://www.infoworld.com/article/05/03/16/HNleadfreemove_1.html March 16, 2005

No Drop-in Replacement for Tin-lead

- **There are <u>no</u> "drop-in replacements" for tin-lead solder**
- **The <u>entire</u> manufacturing process must be revised to properly apply replacement materials**
- **Industry has not standardized on a replacement for tin/lead solder**
  - Different alloys have different reflow temperatures
  - Various alloys may not interact well
- **Some alloys covered by patents or copyrights**
  - Finished solder joint compositions covered too!

Potential Risks Associated with Lead-Free

- **Mixing technologies during assembly, repair, or upgrade**
  - Difficulty in tracking parts with differing finishes
- **Inability of users to know what type parts they are getting**
  - Plating may be performed by a third or fourth tier supplier
- **Fatigue life not yet comparable to tin-lead**
  - Continuing studies with CALCE, Boeing, IPC, AVSI, …
- **Tin whiskers**
  - Reemergence of a subtle failure mechanism
- **Tin “plague” causing lead-free solder failures in long-term low temperature applications**

What are Tin Whiskers?

- **Tin whiskers are spontaneous, single crystal, hair-like growths from surfaces that use lead-free Tin (Sn) as a final finish**
  - Electrically conductive
  - May grow in days or years
  - Tin-plated electronic and mechanical parts (e.g., nuts, bolts) grow whiskers

- **Whisker growth mechanism still not understood after decades of study**
  - Much conflicting experimental/documented evidence
- **No effective tests to determine the propensity of platings to whisker**
- **No mitigation technique provides effective protection against whisker formation except the addition of 3% or more of lead**

Courtesy: NASA Electronic Parts and Packaging (NEPP) Program

What Causes Tin Whiskers?

Plating Chemistry
- Pure Sn Most Prone
- Some Alloys (Sn-Cu, Sn-Bi, rarely Sn-Pb)
- Use of "Brighteners"
- Incorporated Hydrogen
- Codeposited Carbon
- pH

Substrate
- Material (Brass, Cu, Alloy 42, Steel, etc.)
- Substrate Stress (Stamped, Etched, Annealed)
- Intermetallic Compound Formation
- Substrate Element Diffusivity into Sn

Plating Process
- Current Density
- Bath Temperature
- Bath Agitation

In General, Factors that Increase STRESS or Promote DIFFUSION Within the Deposit

GREATER WHISKER PROPENSITY

Environment
- Temperature
- Temperature Cycling (CTE Mismatch)
- Humidity (Oxidation, Corrosion)
- Applied External Stress
  - (Fasteners, bending, scratches)
- Current Flow or Electric Potential???

Deposit Characteristics
- Grain Size/Shape
- Crystal Orientation
- Deposit Thickness
- Sn Oxide Formation

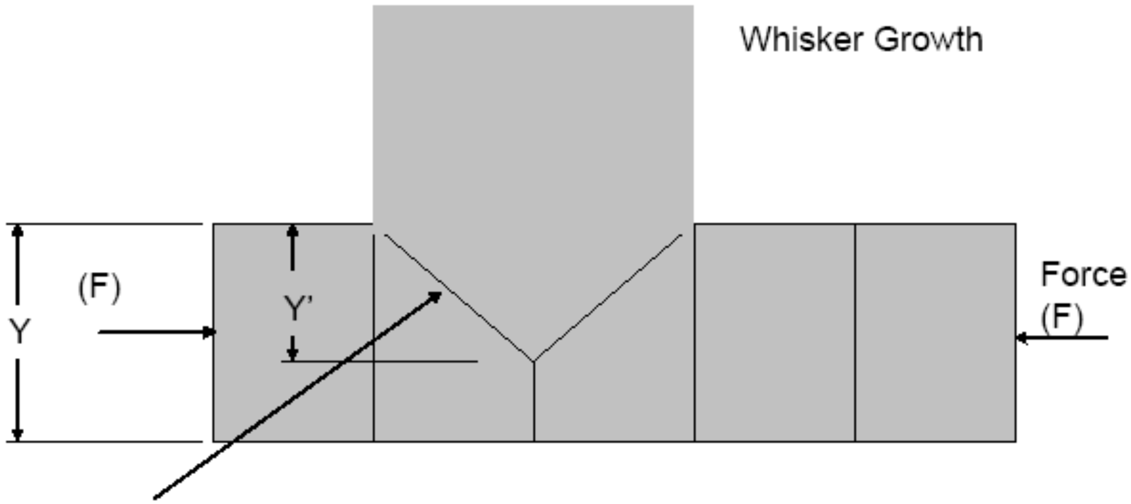
HOWEVER….

Many Experiments Show Contradictory Results For These Factors

Courtesy: NASA Electronic Parts and Packaging (NEPP) Program

New Theory Possibly Explains Whiskers

Summary of Whisker Growth



The Force (F') at this grain boundary interface results in "micro motion" with both a vertical and horizontal component (due to the angle that the force is acting upon the surface) This causes grain boundary sliding (creep). The grain boundary sliding results in vacancies in the Sn lattice at the base of the whisker. Diffusion of Sn atoms to the lower stress grain boundary, which now has vacancies, from the higher stress grain boundaries. Sn atoms move to the base of the tin crystal resulting in whisker growth.

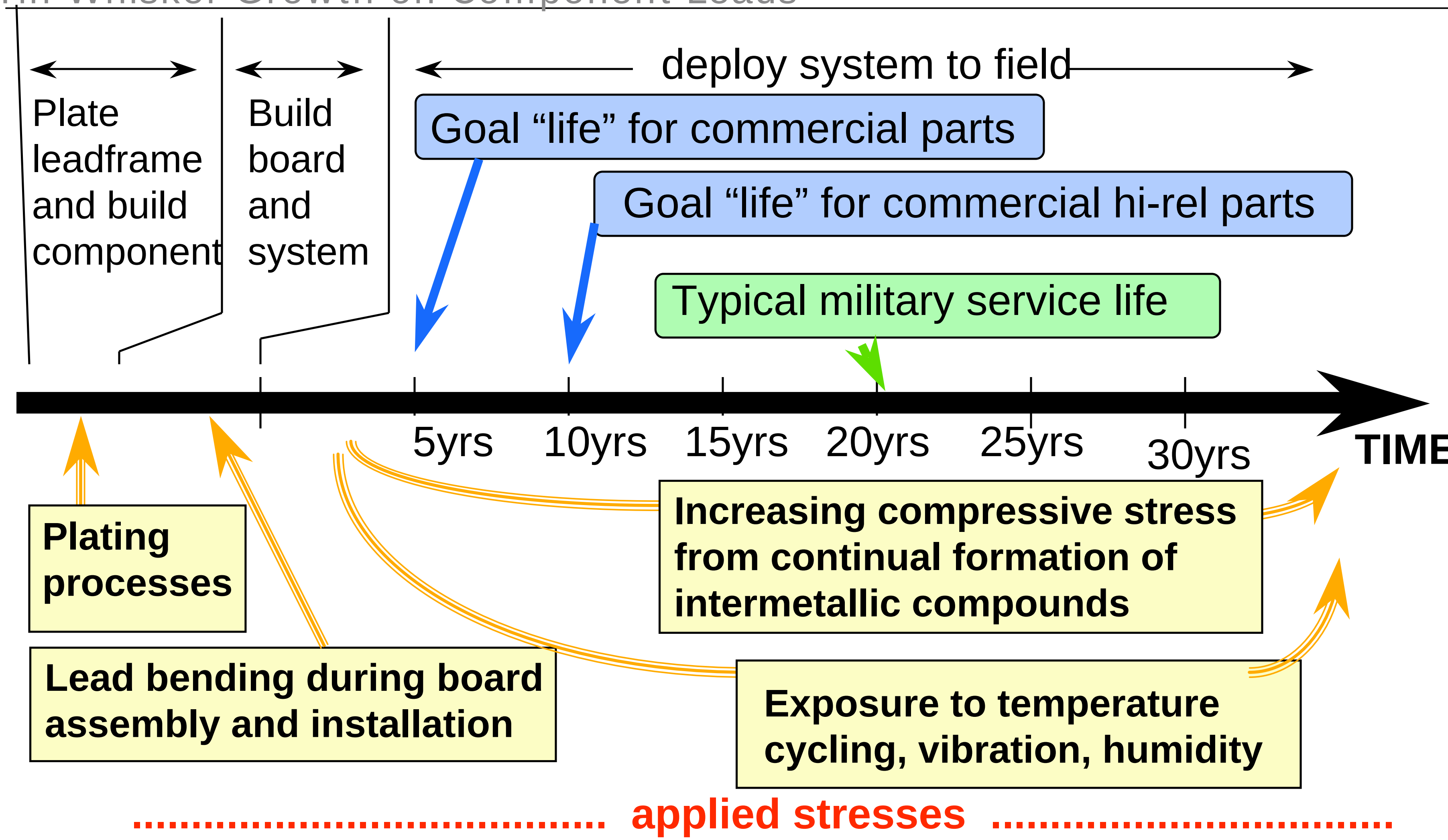
Reference: "Theory of Tin Whisker Growth – The End Game", Joe Smetana

New Theory Possibly Explains Whisker

- **Based on Smetana's theory of tin whisker growth, a SnPb grain structure does not support significant tin whisker growth**
  - Lots of horizontal grain boundaries
  - Almost an equiaxial grain structure
    - Not a columnar grain
  - Addition of Pb has also been theorized to prevent whiskers by:
    - Substitutional diffusion of a large atom
    - Addition of a soft phase that cushions the Sn grains from high compressive stress

Stress Inputs Versus Time

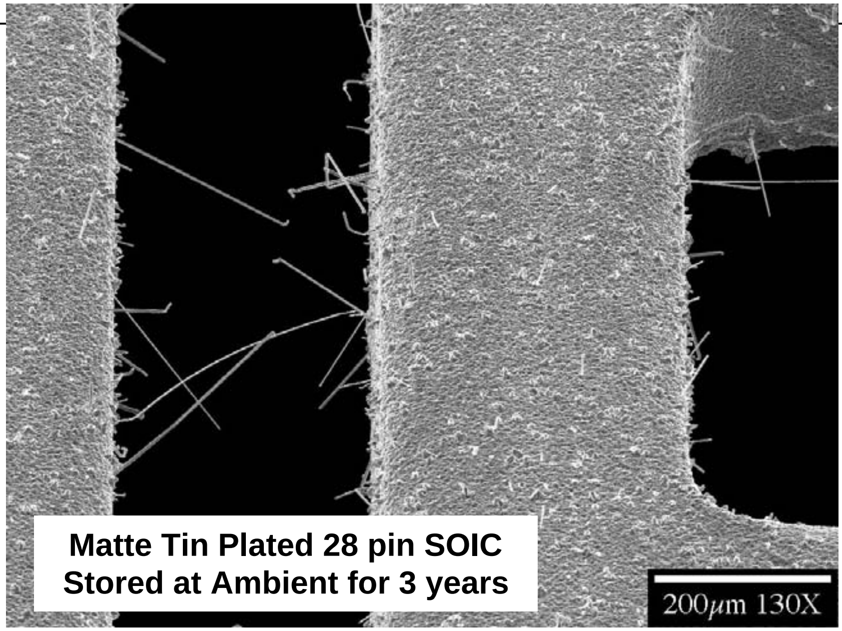
Tin Whisker Growth on Component Leads



Courtesy: Bill Rollins CALCE Tin Whisker Group

Why are Tin Whiskers an Issue Now?

- **Smaller circuit geometries**
  - Whiskers can now easily bridge between contacts
  - Adjacent whiskers can touch each other
  - Broken off whiskers can bridge board traces and foul optics or jam MEMS



Matte Tin Plated 28 pin SOIC Stored at Ambient for 3 years

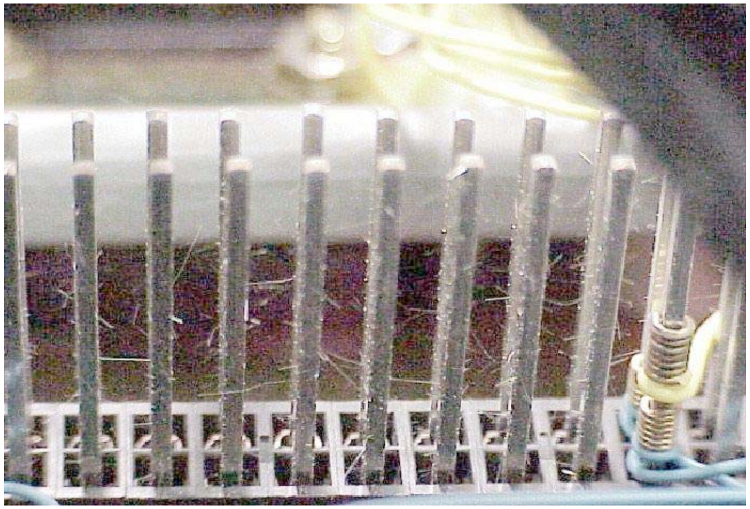
- **Lower voltages**
  - Whiskers can handle tens of milliamps without fusing
- **Manufacturers rapidly moving to lead-free tin platings**
  - Pure tin plate included

Courtesy: Peter Bush, SUNY

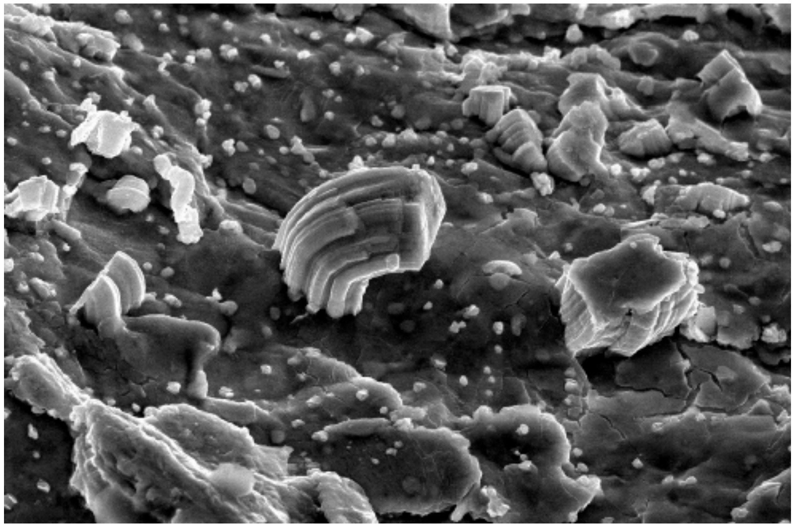
Tin Whisker Failure Mechanisms

- **Stable short circuit in low voltage, high impedance circuits where current insufficient to fuse whisker open**
- **Transient short circuit until whisker fuses open**
- **Plasma arcing is potentially the most destructive - whisker can fuse open but *the vaporized tin may initiate a plasma that can conduct over 200 amps!* This can occur in both vacuum and atmospheric conditions**
- **Debris/Contamination: Whiskers or parts of whiskers may break loose and bridge isolated conductors or interfere with optical surfaces or microelectromechanical systems (MEMS)**
- **High frequency circuit performance degradation**
  - 6 GHz RF and above

Tin Whisker Examples



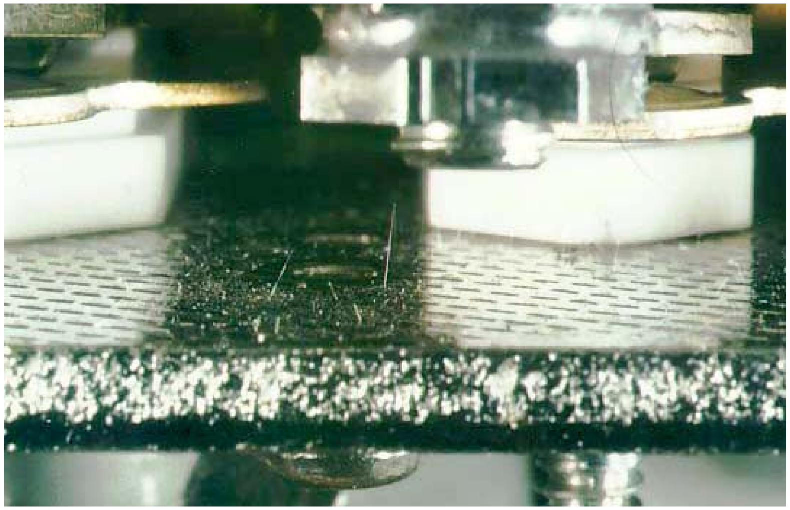
Connector Pins (Pure Tin-Plated)
~10 years old
Observed in 2000
Courtesy: NASA Electronic Parts and Packaging (NEPP) Program



Tin whiskers on chip resistor end-cap, tin-silver-copper solder dip finish. Whisker is ~5µm

Courtesy : Peter Bush, SUNY-Buffalo

Tin Whisker Failure



Tin whiskers on armature of relay.
Many whiskers longer than 0.1 inch (2.5 mm)

Courtesy: Gordon Davy, Northrop Grumman Electronic Systems

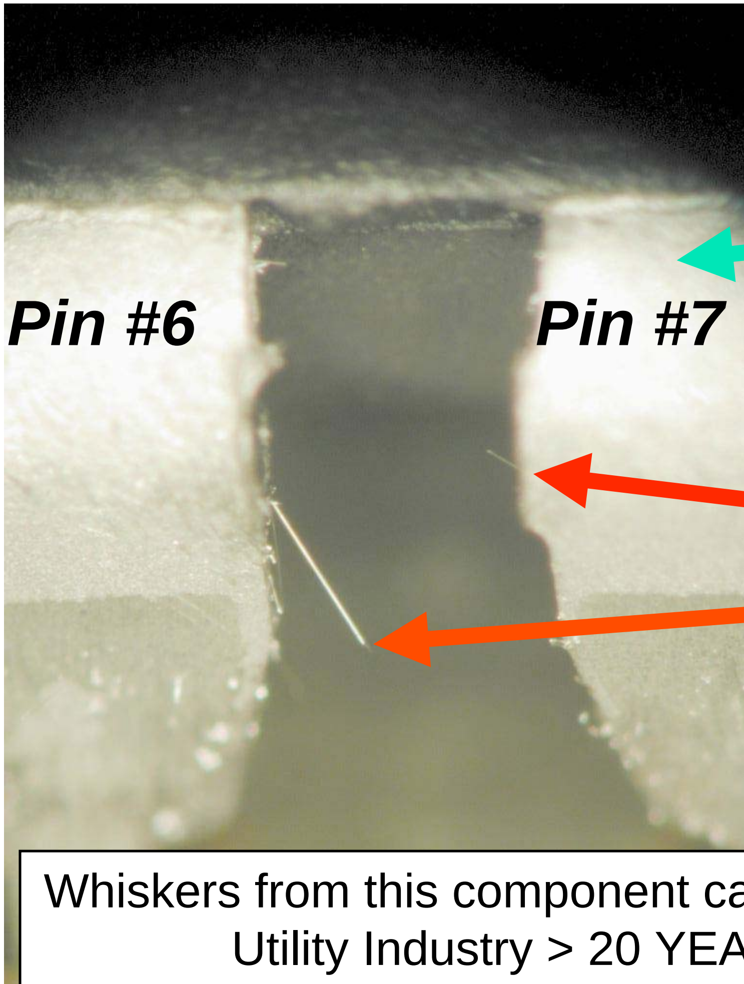
Relay failure due to whisker induced plasma arcing at atmospheric conditions

Courtesy: Gordon Davy, Northrop Grumman Electronic Systems

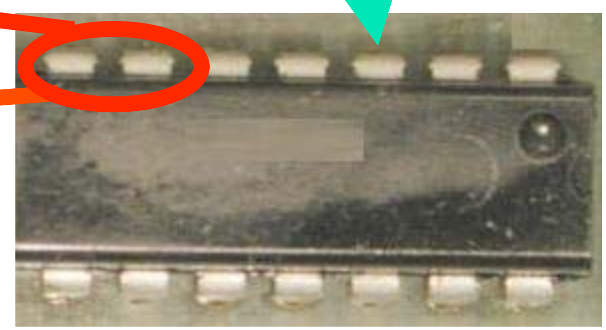
Lead-free Tin Whisker Mitigation Techniques

- **Matte tin (tin with a dull low gloss finish and larger grain size) is more resistant to whiskering than bright tin**
- **Annealing tin can reduce some of the stresses in plating that contribute to whisker growth**
- **Soldering or solder dipping with tin-lead solder is a solution for most components**
- **Stripping the finishes and replating with lead-tin solder may be possible for some components**
- **Conformal coatings can be applied**
  - Currently subject of much research
- **No technique has been proven effective in a long-term high stress environment**

Tin Whisker Short on Matte Tin



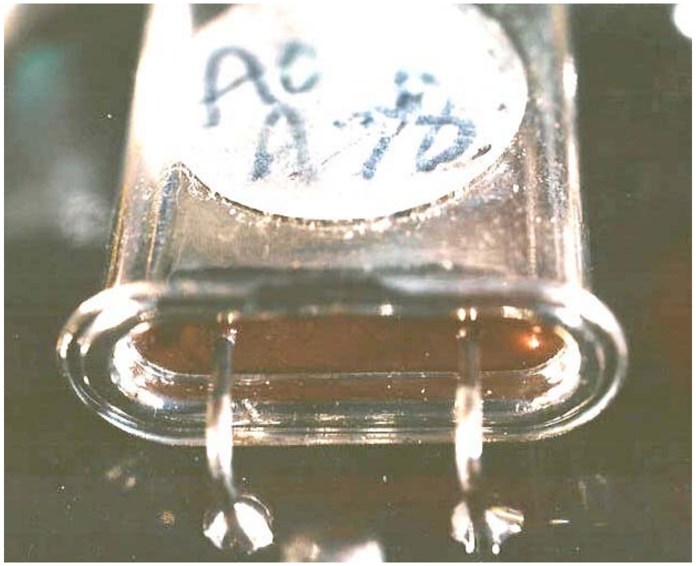
Microcircuit Leads (“Matte” Tin-Plated)



Whiskers from this component caused a FAILURE in the Electric Power Utility Industry > 20 YEARS!!! after fielding the system

Courtesy: NASA Electronic Parts and Packaging (NEPP) Program

Tin Whisker Failure on Oscillator

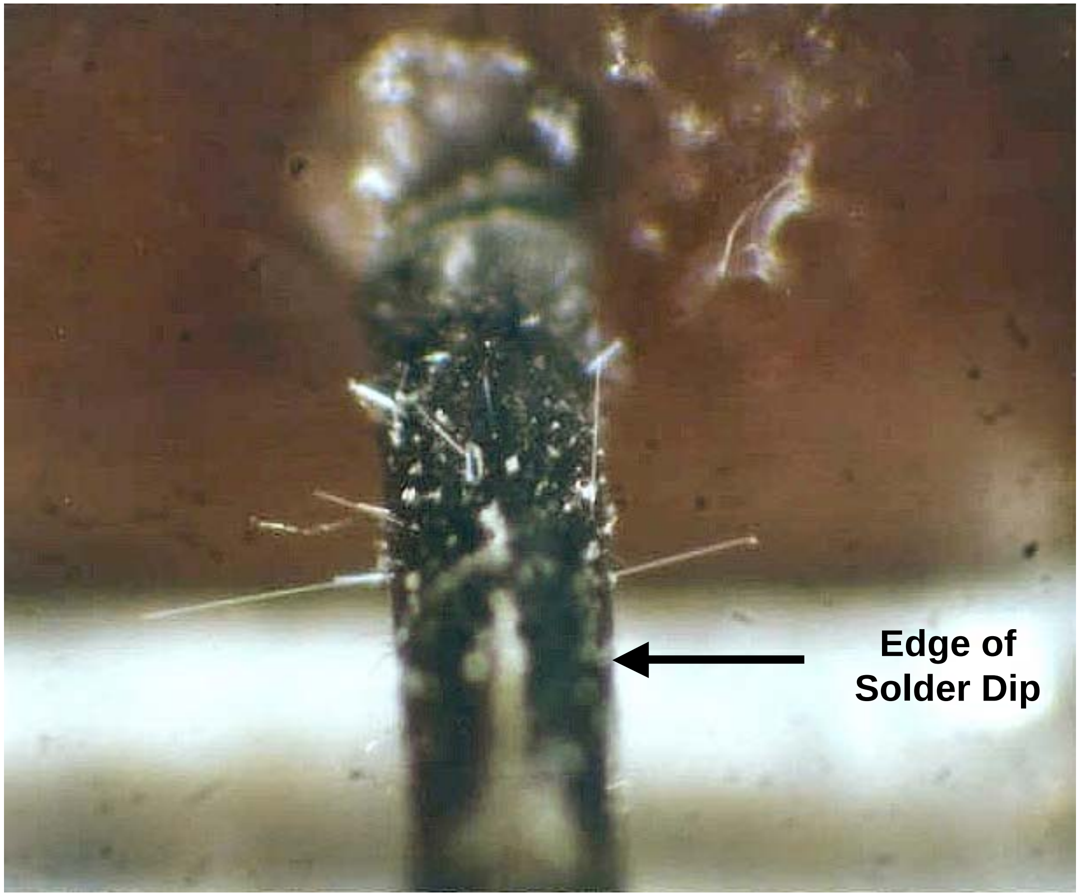


Thru hole oscillator.

Lead diameter 18 mils.

Bright tin finish leads and case.

Tin/lead solder dipped within 50 mils of glass seal and hand soldered to PWB.



Tin whisker growth noted from seal to about 20 mils from edge of solder coat. Electrical failure was traced to a 60 mil whisker that shorted lead to case.

Courtesy: NASA Electronic Parts and Packaging (NEPP) Program

Photos by Ron Foor

Tin Whiskers Through Conformal Coating

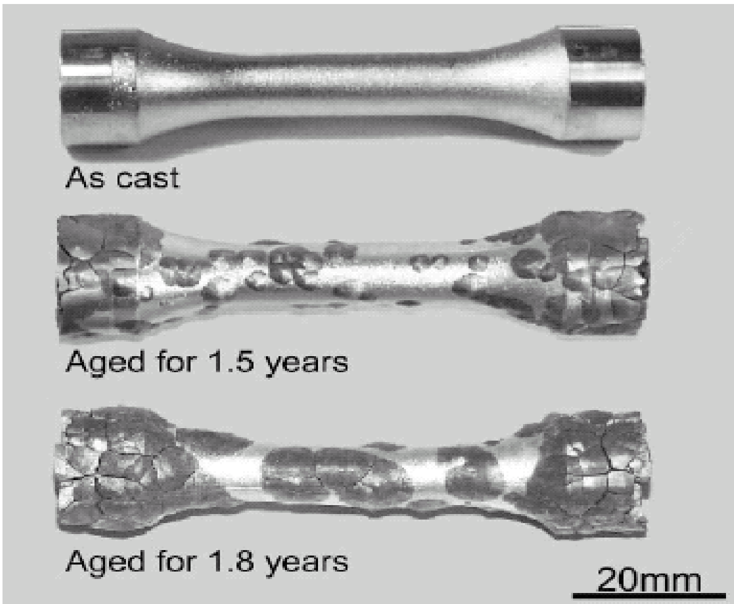
Whiskers penetrating acrylic conformal coating

Source: Thomas Woodrow, Boeing Corporation

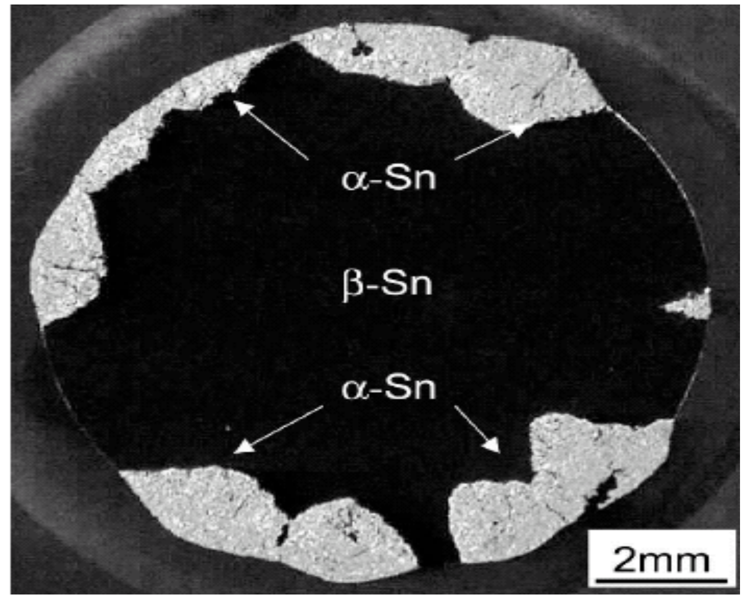
Tin Plague in Lead-free Solders

- **Tin-based lead-free solders may be subject to "tin plague"**
- **Tin plague is the change from tetragonal crystal structure (beta-phase) to cubic crystal structure (alpha-phase) tin starting at 13.2° C**
  - Maximum rate of conversion is approximately -30° C
  - Alpha-phase tin is brittle, powdery, and has 26% greater volume than beta-phase (metallic) tin
  - Reversible when heated above 13° C
    - Does not restore structural integrity
  - Silver, copper, and/or zinc addition worsen the problem
- **Prevented by addition of lead, antimony, or bismuth**
  - More than 5% lead by weight
  - More than 0.5% antimony or bismuth by weight

Examples of Tin Plague



Tin - 0.5 mass % Copper After Aging at Minus 18° C



Cross-section of the sample at a grip end
(aged for 1.5 years)

Photos Courtesy: Y. Kariya, N. Williams, & W. Plumbridge
The Open University , UK
http://materials.open.ac.uk/srg/index.htm

Lead-free Mitigation Techniques - Summary

- **There are techniques that can be used to mitigate the risks associated with lead-free tin**
  - No single technique is ideal for all applications
- **Assembly with tin-lead solder is the single most effective mitigation technique**
  - Only mitigation technique with an established track record in long-term severe service environments
  - Areas not covered by solder are still vulnerable
- **Multiple techniques may be needed until more information is available on lead-free manufacturing**

Standards Activity

- **There are a number of standards just released or being developed**
- **JEDEC JC14 Quality and Reliability of Solid State Products**
  - JESD22A121, "Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes"
    - "This test method may not be sufficient for applications with special requirements, e.g., military or aerospace."
  - Draft JEDEC JESD201, "Environmental Acceptance Requirements For Tin Whisker Susceptibility Of Tin And Tin Alloy Surface Finishes"
    - "The testing described in this document does not guarantee that whiskers will or will not grow under field life conditions."
    - Not really intended for life/mission critical applications such as military, aerospace, and medical

Standards Activity

- **AIA Lead-Free Electronics in Aerospace Project (LEAP-WG)**
  - Standards under development
    - "Program Management/Systems Engineering Management Guidelines For Managing The Transition To Lead-Free Electronics"
    - "Technical Guidelines for Aerospace and High Performance Electronic Systems Containing Lead-free Solder"
    - "Performance Standard for Aerospace and High Performance Electronic Systems Containing Lead-free Solder"
    - "Standard for Mitigating the Effects of Tin Whiskers in Aerospace and High Performance Electronic Systems"

Government Positions

- **NASA**
  - "Pure tin plating is prohibited as a final finish on EEE parts and associated hardware." NASA Parts Advisories NA-044 and NA-044A address this topic and contain extensive lists of specifications, a large number of which prohibit pure tin; many specify a minimum inclusion of 3% lead content.
- U.S. Air Force
  - Airworthiness Advisory AA-05-01, Lead-Free Solder
    - "no lead-free solder has matched the qualities found within leaded solder"
    - "Though there are many alternative solder alloys available to replace traditional tin-lead, none of them has passed the reliability testing required of aerospace-quality hardware."
    - "Until such time that a suitable, reliable, lead-free solder replacement is identified, all program managers should ensure their electronic equipment suppliers continue to provide items which meet all performance, compatibility, and reliability requirements."

Summary:

- **EU environmental legislation is driving lead-free assembly**
  - Tremendous costs associated with conversion to lead-free products
  - Continuing pressure from “environmentalists” via legislation
- **Hi-Reliability, Severe Service, Long Life industry has insufficient data to warrant transition to new materials**

Question

&

Answer

Reference Material

Tin Whisker Background

- **Tin whiskers were first reported by Bell Labs in 1947**
- **Growth varies widely**
  - Within hours
  - After years of dormancy
  - Anytime in between
- **Whisker shapes and forms vary from few microns to several millimeters**
- **Up to 200 whiskers per square millimeter have been observed**
- **Whiskers can grow through thin conformal coating**

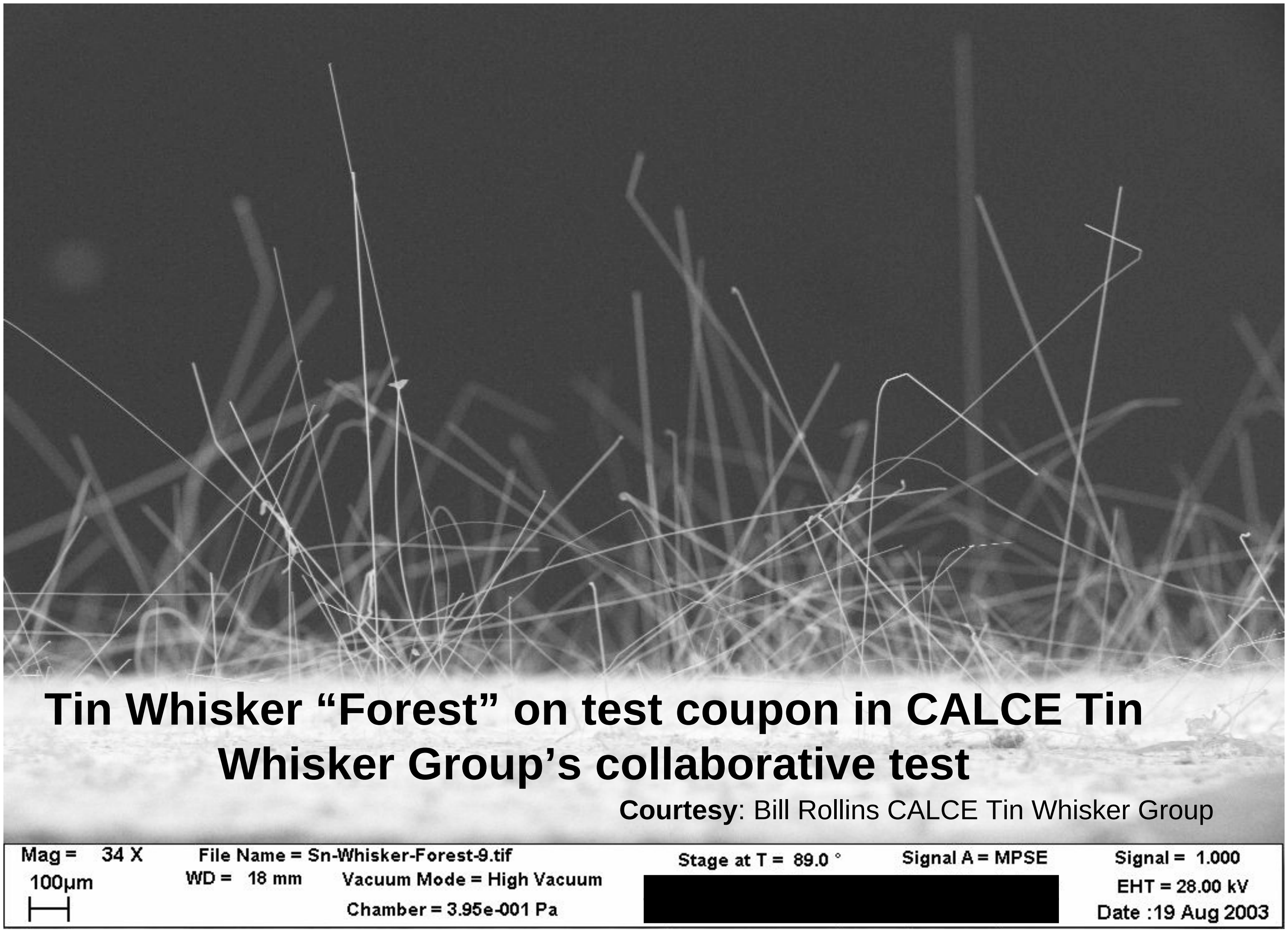
http://www.calce.umd.edu/lead-free/

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

Some Tin Whisker Failure Experience

- **Weapon systems that were built between 1985 and 1992 have had documented tin whisker failures**
  - Failure rates attributed to tin whiskers varied from 1% to 10%
  - Manufacturers of microcircuits/semiconductors BEGAN shifting to pure tin in 1996-97
- **6 Satellites were partial or complete losses 1998-2002:**
  - Galaxy – 3
  - Solidaridad 1
  - Direct TV3
  - HS 601

Tin Whisker Example



Tin Whisker “Forest” on test coupon in CALCE Tin Whisker Group’s collaborative test

Courtesy: Bill Rollins CALCE Tin Whisker Group

Tin Whisker Example

Normally, whiskers are so thin that they are difficult to see without a microscope

Whisker Growing a Whisker