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Introductory invited paper

Risk of tin whiskers in the nuclear industry

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ABSTRACT

This paper identifies tin whisker-related faults and failures that have been reported in the nuclear power industry and discusses the unique reliability and safety challenges faced by nuclear power plants. Specific areas of concern include supply chain and parts selection, fault reporting, regulations and measurement techniques, and the adoption of lead-free legislation. Issues of parts availability and obsolescence are also discussed. The paper concludes with strategies and recommendations that can be used to mitigate and manage risks from tin whiskers in the nuclear industry.

1. Introduction

Nearly all of the 100 commercial nuclear power plants (NPPs) in the U.S. were built decades ago and were initially licensed to operate for 30 years by the Nuclear Regulatory Commission (NRC). Over two-thirds of the commercial NPPs have now received license extensions to operate for 60 years, and many are submitting applications to be recertified to operate for 80 years. Recertification often necessitates updates to safety and operations systems.

System failures in multiple industries, including nuclear power, have been linked to tin whiskers in electronic assemblies, especially in electronics that lack lead constituents, which are known to mitigate tin whisker formation. However, since lead-free products comprise the majority of newly manufactured electronic components, the risks to safety and reliability from tin whisker growth are of particular concern.

Continuing an existing system with replacement components is common in many safety-critical applications. To assess the reliability and safety of replaced components, current tin whisker standards and Reduction of Hazardous Substances (RoHS) compliance measures must be evaluated for their applicability in the nuclear industry.

Tin whiskers are conductive structures that can spontaneously and unpredictably grow on tin-rich surfaces (Fig. 1). Whiskers can also grow from other metallic coatings including zinc (Fig. 2) and cadmium. Reports of tin whiskers in electrical equipment date from the mid-20th century. Bell Labs started using pure tin as a replacement for cadmium plating after equipment failures during WWII were attributed to short circuits from cadmium whiskers. However, the pure tin plating exhibited similar whisker problems as the cadmium plating did [1]. Therefore, tin-lead alloys were used to prevent whisker growth. In July 2006, the RoHS Directive from the European Union went into effect, resulting in the removal of lead from electronic components. Since then, tin whisker growth has re-emerged as a concern, not only for RoHS-compliant electronics, but for all systems that use RoHS-compliant components.

Whiskers can cause short circuits between the traces of printed circuit boards (PCBs) or the leads of components. Intermittent failures may also occur when a whisker causes an uncontrolled electric current flow that eventually melts the whisker, thus making the source of the failure nearly impossible to detect. In this way, tin whiskers can be especially problematic in high-risk or life-sustaining applications such as nuclear power and medical devices. Unfortunately, tin whisker formation is not fully understood and is hard to predict and detect before it causes problems [2].

This paper discusses the characteristics of tin whiskers and their growth mechanisms in Section 2, and then gives some examples of tin whisker-induced failures in the nuclear industry and reviews the industry's regulations in Section 3. The potential impact on nuclear plants with the adoption of RoHS compliance is presented in along with best practices and risk mitigation strategies. The conclusion and recommendations are presented in Section 5.

2. Tin whisker characteristics and growth mechanisms

As defined by JEDEC Standard JESD 22A12 [4], tin whiskers have an aspect ratio (length/width) greater than 2. They are 10 μm or longer, and can be straight, kinked, bent, or twisted. Component cleanliness, humidity, and residual stress are among the reported factors that favor tin whisker growth, but predicting tin whisker growth and risks has

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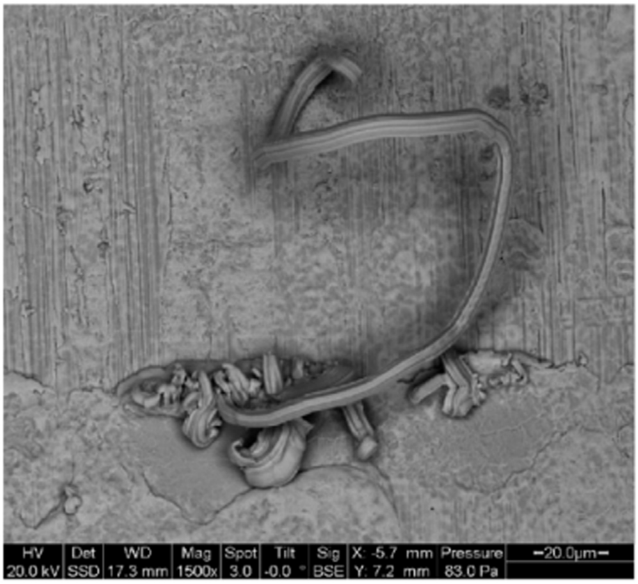

Fig. 1. Example of tin whisker on the surface of the acceleration position sensor board connection terminal of a 2002 Toyota Camry [1].
Courtesy of CALCE.

Fig. 2. Hot dip galvanized steel pipe with extensive zinc whisker formation [3].
Courtesy of NASA Electronic Parts & Packaging (NEPP) Program.

been a challenge. For applications with electrical equipment expected to operate for decades, mitigation strategies are the primary method of reducing the risks from tin whiskers.

Most commercial suppliers of commodity electronic components have migrated to lead-free products, and customers have to choose between using those low-cost commodity components or specialized high-cost components with designed-in mitigations. This choice even applies to customers who can get an RoHS compliance exemption (e.g., NPPs, see Section 3) because so many electronics contain commodity components. For example, NASA has reported receiving pure tin-coated components from specialty suppliers, even when they had specified that leaded alloys were to be used and the supplier's certificate of compliance stated a certain amount of lead was involved [5]. It is reasonable to assume that, even if the RoHS compliance exception can be used, the nuclear industry will be forced to use lead-free electronics and will have to deal with their drawbacks.

Lead alloys have been used for decades to reduce the bonding temperature of intermetallic compounds (IMCs), improve the quality of solder joints, and avoid the risk of tin whisker formation. Most lead-free alternative materials are not as abundant as lead, so their limited availability makes them more costly to use and challenging to obtain, compared to lead. In addition, lead-free solders can contain external layers of pure tin that are prone to whisker formation. Tin-lead solder provided excellent solderability, however, when PCB assembly manufacturers stopped using it on components, tin whisker growth was reported [6]. Assemblies manufactured with lead-free alloys must be at least as reliable as those made with tin-lead materials [7].

Tin whiskers can cause short circuits by bridging across electrical components [7]. Stable short circuits can occur in low-voltage, high-impedance circuits where there is insufficient current to fuse and destroy the whisker. A transient short circuit may occur if the available current exceeds the fusing current of the whisker. In this case, the circuit may only experience a transient glitch as the whisker fuses and is then destroyed, presenting as an intermittent failure of unknown origin. Depending on a variety of factors, including the diameter and length of the whisker, it can take more than 50 mA to melt the tin whisker. Another more destructive failure can occur when the short circuit produces a metal vapor arc (plasma). If currents above a few amps are available and the supply voltage is above approximately 12 V, the whisker will fuse and be destroyed but the vaporized tin may initiate plasma that can conduct over 200 A. An adequate supply of tin from the surrounding plated surfaces can help to sustain the arc until all available tin is consumed or the supply current is interrupted. Tin whiskers can also cause quality or maintenance problems because of the debris or contamination formed by the tin whiskers on the electronic boards. Whiskers or parts of whiskers may break loose and bridge isolated conductors remote from the original site of whisker growth. In addition, whisker debris may interfere with optical surfaces or the smooth operation of micro-electromechanical systems.

2.1. *Tin whisker-related failures and regulations in the nuclear industry*

On April 17, 2005, a protection mechanism was actuated unexpectedly in the Unit 3 reactor at the Millstone Nuclear Power Station in Connecticut, USA [5,8]. The reactor shut down suddenly because its steam system protection electronics detected a pressure drop, which was out of specification and typically occurred when there was leakage in a steam line. The fault was identified in a Westinghouse solid-state protection system (SSPS) circuit board that caused the reactor to trip the injection protection system. The NPP operator examined the failed circuit board and observed a 2-mm-long tin whisker that bridged between a diode and an output trace on the circuit board [8]. The tin whisker had grown out of the tin coating, which covered the leads of the diode. The operator checked other SSPS circuit boards and also observed tin whiskers on them. In all cases, the tin whisker seemed to grow from the tin coating on the diode.

A similar situation occurred in the Unit 3 reactor of France's Dampierre Nuclear Power Plant on April 9, 2007 [9]. The reactor lost the ability to engage its emergency diesel generator because of a relay failure that caused the loss of one of the two safety switchboards. The entire switchboard function was lost and could only be accessed from the duplicate switchboard. Synchronous malfunctions made the situation worse and eventually led to an emergency shutdown of the reactor. Analysis of the faulty switchboard and relay revealed that zinc whiskers, which are similar to tin whiskers, had caused the incident. The operator inspected all similar safety relays on identical units and found that almost all of them were affected by these whiskers, although the extent varied.

Table 1 summarizes selected whisker-induced failures in the nuclear industry [10]. In most cases, conductive whiskers induced short circuits in the local power range monitor (LPRM) detectors, which resulted in a momentary spike of the average power range monitors (APRMs). In other cases, failures in the channel input relay of the engineered safety features (ESFs) actuation logic were found. Most of these failures did not induce a full reactor protection system (RPS) or the ESF actuation