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Tin Whiskers in Electronic Circuits

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Fibrous, conducting"whiskers" often grow on pure tin plating. These tin whiskers have, for many years, been known to pose a reliability problem in electronic circuitry. The use of pure tin coatings in any critical electronic application is therefore not recommended. Despite the warnings of the experts, tin plating is still found on electronic and mechanical components and problems with whiskers still arise. This document summarizes what is known about the growth of tin whiskers. A number of factors (e.g., coating thickness, plating conditions) are thought to be important in determining whether whiskers will grow. Although tin whiskers have been investigated from some decades, there is still disagreement on the effects of virtually every coating parameter. There is no disagreement, however, on the essential fact that it is very difficult to predict with certainty whether whiskers will grow on any specific tin-plated component, which of course is the basis of the "experts" advice not to use pure tin plating.

If tin-plated components are found in an electronic system, replacement is the safest policy. Some additional recommendations to minimize risk are presented here that may be of use in situations in which replacement of all suspect components is not the option of choice because of cost or schedule constraints.

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I. INTRODUCTION

A number of programs have recently encountered whiskers on tin-plated electronic components. Whiskers, as their name implies, are fibrous growths that characteristically have lengths much greater than their cross-sectional dimensions. These conducting metal whiskers can cause electrical shorting. This document briefly summarizes what is known about the growth of tin whiskers and, just as importantly, points out what is not known with certainty. Despite the fact that whisker growth on electronic components has been a matter of concern for more than 40 years,[1,2] many aspects of the phenomenon are still not completely understood. Contradictory results abound in the literature.

Metal whiskers are single crystals and are very strong because of the absence of internal defects such as dislocations. Their interesting mechanical properties made whiskers a very popular research area in the 1950s and 1960s. In recent decades, interest has largely centered on the use of whiskers in fundamental investigations of superconductivity.

Whiskers are known to grow spontaneously from the surfaces of a number of metals including tin, cadmium, antimony, indium, and zinc and less frequently from lead, iron, silver, gold, nickel, and palladium.[3] Whisker growth is, however, most commonly associated with coatings of tin.

This discussion is limited to the growth of whiskers on tin coatings. The available experimental data on tin whiskers will first be summarized. Theories of the physical mechanisms of whisker growth will then be described in order to gain a better understanding of the phenomenological observations. Finally, recommendations on how best to deal with whiskers in practical situations will be offered.

II. PHENOMENOLOGICAL OBSERVATIONS

Studies of whisker growth have tended to employ very simple and not very well controlled experimental methods. Typically, tin-plated specimens have been prepared and placed in storage. The investigators then sit back and wait, observing the specimens at intervals.[4] Among the variables that might influence whisker growth on tin coatings are: coating thickness; impurity concentration; the nature of the substrate on which the coating is deposited, temperature, plating process parameters, and the applied stress. These variables have been poorly defined in many experiments.

A. PHYSICAL APPEARANCE

Tin whiskers have a distinctive appearance. Their size varies, with the smallest reported whiskers having diameters of about 6 nm and the largest having diameters of 6 µm. Diameters of 3 to 4 µm are most common.[1,2] Whiskers are quite straight, although they may jog abruptly (Fig. 1). The angles through which the whiskers suddenly turn are not arbitrary, but are related to their crystal structure. Whisker population densities typically range between 5 - 300 /mm [2, 5] Whiskers are visible using an optical microscope at relatively low (3-10 X) magnification. Lighting conditions are critical, however, and whiskers can easily be overlooked. The whiskers themselves are often associated with larger eruptions of the tin termed "nodules". Nodules have no particular orientation and are reminiscent in appearance of toothpaste squeezed from a tube.

B. GROWTH RATES

Reported growth rates of tin whiskers range between 0.03 and 9 mm/year.[1] Measurement of growth rates is fairly simple, requiring only occasional optical or electron microscope examination of test specimens. Ambiguities arise in attempting to control the numerous variables that affect the growth rate. Many studies have reported that an "induction period" is associated with whisker growth, i.e., for some time after the coating is deposited, no whisker growth is observed. The growth of whiskers only after 8 to 10 years of storage has been noted.[5] Whiskers do not continue growing indefinitely. Growth eventually slows and stops although maximum lengths can reach several mm.[2]

1. Substrate Effects

The nature of the substrate on which a tin coating is deposited is reported to be an important factor in whisker growth. The substrates most often studied, steel and brass, are the metals most important in commercial applications of tin plating. Most authors agree that whiskers grow rapidly and with a short induction time (several days) on tin-plated brass. Whiskers on brass have been observed to grow at about 8 µm/day.[2] Tin-plated steel can take several months to exhibit short whiskers. It should be noted that some earlier workers came to exactly the opposite conclusion, i.e., that whisker growth occurred on tin-plated iron but not on tin-plated brass or copper.[3] Some authors report that copper undercoats are effective in reducing whisker growth on brass substrates.[4] Other researchers differ.[5]

2. Coating Thickness

Whiskers are not usually seen on bulk tin.[3] This observation implies that there should be some maximum thickness of tin coatings on which whisker growth can occur. Various authors have suggested that this maximum thickness is 8 µm, 12 µm, and 18 to 20 µm[1,4,5] Given the other uncertainties in the field, this degree of agreement should be considered good. Whisker growth clearly must cease

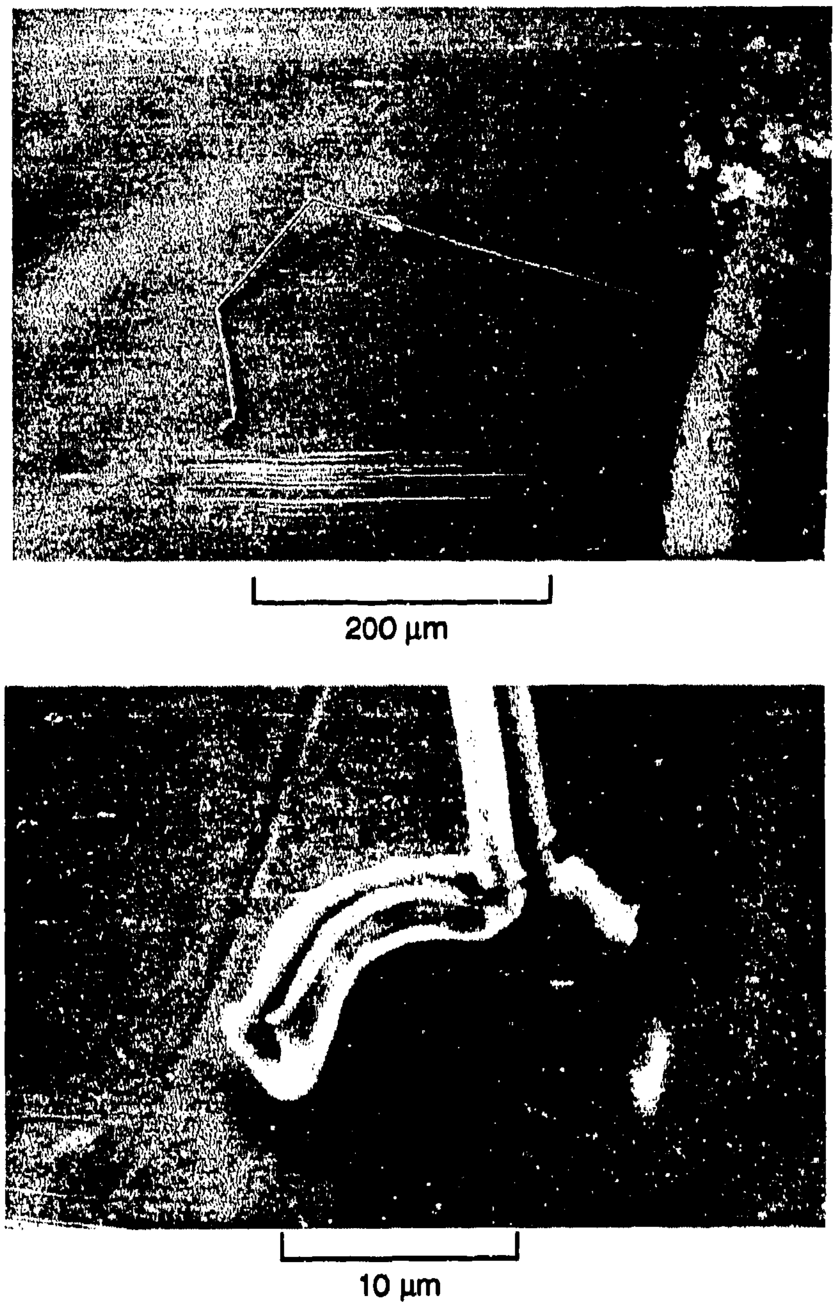

Figure 1. Tin whiskers (ref. 2).

as the coating thickness (i.e., the amount of tin) decreases to zero. Given the lack of growth on bulk material, it is therefore logical to expect that for coatings thinner than the roughly 8-20 µm maximum thickness cited above, whisker growth rate will increase with decreasing thickness until some limiting lower thickness is reached. This expectation is borne out experimentally. Profuse whisker growth has been reported on 1.25-µm thick coatings, while 0.5-µm coatings did not develop whiskers.[6]

3. Impurities

Whiskers are not reported to grow on tin-lead alloys, including of course, solder. Concentrations of lead greater than about 1% are said to "greatly reduce" whisker growth.[1, 7] Note that some other elements can be incorporated in small concentrations in tin whiskers. Dunn found that whiskers grown on steel substrates and on brass substrates with a copper intermediate layer were pure tin (within the detection limits of energy dispersive x-ray analysis).[5] Whiskers grown on tin-plated brass incorporated about 2% by weight of zinc. Certain constituents added as brighteners to plating baths supposedly promote whisker growth.[1]

4. External Stress

Although the driving force behind whisker growth is certainly mechanical stress, the origin of the stress is in dispute. Consider the following statement:

> *Whisker growth rate is almost directly proportional to the compression stress exerted on the material. It is possible, by applying pressure, to accelerate whisker growth to a degree perceptible to the naked eye. As it is, whisker growth can be provoked by subjecting allergic materials to compressive stress, for example, by clamping them in a vise: after a lapse of only a few hours whiskers develop immediately adjacent to the area of clamping ("squeeze" whiskers). On this account, in load-carrying applications, tin coatings must be avoided. Clamped connections, such as in bolted constructions, are rather sensitive and tin whiskers can occur even if the top coat is of hot-dipped tin-lead.*[1]

In other words, it is asserted that externally applied macroscopic stress is an important factor in whisker growth. This view has the support of other authors. Contrast the above statement with quotes from the author of some of the more recent studies who asserts that external stress is not a major factor in whisker growth:

> *"Highly" stressed samples do not reflect short nucleation times for whisker growth, or support longer whiskers than observed on the unstressed C-rings. A major finding was that compressive stresses applied to tin plate did not accelerate whisker growth rates.*[5]

At the end of the first of the above quotations, note that the author has added the caveat that "squeeze" whiskers can grow even on tin-lead solder in regions of high compressive stress, e.g., near bolts. The same assertion has been made by at least one other author.[8]

5. Temperature

Coating thickness does not appear to decrease even around regions of profuse whisker formation. Tin must clearly be supplied to the growing whiskers by diffusion from considerable distances. Diffusion rates depend on temperature as $(\exp(-Q/kT)$, where Q is an activation energy, and the whisker growth process would be expected to be highly temperature dependent. However, increasing the temperature helps anneal the stress also essential for whisker growth. It has therefore been suggested that each metal should have a temperature range optimal for whisker growth, which for tin is said to be 60 to 70°C.[1] Few, if any, studies of whisker growth as a function of temperature have been reported.

6. Ambient Conditions

A hot, humid atmosphere is reported to promote whisker growth. Whisker growth has, however, been seen in vacuum.[1]

7. Plating Conditions

Many authors state that whisker growth on electroplated tin depends on the conditions of the plating bath. The bath temperature, plating current, and impurity content are probably important parameters in whisker growth. Unfortunately, these effects have been not quantified to provide predictions of the susceptibility of a coating to whisker formation based on deposition conditions.

C. MECHANICAL PROPERTIES

The mechanical properties of whiskers have been measured using essentially standard techniques albeit complicated by the small size of the test specimens. Young's modulus, the ratio of applied stress to strain, gives an indication of the stiffness of materials (strain is by definition the change in length of a material divided by its length). Dunn determined the Young's modulus of whiskers by measuring their deflection as a function of the applied force.[9] Measured values fell into two ranges characteristic of two growth directions, with an average value of 3200 kg/mm^2 (3.14 X 10^{13} dynes/cm^2). In contrast, Young's modulus is around 10^{11} dynes/cm^2 for most bulk metals. Tin whiskers, in other words, are quite stiff. The ultimate tensile strength of the whiskers was found to be 0.8 kg/mm^2 (7.8 X 10^7 dynes/cm^2). The ultimate tensile strength of bulk tin is about 1 kg/mm^2. Because they are dislocation free, however, whiskers can withstand considerable strain without breaking. Tin whiskers thus have a relatively low tensile strength and are highly ductile. Dunn also investigated the response of whiskers to mechanical vibration. Whiskers were not broken or dislodged from tin plated specimens even when subjected to accelerations of 6 g for 60 s, in air, at frequencies near their natural mechanical resonance (50 - 250 Hz). Mechanical shock at 2060 g also did not break any whiskers. Ultrasonic vibrations in liquid did remove whiskers from surfaces, although not from the interiors of plated through-holes in printed circuit boards. Once again, as one comes to expect in this field, other workers differ. Some say that whiskers are easily broken by mechanical shocks. In one fairly recent study undertaken to investigate the reliability of electronic systems in U.S. Air Force aircraft, tin whiskers were said to have formed and broken loose inside hybrid circuits used in radar units.[10] Both intermittent and permanent, irreversible failures were attributed to these "floating" whiskers.

D. CURRENT- CARRYING CAPACITY

The current-carrying capacity of whiskers is a topic which arises frequently in discussions of their potential effects on electronic circuits. Dunn plucked whiskers from a tin-plated specimen using tweezers and attached them to glass microscope slides with silver epoxy adhesive.[9] Electrical contact to the whiskers was made by mechanical probes. The whiskers were observed in an optical microscope, and the current through and the voltage drop across the whiskers were recorded. The current was increased until burn-out. At low currents, the whiskers had the resistivity of pure tin (11.3 μΩ/cm) and their I-V behavior was linear. At higher currents, joule heating became important and the measured resistivity increased. Some of Dunn's data are reproduced in Table 1.

These measurements of the current-carrying capacity of whiskers are, for several reasons, not very precise. The surface area of the whiskers is uncertain since they are often fluted cylinders rather than perfectly circular cylinders. In fact, Dunn points out that a number of studies assert that whiskers are often hollow.[3,11] Connection of probe electrodes, as in the experiments cited in Table 1, can lead to uncertainties in the accurate determination of whisker length. Dunn plotted the data of Table 1 to give designers a quick, though rough, graphical indication of the burn-out characteristics of tin whiskers. His plot has been reproduced in Fig. 2. Note that this graph is based on only the four data points in Table 1 and must be considered qualitative. Additional collaborative data are provided by Arnold who states that tin whiskers 2mm long burned out at 10 mA.[12]

E. ELECTRICAL DISCHARGE

High electric fields arise at the surfaces of charged conductors with a locally high radius of curvature (i.e., "points"). The sharp ends of tin whiskers are no exception. Electrical discharges at whisker tips are another mechanism by which whiskers may affect electronic circuits even though the whiskers may not actually provide a continuous path between two conductors. Dunn observed discharges from the ends of whiskers being examined in a scanning electron microscope.[9] The electron beam of the microscope itself caused the whiskers to charge and the effects were easily observable.

Table 1. Measured Current-Carrying Capacity of Tin Whiskers

Diam. (μm)	Length (mm)	Max. Curr. (mA)	Max. Curr. Dens. (A/cm^2)
1.1	0.3	10	10.0×10^5
1.5	0.7	20	11.0×10^5
3.0	0.8	32	4.5×10^5
2.8	0.8	22	3.5×10^5

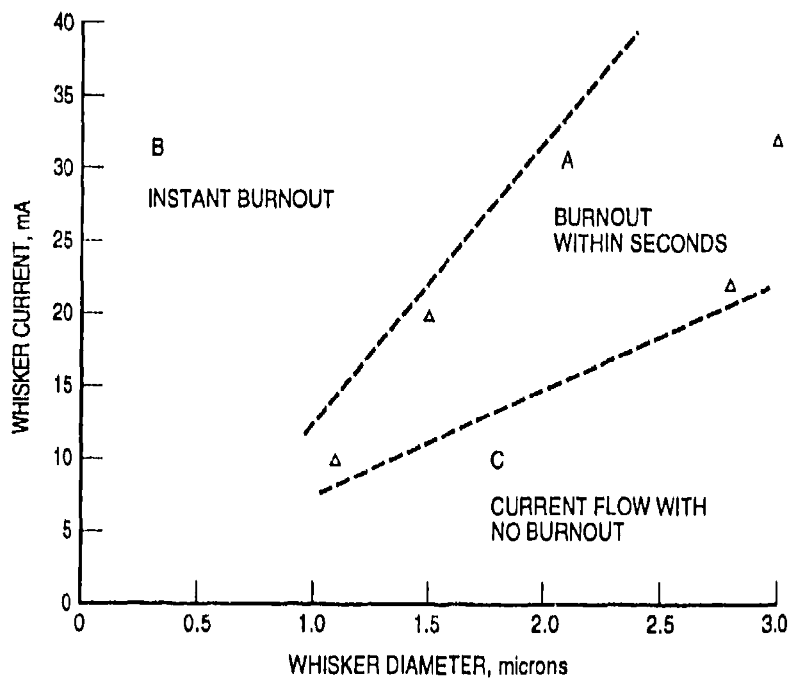

Figure 2. Burn-out characteristic of tin whiskers

III. DISCUSSION

A discussion and interpretation of some of the phenomenological observations, in particular a consideration of possible whisker growth mechanisms, will hopefully help to sort out the often seemingly contradictory experimental results.

A. WHISKER GROWTH MECHANISM

Some "facts" appear firmly grounded. Whisker growth is a purely mechanical phenomenon. Unlike certain quite different dendritic growth phenomena which can also lead to long, fibrous structures, neither moisture, ionic species, or electric fields are necessary for the generation of tin whiskers. The metal whiskers considered here are sometimes also termed "proper whiskers" or "spontaneous whiskers". They grow from the whisker base by extrusion of material from the substrate. Clearly, tin atoms must migrate from the surrounding substrate in response to some driving force. Models of whisker growth must explain both the actual extrusion of the whisker and the origin of the driving force.

Dislocations in tin coatings are certainly involved in whisker extrusion. Dislocations are formed by misalignments of crystal planes in the tin lattice. Material on opposite sides of the dislocation are displaced or "slipped". An edge dislocation corresponds to a missing plane of atoms, while in a screw dislocation ,the boundary between slipped and unslipped material parallels the slip direction (Fig. 3).

A screw dislocation arranges successive atomic planes into the form of a helix. A step is formed when a screw dislocation intersects a surface. Atoms are much more likely to adhere to the surface at such a step than on flat regions. Whiskers of some nonmetallic compounds are known to grow from the vapor phase by deposition at the tip of the extruding whisker. The role of dislocations in such a case is easy to visualize. The whisker grows out as atoms are added at the step. For tin whiskers, which

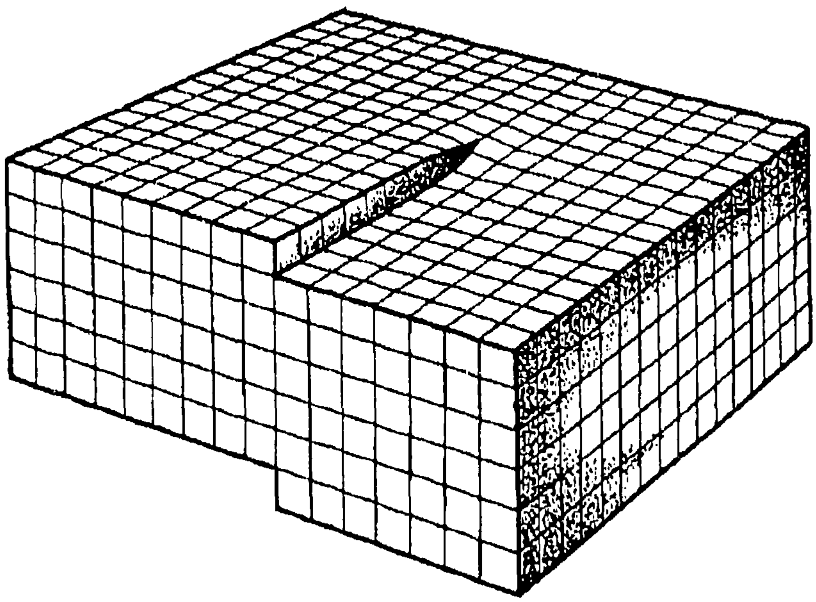

Figure 3. A screw dislocation in a crystal lattice (from ref. 13).

are known to grow at the base, a screw dislocation mechanism is also operative although the active region is interior to the tin. The "extra" tin atoms which feed the whisker, and a compensating number of lattice vacancies (i.e., holes in the crystal lattice), can be generated by known mechanisms such as Frank-Read sources or at grain boundaries.[13] Tin atoms fed into the active whisker region then cause the whisker to grow out from the surface. Note again that the atoms reaching the growth region are supplied by diffusion from a considerable distance. Thinning of the coating near the whisker base is never observed.

We turn now to a consideration of the driving force behind whisker formation, i.e., what causes the atoms to move? The driving force is generally conceded to be mechanical stress, but much of the uncertainty and controversy in the metal whisker area centers about the precise origin of this stress.

One of the first models of whisker growth attributed the development of stress to oxidation of the whisker surface.[14] The subsequent observation of whisker growth in vacuum shows that the oxidation mechanism clearly can not be entirely correct, but it is likely that oxidation or corrosion of substrate material underlying tin plating do contribute to whisker growth. If the volume of the corrosion products at the tin/substrate interface exceeds that of the original material, the overlying plating will be in compression.

B. D. Dunn, who concluded that external macroscopic stress does not affect whisker growth, attributes the whisker phenomenon entirely to microscopic local stress.[5] Dunn includes stresses built-in during coating deposition within his definition of microscopic stress. His model was developed largely from data on whisker growth on brass but has been generalized to other substrates. On brass or copper, the internal microscopic stress is produced by diffusion of zinc or copper through tin or along grain boundaries and by the formation of the intermetallic compound Cu_6Sn_5. In this model, whisker growth should slow or cease when the recrystallizing tin grains have grown to dimensions comparable to the coating thickness. There is experimental evidence in support of this prediction. Intermetallic compounds are not formed between tin and the constituents of steel. As the driving force in this case, Dunn suggests grain boundary diffusion or oxidation at the plating interface.

Dunn, a researcher at the European Space Agency, points out that thermal cycling, static charging, and particle irradiation can introduce stress in coatings used in the space environment.[2] Although the vacuum environment itself should not promote whisker growth, and in fact is very likely beneficial, thermal cycling, charging, and radiation can of course be encountered after launch. These factors all can generate internal stress. Before launch, a poorly controlled humid environment would likely contribute to whisker formation.

B. CURRENT-CARRYING CAPACITY

Reasonable agreement can be found on the current-carrying capacity of whiskers. Current-carrying capacity is of considerable interest since it is often argued that whiskers will be blown open if sufficient current is available.

The experimental observations cited in Section II, which indicate that typical whiskers burn out at currents on the order of milliamperes to tens of milliamperes, are in reasonable agreement with a simple model. The temperature distribution in a whisker electrically shorted between, say, a tin-plated transistor case and a neighboring metal wall, can be calculated by assuming that the situation is approximately represented as a problem in one-dimensional heat flow. Maximum current is reached when the whisker is heated to the melting point. Details of the calculation are included in the Appendix. The essential result is that

$$I_{melt} = .076 \frac{A(\mu m^2)}{L(cm)} mA$$

For a whisker 3 µm in diameter and length 0.1 cm, evaluation of this expression yields I_{melt} = 5.4 mA, a number which could be considered to be in satisfactory agreement with the available data. The current-carrying capacity of a whisker should be inversely proportional to its length, a dependence that does not seem to have been taken specifically into account by Dunn, possibly because of the limited number of whiskers measured.[9]

C. DISCHARGE PHENOMENA

Spark and glow discharges depend on the ambient pressure. A few free electrons are always available in any gas. As the pressure is reduced, the mean free path of electrons in the remaining gas increases. If an electric field is applied, electrons will be accelerated, and when the energy that they can gain before a collision (i.e., the electric field times the mean free path) equals the ionization energy of the atoms in the gas, a cascade of free electrons and ions can establish a conducting path. This is a glow discharge. The relevance of these considerations to the problem of whiskers on spacecraft lies in the fact that discharge conditions can change quickly during launch. While potentially serious, discharge effects involving whiskers are difficult to quantify.

It has also been suggested that a glow discharge, once initiated, will result in the vaporization of metal (tin or perhaps other nearby metals). The vaporized metal forms a conducting plasma which can carry more current than the whisker itself for some period of time.[15]

D. PREVENTION AND AMELIORATION OF WHISKER PROBLEMS

1. During Manufacture

A number of authors have given their recommendations on design steps to be taken at the time of manufacture to prevent or ameliorate whisker growth.[1,4,5] Note that the recommendations of earlier authors have not always been accepted by later researchers.[5]

The use of hot dipped layers instead of electroplating is suggested. Dipped coatings presumably have less built-in stress. "Refusing (reflowing)," i.e., briefly heating electroplated coatings above the melting point of tin, is also often suggested as a method of whisker reduction.

As stated in the above discussion, pure tin coatings should be more than about 10 µm thick, although this thickness does not guarantee the absence of whiskers.

NASA (the NASA Parts Project Office, Goddard Space Flight Center) states that their electrical, electronic, and electromechanical parts are procured in conformity to various MIL standards.[16,17] It is further claimed that although the standards vary in their effectiveness at minimizing whisker growth, their effectiveness is "understood and predictable". This statement does seem rather bold in view of the considerable disagreement evident in the literature, but presumably reflects the particular experiences of NASA. Printed circuit boards, specifically, are protected either by "tinning" (i.e., the application of tin/lead solder rather than pure tin) or by the use of conformal coatings.

2. In the Field

It is recommended that storage conditions should be such as to minimize corrosion of the underlying metal (i.e., clean, dry environments are best).

It has been suggested that conformal coatings applied to both the tin surface and the surrounding surfaces which whiskers might contact could prevent shorting. It is unlikely that the emergence of whiskers would be completely prevented by a conformal coating. At least one paper alleges, without citing any specific evidence, that whiskers will be deflected by a second coating layer on adjacent surfaces.[8] Unfortunately, not all tin-plated surfaces may be accessible for conformal coating. Transistor cases, for example, are tin plated on the bottom as well as on the top and sides. Britton does make the (rather obvious) statement that

> *Although organic coatings of the thickness commonly used for protection cannot be relied on to prevent emergence of whiskers, the use of thick layers of resin or the introduction of a solid insulating barrier between points in danger of shorting is effective.*[4]

There do not appear to have been any systemic studies of the effectiveness of conformal coatings against shorting caused by whiskers. Furthermore, the introduction of additional materials in electronic modules may lead to other problems, such as contamination by volatile species present in the coating materials. Space-qualified polymeric conformal coatings are available.

The only other advice offered by the experts for the rehabilitation of bewhiskered electronics is physical removal of whiskers followed by use of a small vacuum cleaner with alternate "blowing and sucking" to clean up the debris.[4] Such a cleaning procedure does not of course preclude additional whisker growth and can not be recommended as appropriate for high reliability applications.

IV. SUMMARY AND CONCLUSIONS

The information summarized demonstrates that although tin whisker growth is understood in general terms, some facets of the phenomenon have not been investigated under sufficiently controlled conditions to permit the explanation of all details in all circumstances. There is, therefore, general agreement that accurate predictions of whether or when a particular tin coating will exhibit whisker growth are simply not possible. All of the experts strongly recommend that electronic components plated with pure tin not be used in high reliability applications.[1,2] The use of tin-lead coatings eliminates whisker problems and is much preferred, although there is some evidence that "squeeze" whiskers may be formed on solder under bolts.

This conclusion, unfortunately, does not offer much comfort or guidance to those people whose electronic "boxes" already contain tin-plated components. If blanket replacement of all suspect components is deemed undesirable on grounds of cost or schedule impact, the best course of action would seem to be careful inspection of the hardware with a low powered optical microscope, *under appropriate lighting conditions, for* whisker formation. If whiskers are noted, the affected components should be replaced. As a less desirable alternative, the use of conformal coatings may be attempted. The wisest course of action dictates a review of the construction of all tin-plated parts and, at a minimum, the replacement of any devices with brass or copper substrates. Tin -plated steel, although not immune to whisker growth, does seem less susceptible to the problem. If tin plating thicknesses can be determined for the suspect part types, prudence would dictate replacement of any parts with less than about 8 µm of tin. Again, conformal coatings can be applied to remaining tin-plated components and to adjacent conducting surfaces as a precaution if the tin-plated components can not be replaced. Unfortunately, coatings will not completely guarantee that shorting caused by whiskers will be precluded, and the coatings themselves may cause unforeseen difficulties. Conformal coating of some areas such as the bottoms of transistor cases may be impractical and again, in this situation, replacement would be indicated.

The location and function of tin-plated components should also be evaluated. The most danger to mission success is presented by whiskers causing shorts in signal circuits. In power supply and other circuits that can source currents larger than tens of milliamperes, the whiskers may burn off. It is still necessary to consider whether transients associated with whiskers can be tolerated in high current circuits. The launch phase would be expected to be a critical time for power supply circuits because of possible discharge effects. On orbit, in vacuum, discharge phenomena should not be as great a problem.

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APPENDIX
CURRENT-CARRYING CAPACITY OF TIN WHISKERS

It is often argued that whiskers will be blown open if the available current in a particular application is sufficiently large. The experimental data have been summarized in this report. The maximum sustainable current can also be calculated assuming that the current-carrying capacity of a whisker is limited by melting of the tin. The calculation is presented in this Appendix as a guide for those interested readers who might wish to pursue the matter further.

It is assumed that the temperature distribution in a whisker internally heated by ohmic loss is adequately represented as a problem in one-dimensional heat flow. The basic definition of heat flow is:

$$F = -\kappa \nabla T \tag{1}$$

where F is the thermal flux and κ is the thermal conductivity. The continuity equation is:

$$-\nabla \cdot F + \dot{Q} = C_v \frac{\partial T}{\partial t} \tag{2}$$

where

$$\dot{Q} = \rho \cdot J^2 \tag{3}$$

is the resistive heating/unit volume. J is the current density(i.e., the current per unit area). The temperature in a whisker of length "L" and area "A" in the steady state, constrained to a constant temperature T_0 at the ends (i.e., we assume the whisker shorts between massive heat sinks), is found to be

$$T(x) = T_o + \frac{1}{\alpha}\left[\frac{\cos(\gamma x)}{\cos(\gamma L/2)} - 1\right] \tag{4}$$

where

$$\gamma^2 = \frac{J^2 \rho_0 \alpha}{\kappa} \tag{5}$$

κ is the thermal conductivity and J is fthe current density. The temperature coefficient of resistance of the wire, α, is explicitly included in this result, i.e., it is assumed that the resistance varies with temperature as

$$\rho = \rho_o \left(1+\alpha\left(T-T_o\right)\right) \tag{6}$$

The maximum temperature is at the center of the wire (x = 0 in the coordinate system chosen) and is given by

$$T_{max} = T_o + \frac{1}{\alpha}\left[\frac{1}{cos\left(\gamma L/2\right)} - 1\right] \tag{7}$$

The wire melts when

$$cos\left(\gamma L/2\right) = \frac{1}{1+\alpha\left(T_{melt}-T_o\right)} \tag{8}$$

If the temperature coefficient of resistance is not included, the solution of Eq. (1) reduces to a parabolic temperature distribution and in fact for tin, which melts at 232°C, the answer is not much different. Substitution of numbers in Eq. (5) yields a maximum current of

$$I_{melt} = .076\,\frac{A\left(\mu m^2\right)}{L(cm)}\,mA \tag{9}$$

This is the expression used in the numerical calculation presented in Section III.B.

For circuits in which operation is not continuous but pulsed, the thermal time constant of a whisker is of interest in estimating whether whiskers might be blown open. The calculation of the thermal time constant is therefore included here for completeness. A complete solution of the time dependent heat flow equation for the case in which the wire is being heated by a current is

$$T(x,t) = T_o + \frac{\rho J^2}{2\kappa}\left[\frac{L^2}{4} - x^2\right] + \sum_{n=1}^{\infty} A_n \cos\left(\alpha_n x\right) exp - \left[\alpha_n{}^2 \frac{\kappa}{c_v} t\right] \tag{10}$$

For a wire subjected to a current pulse at time $t = 0$, the coefficients A_n are selected so that the Fourier series expansion term cancels the second term at time $t = 0$, assuming that the wire is initially at a uniform temperature T_o. The $a_n = 2\pi n/L$, and one finds that the coefficients A_n are

$$A_n = -\frac{\rho J^2 L^2}{\kappa} \cdot \frac{1}{\pi^2 n^2} \; (n \; odd) \tag{11}$$

The solution for the case of a wire with some particular initial temperature is essentially the same. One just has to pick the coefficients to match the initial temperature distribution which then decays to a uniform temperature. One can construct the solution for the general case of a current pulse of duration comparable to the thermal time constant.

The essential point is that the transient terms decay with time constants given by

$$\tau = \frac{L^2}{4\pi^2 n^2} \frac{1}{\frac{\kappa}{c_v}} \tag{12}$$

with the longest time for $n = 1$. The quantity κ/c_v is known as the thermal diffusivity.

Are the calculated results sensible? The basic approach seems reasonable. Because the melting temperature of tin is low, neglect of any radiation loss from the wire (which varies as the fourth power of the temperature) certainly seems justifiable. Neglect of convection losses from the wire could certainly affect the results for whiskers heated in air, but of course would not be a factor in vacuum. The electron mean free path should be long enough at the temperatures of interest that the use of the bulk resistivity of tin is justified. In general, the agreement with the few available experimental results gives some confidence in the validity of the expressions derived.

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