Space Shuttle Program
Tin Whisker Mitigation

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Agenda

- **Introduction**
- **Background**
- **Flight Control System**
  - Initial Findings
  - Photos: Whiskers in Avionics Box
  - Tiger Team
  - FCS Conclusions
  - FCS Remediation Plan
- **FCS Flight Rationale**
- **Additional High Criticality Hardware**
- **Conclusion**

Introduction

- **Space Shuttle Program implemented tin whisker (TW) remediation strategy following discovery of TW in Orbiter hardware**
- **Complex investigation and planning involved cooperation among many disciplines and geographic locations**
- **Overall goal to arrive at two products:**
  1. Flight rationale (should we fly near-term flights with TW?)
  2. Plan for TW removal/mitigation (what is long-term plan for removal of TW?)
- **What was the project management decision-making process?**

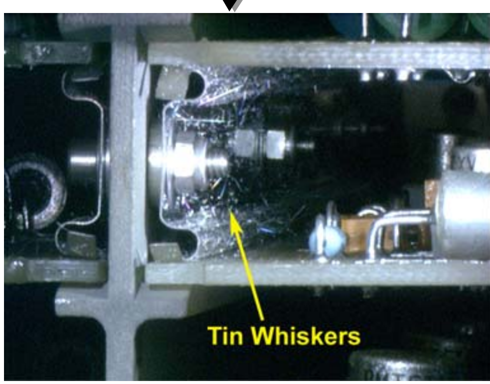
Background

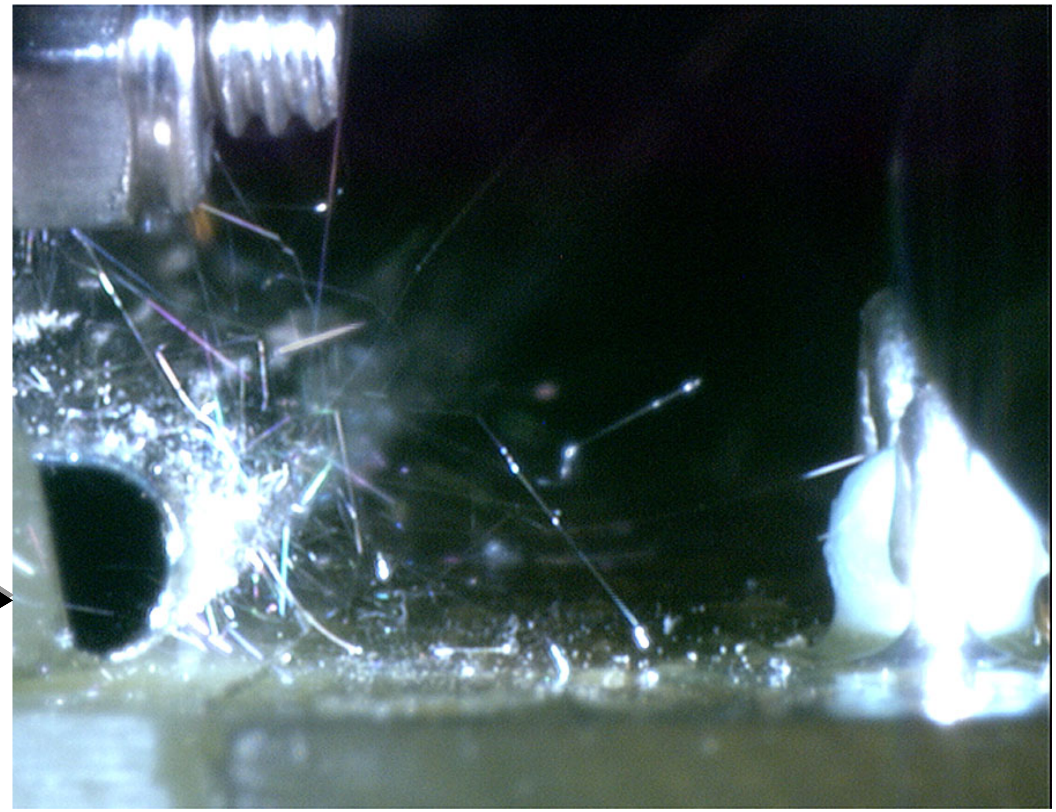
- In March 2006, a Flight Control System (FCS) avionics box failed during vehicle testing, and was routed to the NASA Shuttle Logistics Depot for testing and disassembly
- Internal inspection of the box revealed TW growth visible without magnification
- Among hundreds of electrical boxes on the Space Shuttle, the particular type of box with the initial finding of TW is populated 4 per vehicle
- The family of similarly designed boxes is populated 12 per vehicle

Initial Finding

- **Whiskers grew from pure tin plated circuit card retainers, not from electrical components**
  - Intent of tin plating in original design was for corrosion protection of BeCu retainers
- **Immediate Concerns:**
  - All FCS avionics boxes in the same family were similarly designed and could fail because of TW
  - Whiskers could either grow into conformal coating, or touch electrical components having inadequate coating
  - Active concern for July 2006 launch; particularly if no clean spares exist to rotate into vehicle
  - How can the Program ensure that other Space Shuttle hardware isn't at high risk for TW failures?

Box with cover removed illustrates progressively finer detail





Tiger Team Formed

- **NASA formed multi-disciplinary Tiger Team to investigate extent of findings and develop recommendations**
- **Two Branches of Team's Investigation:**
  1. Detailed investigation of Flight Controls H/W from same vendor (12 per vehicle)
  2. Broad investigation of 100+ other high-criticality Orbiter H/W
- **Functional diversity: design engineering, logistics, test engineering, materials & processes (M&P), ground operations, research**
- **Geographic and corporate diversity: multiple NASA centers (JSC/KSC/GSFC), prime and major subcontractor sites, hardware vendor and supplier**

FCS Conclusions

- **<u>Can TW concern be segregated by s/n?</u>**
- **Quantity of FCS boxes:**
  - 52 total quantity across fleet = 12 per vehicle + spares
  - All from same manufacturer, using same card retainer design
- **Sampled 15 of the 52 boxes across four different types:**
  - 1 & 2) Reaction Control Jets for on-orbit maneuvering (Fwd & Aft)
  - 3) Flight Control Surfaces (e.g. elevons, rudder)
  - 4) Main Engine and Solid Rocket Booster directional control
- **All box types high criticality (Crit. “1/1” and “1R”)**
- **TW only growing from card retainers; up to 18 mm**
- **Some loose TW present**
- **Newer-build boxes (~1989) from Endeavour's initial assembly generally contain longer and more dense TW growth**
- **One box found to have no tin plating on card guides**

FCS Conclusions

- **Conformal Coating:**
  - Coating cannot completely prevent TW growth <u>into</u> coating, but lowers likelihood of contact with underlying electronics
  - Some circuit cards found to have incomplete conformal coating due to "shadowing" of spray-on technique
- **M&P investigated sampled cross-sections of card retainers under scanning electron microscope**
  - Plating method cannot exonerate TW boxes
  - More prominent TW growth in newer Endeavour-era boxes could not be correlated with processing variables such as plating material, time, temperature, pressure, etc.
  - M&P recommends 100% inspection
  - Tin plating not needed to prevent corrosion of card retainers

FCS Conclusions

- **Assessment of vendor's build records could not exonerate/segregate boxes**
- **Design team's position:**
  - 51 boxes still at risk
  - Based on component layout on circuit cards, even the shorter whiskers (~2 mm) are long enough to cause failure

FCS Remediation Plan

- **Remediation plan developed:**
  - Avionics Lab: Remove tin plating and TW
    - » Expedite procurement of non-plated card retainer assemblies from vendor
    - » Cycle boxes through Lab
    - » Incoming testing, disassembly / card removal
    - » Assess gross order-of-magnitude quantity of loose whiskers
    - » Clean chassis and circuit cards
    - » Cards pass magnified inspection
    - » Conformal coating touch-up via brush coating as needed
    - » Reassemble with non-plated card retainers
    - » Full acceptance testing at box level: vibration, thermal, functional
  - Flight Operations: Prioritize Reaction Control Jet firing to minimize likelihood of critical risks

FCS Remediation Plan

- **Plan phased in over multiple years/flights**
  - Flight Controls design team tracks 51 boxes rotating through remediation plan
  - Higher criticality (non-redundant) boxes given schedule priority over redundant boxes
  - Pace of plan accommodates Avionics Lab staffing level, quantity of test stations (2), and diversion of equipment and personnel for unrelated failures on same boxes

Outline of FCS Flight Rationale

- **Is it safe to fly non-repaired FCS boxes?**
  - Remediation of all boxes prior to flight would result in significant delays for Space Shuttle and International Space Station programs
- **Jet Drivers (high criticality / non-redundant)**
  - Inadvertent jet firing concern risks loads on or contact with Space Station
  - TW-caused inadvertent jet firing is not spontaneous; must be coupled with a commanded jet firing
  - Loose TW needs to bridge specific pin combinations; simultaneously avoiding other pin combinations that can vaporize TW
  - Prioritized jet selection to minimize likelihood of plume and contact loads for Space Station
  - Software limits worst case duration of inadvertent firing to very short duration
  - Installed unique box containing non-plated card guides

Outline of FCS Flight Rationale

- **Control Surface & Engine Directional Control**
  - System architecture mitigates catastrophic failure via hardware redundancy
  - Dual-redundant failure mode requires identical failures to occur within small duration window
- **General Rationale**
  - Conformal coating protects circuits
  - Loose TW would need to migrate from growth sites to critical "smart" locations on circuit cards
  - Sampling of quantity of loose whiskers in three boxes led to belief that actual quantity is small, not large

Additional High Criticality H/W

- **Tiger Team assessed other high criticality H/W:**
  - Listing of high criticality H/W screened through Materials database of as-built configuration, searching for pure tin
  - List of essential questions distributed to design teams responsible for H/W at risk for pure tin
- **Types of criteria:**
  - Conformal coating, solder coverage on leads, physical separation, worst case effects having lesser criticality, history of inspections, history of unexplained anomaly trends
- **Some H/W inspections authorized**

Additional High Criticality H/W

- **Findings on two high criticality boxes:**
  - Some short TW found on tin plated eyelets on circuit cards
    - » Corrective Action: conformal coating applied to eyelets without removal of circuit cards
  - One design allowed for either tin plated rivets or solid aluminum rivets on chassis
    - » Spectroscopy performed on large sample of boxes verified solid aluminum rivets

Conclusion

- **Program elected to fly with tin whiskered avionics hardware in parallel with implementing remediation plan and adopting operational controls**
- **TW growth in programs with high reliability standards such as human spaceflight can result in lengthy and costly investigations and remediation plans**
  - Remediation plan phased in for flight: July 2006, Sept. 2006, Dec. 2006, Mar. 2007
  - TW remediation plan continues into CY2009
  - No failures to date positively attributable to TW
- **As electrical components adopt lead-free philosophy, caution should be taken when designing and procuring new hardware**
- **Design decisions can have unintended consequences**
- **Development and refinement of TW mitigation techniques will benefit programs that have future TW findings**