Tin Whiskers – A Long Term RoHS Reliability Problem

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"It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so." - Mark Twain.

History of the Problem

The first recognition of electrical problems caused by metal whiskering appears to have happened in 1942-43 in aircraft radios made by the Aircraft Radio Corporation in Boonton, New Jersey.[1] Air-spaced variable capacitors were cadmium plated to retard corrosion; then the cadmium plating whiskered, and these whiskers dropped the Q of the tuned circuits to unusably low values. This company's radios included those used to land under conditions of zero visibility. How many died as a result of these whiskers? As this was during the war, perhaps there were reports, classified at the time, and now perhaps declassified since more than 50 years have passed; does anyone know where to find such?

That the growth of whiskers is not a new phenomenon may be concluded from the examination of undisturbed old equipment. For example, a number of zinc plated details installed in a telephone central office in 1912 were removed for study.
Surfaces which had been protected from cleaning operations and from excessive air circulation had numerous whiskers present. Bell Labs learned during the early part of 1948 that "channel filters", used in carrier telephone systems, were failing, and that Bell eventually traced the problem to whiskers growing from zinc plated steel. (Note: tin plating was not the cause in this case [2].)

NASA Goddard Space Flight Center (GFSC) scientist Dr. Henning Leidecker reports that studies showed that as little as 0.5% lead was effective in lessening tin whisker growth. These studies have been repeated with the same findings. Because many plating shops do not hit the target of lead concentration with high precision, specifications often call for 2% or even 3%, in order to increase confidence that one will get at least 0.5%. [3]

Tin whiskers grow in the absence of lead in solder, and pose a serious reliability risk to electronic assemblies. Tin whiskers have caused system failures in earth and space-based applications, as well as in missile systems. At least three tin whisker-induced short circuits resulted in complete failure of in-orbit commercial satellites. The cause of the side-B failure in Galaxy 4 is highly certain. The cause of the other *side failures* (it takes the failure of both side A and B to kill the satellite) is less certain [4].

Ignorance of the scope of the tin whiskering problem is the simple, sad answer as to why it took NASA GFSC until the 1990s to act on what Bell Labs had clearly published in the 1950s and 1960s.

During a conversation with GFSC scientist Dr. Henning Leidecker, he said, “We were taught the seriousness of this problem by a contractor in 1998, and have continued learning about it since then, and have been sharing what we have collected.”

Here is a list of publically known catastrophic failures resulting from tin whiskers. [4]

- 1974 – 20 Years of Observation – Trans. Inst. Of Metal Finishing
- 1986 – Pacemaker FDA Class 1 Recall - Total Failure Crystal Oscillator Short
- 1989 – Phoenix Air-to-Air Missile Failures
- 1991 – Raytheon Patriot Missile Intermittent Misfire Problems
- 1998 – Galaxy IV & VII (PanAmSat)
- 2002 – Northrop Grumman Relay Failures - Military Aircraft -- approximately 10 years old -- failed. Rated at 25 amps/115 Vac/3 phase
- 2005 – Millstone Unit 3 Nuclear Reactor Shutdown: Dominion Learns Big Lesson
- 2006 – Galaxy IIIR (PanAmSat)

A nuclear reactor shutdown was a particularly disturbing event. During the first 24 hours of a sudden nuclear reactor shutdown at Millstone Power Station this spring, technicians were stumped zeroing in on a computer malfunction as the culprit. One of the technicians picked up a magnifying glass, and took a closer look. “They saw something different,” Reyher said, “and they asked themselves, ‘What can this be? A piece of solder? Something’s there. Let’s take a picture.’” [4]

Within a few hours, under a high-powered microscope, they spotted a thin filament of metal, barely visible to the naked eye, spanning the card’s surface, and bridging a line of conductive material, called a trace. That metal fragment, they soon learned, had single handedly caused the electrical short that gave a false low-pressure reading, and forced an unplanned shutdown. The tin whisker that shorted out at Millstone's Unit 3 reactor on April 17 triggered an automatic shutdown designed to protect the reactor. However, that is not what worries the Nuclear Regulatory Commission. Rather, it is that the tin whisker could prevent a safety system from working properly, a concern of NRC spokesman Neil Sheehan, whose agency is responsible for overseeing safe operations in the industry.

NASA found a problem with the space shuttle. GSFC has rules prohibiting the use of pure tin coatings, and also zinc and cadmium coatings, but applied these universally only since the early 1990s. Unfortunately, there were no shuttle program specifications prohibiting the use of (pure) tin plating on sensitive electronics. The original shuttle program had some rules prohibiting pure tin, but not universal rules, applying across all procurements, including fasteners used near electrical circuits. The first batch of shuttles was made by Honeywell using card guides plated with leaded-tin. In 2007, these guides were examined for whiskering. Only a few whiskers were seen; all were shorter than a few mils in length.

The space shuttle Challenger exploded in 1986, tragically killing its crew. Congress supplied NASA with the funding for a replacement shuttle: OV-105, Endeavor. NASA started building Endeavor in 1986, almost a decade after the first batch. At least one waver was granted at the request of a manufacturer. During that decade, OSHA made it more expensive to dispose of tin plating baths that had some lead in them. The contractor, that had won the bidding to make the electronics for NASA was, again, Honeywell (Clearwater, FL). They proposed to *go green* by providing pure tin-plated card guides. NASA's procurement department effectively approved their proposal with their understanding that pure tin coating might grow tin whiskers, but that these whiskers were only theoretical.

During 2006, NASA found some 100 to 300 million tin whiskers growing on Endeavor's card guides, with lengths between 0.2 mm, and 25 mm. There were also whiskers having lengths approaching zero; it is not the case there were NO whiskers with lengths shorter than 0.2 mm. Rather NASA only counted whiskers with a range of lengths between 0.2 mm and 25 mm. The wildly ironic thing is that the card guides are beryllium copper, and never needed any tin plating to protect them from corrosion! They found a guide that was uncoated, and it was perfectly free of any corrosion at all, because the Be-Cu metal does not corrode, and does not to present a risk of problems by peeling (i.e., shedding conductive chunks of tin onto the electronics). The tin coatings grew whiskers, and they did present a threat of causing short circuits. Clearly, the tin coating failed to satisfy the requirement: no production of conductive debris.

NASA Goddard tin whiskers scientists believe that there was a shorting event induced by a tin whisker while undergoing ground testing in an electronics box made for use in OV-105, but not installed in OV-105. The box failed. The team that maintains the shuttle does not believe there is sufficient evidence to claim that a tin whisker was the cause of the event. This fact illustrates the difficulty of assignment of cause, which is more common than not.

Preventing Whisker-Induced Failures

When using the term *failure*, one must be clear as to what system failed, and in what way it violated its *work requirement*. Violating a work requirement is just as serious a situation as a failure, especially in critical systems such as the space shuttles, nuclear power plants, weapon systems, and medical devices. To be clear, the Shuttle Endeavor (OV-105) works fine, and so *that* system did not fail.

Why did this happen? Why did this NASA approver not know about tin whiskers? The decision to use pure tin and regard whiskering as "only theoretical" was a mistake based on ignorance of the actual threat of whiskering. The NASA approver and contractor were distinguished professionals with long experience in space systems, but they were unaware that tin coatings can grow whiskers. Matte tin coatings of typical thickness usually grow whiskers at a density of some 900 whiskers per square centimeter; or some 14,000 whisker per square centimeter for bright tin on brass. That these cause damage can be rare; it depends on whether there are connectors at sufficient potentials nearby, and whether shorting to these connectors is a problem. Perhaps they *were* correct in this last estimate? None of the shuttles thus far are known to have encountered a whisker-induced problem in flight. *Finding* the damage is rare.

There is another reason. NASA requirements echo the style of requirements used by the military, and by many areas of aerospace. These are directive, of the form 'do this; do not do that,' with no explanations as to what happens if these requirements are contradicted, and no references back to the literature that generated these requirements. NASA has requirements that say to use 3% lead in the tin coating, but they have no pointers to the Bell Labs words that say, "Pure tin coatings have caused entire product lines to fail in service." [5]

So the NASA rep allowed a waver when asked for it by the manufacturer who wished to optimize *his* process by using pure tin coatings. Probably, the NASA rep had not had experience with tin whisker damage, and did not recognize the very real possibility of this occurring. This style of directing, without any references to reasons, has been costly to NASA. [3]

Why are so many people unaware of tin whisker risks? Most people don't care about it, because it hasn't happened to them, not realizing that it is happening to them. Most people address problems that they know they have had before. They do not recognize a steady drizzle of problems caused by metal whiskers. It is hard to *see* whiskers even when whiskers are present.

Do all tin, zinc, or cadmium coatings produce whiskers? Not all of these coatings produce whiskers within the time of use of the equipment. For example, NASA Goddard's Jay Brusse has what he terms a 'busy box' with a number of tin-plated soldering lugs, each bolted down tightly so there is stress present on part of the lug: only 20% are showing any whiskering at all. Another example: NASA inspected 100 walnut-sized tin plated relays, stored for at least 5 years (no contacting that might rub off whiskers). About 20% were growing whiskers.

No one yet understands how to predict the whiskering proclivities of a given tin coating. The distribution of lengths is close to log-normal, and it is the median value of length that grows at a rate of 0.5 mm to 1.0 mm per year. Leidecker has gotten these values from a number of different reports on experiments dating from the 1950s onward to 2005 (and later). When the tin coating does grow whiskers, and not all do, they may grow only minimal ones. [3]

Some whiskers grow faster, some slower. Surface compressive stress seems to play a role, and humidity definitely does. For every datum that is reported about tin whisker growth, it sometimes seems that one can find a report of a contradictory datum.
There is a general consensus of opinion amongst the scientific community that temperature cycling greatly promotes growth, especially cycling above and below the 13.2ºC phase-transition temperature of tin. Some find faster growth around room temperature. Leidecker suspects that new whisker growth depends on a cascade of several events, and that these have opposite temperature dependences, and different net

impacts, under different circumstances. All other things being equal, they probably grow faster in warmer conditions [3].

Whisker containment is not perfect with conformal coatings, but it is very good. Parylene lasts a few years, and then a tin eruption blows out a divot of it. Elastomers stretch a bit, then crack, and tear. Containment depends in part on inducing Euler buckling. [7]

To complicate matters, not all whiskered surfaces cause circuit malfunctions. Size, and geometry can increase risk more than six orders of magnitude. When more than about 100 mV is applied across the metal part of the whisker (i.e., after the tin oxide layer is dielectrically ruptured), then enough current will flow to melt the whisker open, usually within a millisecond or less. Sometimes, this current event is so brief that it escapes being logged as a fault. Other times, the event is able to "latch" an enduring fault (as in alarm circuits), and then the trouble-shooter has difficulty finding where the now opened whisker was before the event.

Not all whisker-induced failures can be identified. Very few analysts correctly identify whisker-induced problems. A professional failure analysis can run between $300 and $3,000 per job. Almost no broken commercial equipment is ever put through any such analysis. Rather, the failed unit is junked or refurbished without any assignment of the fault. It is characteristically only equipment used in tasks of high importance that gets any analytic attention. Sadly, only a very few analysts are able to correctly recognize whisker induced problems!

Does commercial-grade equipment have this problem? It is typically only the military and space communities that carry out the analysis that is necessary to locate the source of the damage. And then, only a few of the analysts are perceptive as to the real cause.

Not all cases of whisker-induced failures are reported! NASA has logged, in 5 years, 3 to 5 reports per month of tin whisker infestation that required urgent help (almost all reports are from non-NASA sources). Very few manufacturers have allowed NASA to document the problems in detail, or share results publicly due to fear of lost sales, warranty claims, punitive damages, injuries, and embarrassment. There is no desire to share solutions to problems with competitors.

“The hundreds of cases we have documented scale to roughly a few million to a few hundred million cases of whiskering problems over the last fifty years --- this seems about right to me,” stated NASA’s Leidecker [3]. He suspects that about 3% to 30% of electronics systems that are using pure tin plating are growing whiskers, that about 0.5% to 5% of the total are having shorts caused by these whiskers, that about 0.005% to 0.5% of the total are having the cause of these shorts correctly identified, and then about 0.00001% to 0.01% of the total are being publicly named.

The public perception is that there are only a few cases, and that these have happened ‘*to other folks.*’ A man operated a computer room in which 75% of the computers blew the fuses in their power supplies in the space of a few hours. It took him several months to trace the cause to zinc whiskers, and during that period those computers were not generating revenue [3]. The whiskers probably had been growing for years beneath the room's raised floor, but hadn't created trouble until a water spill occurred. Air blown into the space between the tiles and the sub floor to dry up the water dislodged the whiskers, which then wafted into the computers through vents in the floor.

Texts that teach newcomers about ways to make systems more reliable do not mention the dangers of whiskering as strongly as they should. A few allude to whiskering, usually as *rare* without distinguishing between *rarely happening*, and *rarely publicly documented*.

A typical company, selling parts with pure tin coatings that are occasionally causing a short, will continue this practice. They will promptly replace any one of their parts that the customer can show has shorted as a result of a whisker. And buyers of these parts will point to this *prompt replace* policy, and to the lack of a publicly documented problem with the use of pure tin coatings, to support the choice of purchasing these relatively inexpensive parts in favor of more expensive parts with whisker-free coatings. No one is charged with tracking injuries or deaths that result from this practice.

Do suppliers give us what we order? If you specify 3% leaded-tin coating, will you be certain that you receive it? NASA and other hi-rel manufacturers find *pure tin coatings* 1.5% to 3% of the time (month to month), even when the contract and Certificate of Compliance say it is to contain a certain percentage of lead. The rate of such findings jumped to 70% for a brief period of time.

There is no prescription for reliably predicting which plated surfaces will grow whiskers, and which will not. Whisker growth is stochastic. Perhaps someday we will learn the controlling parameter(s), and will then be able to apply coatings that are reliably whisker free. Some would say that we now know how to do this: we get stress-free coatings. Leidecker neither agrees, nor disagrees with this remark. He claims that he cannot look at a tin plated surface, make measurements (or look at production sheets), and make a reliable prediction [3]. In particular, he can't apply a 'stress meter' to the surface.

<u>Are there mitigations?</u>

1) Apply conformal electrical insulating coatings to block any loose whiskers from shorting electrical conductors/components.

2) Apply a 2 mil thick whisker-tough coating which contains whisker growth. When an appropriate coating is used, and is correctly applied everywhere (and does not introduce its own damages), then the risk of shorting can be substantially lowered.

3) Re-plate with tin-lead solder, which dissolves any pure tin plating. Corfin Industries, Salem, NH, implemented a robotic hot solder dip (RHSD) for tin whisker mitigation. It is a US Navy-qualified process.

4) Ball Grid Array (BGA) reballing for conversion to tin-lead flushes all balls and alloy residue on the pads, and replaces balls with tin/lead solder balls.

5) X-Ray Fluorescence (XRF) Analysis, is used to determine lead (Pb) content of termination finishes, and plating thickness.

Tin Deterioration at Low Temperatures

There's another problem with tin called *tin pest*. Tin pest is an autocatalytic, allotropic transformation of the element tin which causes deterioration of tin objects at low temperatures. Tin pest has also been called tin disease, or tin leprosy. It was observed in medieval Europe that the pipes in church pipe organs were affected in cool climates. As soon as the tin began decomposing, the process sped up, and seemed to feed on itself.

At 13.2 ºC (about 56 ºF) and below, pure tin transforms from the (silvery, ductile) allotrope of β-modification white tin to brittle, α-modification *grey tin*. Eventually it decomposes into powder, hence the name tin pest. The decomposition will catalyze itself, which is why the reaction seems to speed up once it starts; the mere presence of tin pest leads to more tin pest. Tin objects at low temperatures will simply disintegrate.

The tin crystal has anisotropic coefficients of expansion, so any temperature change generates a compressive stress somewhere that drives tin atoms to travel, then dropping into the lower energy state of a crystal [6]. Tin atoms are itinerant at room temperature, even left to themselves!

Conclusions

For high reliability electronics, such as for NASA, military, aerospace, or medical applications, specify on your equipment *no pure tin, or zinc, or cadmium plating*, or at least try to mitigate whiskers with conformal coatings. Check your incoming materials at the document-level, and use explicit assays. NASA strongly prefers *no pure tin, or zinc, or cadmium* on their equipment. Their rules forbid the use of these materials, and they check their incoming materials at the document-level using explicit assays. They sometimes find that they have one or more of these forbidden materials anyway, despite their rules and checks.

Then, NASA has to decide whether to scrap the delivered equipment, or to take it apart and rebuild it, or to *fly as is*. NASA is working to develop science-based methods for aiding the managers who must make these decisions.

There is a tongue-in-cheek qualification test which all parts manufacturers (such as Analog Devices and National Semiconductor [8]) use to claim that their RoHS parts do not grow tin whiskers. iNEMI [9] proposed a tin whisker test method in 2003. Since that time, JEDEC [10] has developed a test method which is based largely on the iNEMI proposal. This JEDEC test method passed ballot, and was released in May 2005 as JESD22A121. The JEDEC acceptance criterion, JESD201, was released in March 2006.

JESD201 is a 4,000 hour test. How many hours are in a year? 8,760. This is a guarantee that tin-plated parts will not develop tin whiskers within six months. Does that make you feel good about RoHS reliability in lead-free heart pacemakers? Air bag deployment electronics? Auto braking systems and speed controls? Railroads, airplanes, and air traffic control electronics?

The Joint Boston - New Hampshire - Providence IEEE Reliability Society Chapter has just initiated a project titled *RoHS6 Pushback*. RoHS6 may be technologically feasible for simple boards with simple electronic parts. As the complexity increases, the risks become large. The long term reliability is not assured. The issues and risks need to be quantified and shared.

Unless we discover the magic bullet replacement for 3% lead in tin solder, within the next 5 years we will start to see significant, random, next to impossible to diagnose failures. Reliability in electronics will be a myth.

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