Whisker Formation on Electronic Materials

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ABSTRACT—The filamentary growths of single crystals on material surfaces are termed whiskers. They are seen to nucleate and grow on certain electronic materials either from vapour and liquid phases or by a process induced by residual stresses in electroplated surfaces. Whisker growth does not depend on the existence of an electric field and surfaces prone to their growth may nucleate and form whiskers as a result of exposure to a space environment. This paper includes a detailed examination of tin whiskers which were found to have 1 to 4 micron diameters and lengths exceeding 2 mm. Some were found to carry currents between 22 and 32 mA before burning out. Conductive whiskers can cause extensive short circuit damage to spacecraft electronics particularly as miniature devices progressively employ closer spacings between conductors. Several modes of whisker growth on spacecraft electronic materials (molybdenum, tungsten, Kovar, tin) have been observed and are described. Tin, cadmium and zinc surfaces can support stress-induced whisker growth and it is recommended that these metal finishes are excluded from spacecraft design and possibly replaced by a tin-lead alloy.

INTRODUCTION

Scientists have been interested in the filamentary growth of crystals since long before the advent of the electronics industry. In the nineteenth century Robert Boyle observed that protuberances of silver on certain materials increased in length from one day to another. It was not until 1946 that single crystals, or whiskers, were found to grow on the surfaces of materials utilised in the manufacture of electronic circuits. Undoubtedly electrically conductive whiskers have inflicted detrimental effects to such circuits. Some of the typical electrical failures reported[1,2,3] to have been caused by whiskers include:

- channel-frequency filters failing when whiskers growing on a plated bracket bridged across air capacitors;
- a potentiometer which failed when whiskers fell across a coil winding;
- a copper oxide rectifier failed when whiskers bridged across tin plated terminals;
- a relay operating a circuit of 200 volts which had a persistent arc caused by tin whiskers.

The topic of whisker growth has often arisen during the course of the materials and processes meetings which are held at regular intervals with the many European contractors involved in the fabrication of European Space Agency (ESA) spacecraft hardware. Specialist materials engineers gathered at these meetings have expressed concern that surfaces prone to whisker growth could cause considerable damage to spacecraft electronic hardware. Although several engineers knew of electrical failures within their own companies which were accountable to whisker growth, commercial considerations had prevented such items from being made generally available for unrestricted failure analysis evaluations.

The scientific programmes initiated twelve years ago by ESA (originally the European Space Research Organisation) involved the building of satellites requiring a mission life of only one or two years.

The complex ESA Applications satellite programme and the SPACELAB programme must have mission life requirements assured for periods of up to at least seven or ten years respectively. It has therefore become essential that ESA place a greater emphasis on confirming the reliability of many technologies which, until now, have been accepted as virtually fault-free. In this context a literature survey and a short laboratory examination was initiated in the Materials Section at ESTEC which would evaluate the problem of whisker growth on tin-plate. Such coatings were previously used quite extensively as protective, solderable finishes in satellite design.

One poor quality electronic box containing a failed tuner circuit (not space equipment!) was submitted to our laboratory for examination. It was noted to support an abundance of whiskers. The donor stated that whiskers had started to grow inside the box during the first year and that their growth had continued for ten years to their present size. The steel box had been electroplated with a matt tin finish and the soldering of its contents was carried out with cored eutectic tin-lead solder having a halogenated flux. This item had been stored under ambient conditions throughout its life.

SOME BASIC PROPERTIES OF TIN WHISKERS

Experimenters[4] have shown that tin whiskers can grow from various tin plated substrates in environments of vacuum at 10^{-5} mm Hg, dry oxygen, a high humidity of 98 % RH, vaseline oil and even through films of shellac and polyvinyl chloride. The surface morphology of tin, zinc and cadmium whiskers have been studied by scanning electron microscopy.[5] All growths have been noted to possess very similar appearances, being cylindrical and either straight or with a small number of sharp kinks joining straight segments. Their diameters ranged from 2 to 5 microns whereas a large variation in length was seen to range from 0.03 mm to 10 mm. Current carrying capacities of tin whiskers have previously been reported of up to 10 mA, a property which would account for many in-service electrical failures.

Stress accelerated methods of growing tin whiskers have been described by Fisher, Darken and Carroll.[6] They found that by compressing a stack of small square pieces of tin plated steel sheet, such as that from ordinary tin cans, whiskers would sprout from the edges adjacent to the stressed region. By using this method of "whisker production" experimenters have spent many trying hours, working under high powered stereo microscopes, plucking off whiskers and locating them into test jigs in order to perform electrical and mechanical tests. Under certain conditions such whiskers have been found to behave as superconductors, and under uni-axial tensile forces they will withstand far larger stresses than bulk tin material.[7,8]

LABORATORY EXAMINATION OF WHISKER-GROWING SUBSTRATE

Visual Inspection

The submitted electronic box was initially visually inspected with a binocular microscope at magnifications of up to × 10. Certain areas were then viewed with a Reichert projection microscope at far higher magnifications. The overall view of the box is shown in Figure 1. At a magnification of × 2 the internal walls of the box were noted to have a furry appearance. Bright flashes of reflected light were transmitted through the microscopes, from random spots on the box surface as its orientation was slightly changed (see Figure 2). At slightly higher magnifications the whisker colonies became clearly visible. Figure 3 details an oblique view of whiskers adjacent to a mechanical gear wheel inside the box. Figure 4 shows whiskers to have grown sufficiently long to have collided with an exposed inductor coil. These figures clearly highlight the dangers of whisker dislodgement as caused by mechanical forces and also the possibility of electrical short circuiting. The typical topography of the internal surface of the box is detailed in Figure 5. Several whiskers were measured with a graticule attachment to the light microscope and lengths exceeding 2 mm have been recorded.

An interesting feature of the box is that no whiskers were seen to have grown on its external surfaces. The internal surfaces had been directly soldered to in several positions. No whiskers were observed to have nucleated within 1 mm distance of the solder fillet peripheries and none were present on the tin-lead surfaces.

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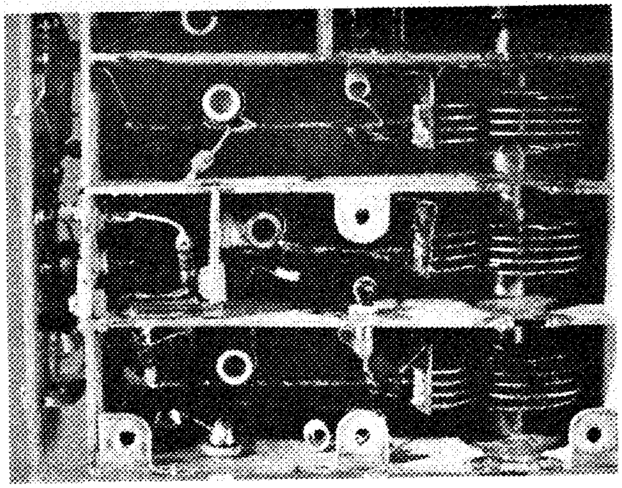

FIG. 1. *Overall view of electronic box with tin plated steel sides.*

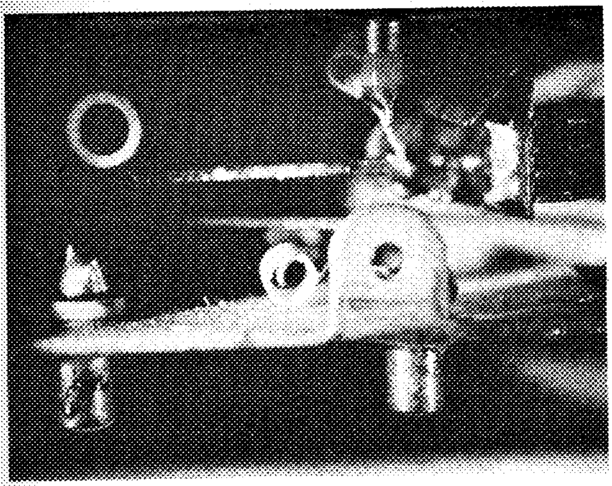

FIG. 2. *Whiskers become visible at a magnification of ×2.*

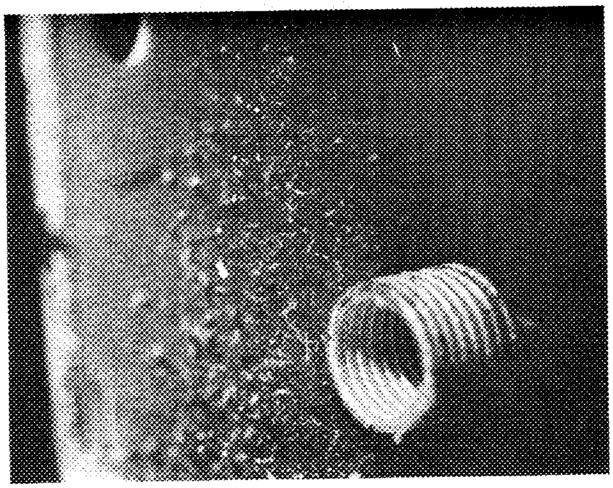

FIG. 4. *Whisker growth clearly visible adjacent to inductor coil within box at ×6 magnification.*

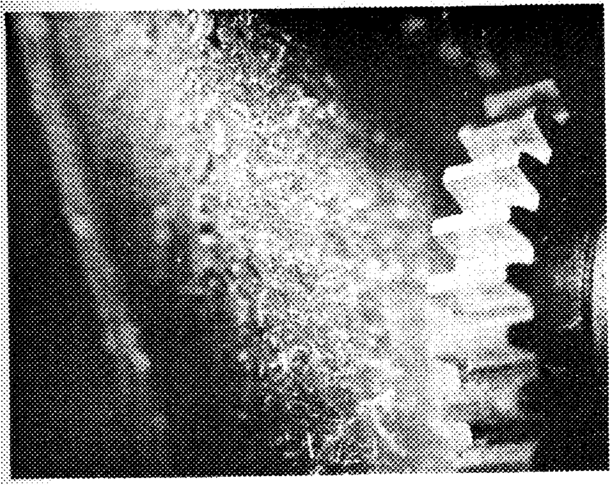

FIG. 3. *Whiskers colony clearly visible adjacent to mechanical gear wheel within box at ×6 magnification.*

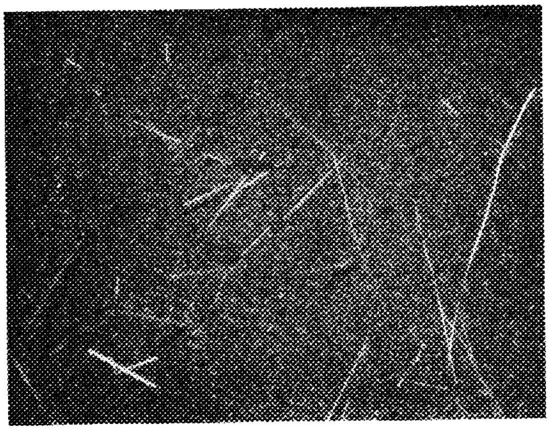

FIG. 5. *Light microscope image of whiskers having a length of 2 mm.*

Adhesion Test

Several small areas of the tin plated steel were very carefully removed from the box wall with a jeweller's saw. A controlled adhesion test,[9] employing pressure sensitive tapes and a tensile testing machine, was applied to both surfaces of these cut samples. The external tin plating was noted to be firmly attached to the steel substrate whereas the internal whisker supporting tin surface was detached from the substrate with average loads of 160 grams per cm width of tape. The underside of the separated tin plate is seen in Figure 6. The longitudinal markings replicate the surface finish of the steel plate. The crazing effect reflects the brittle nature of the plated deposit.

Scanning Electron Microscope (SEM) Study of Whiskers

The extensive depth of focus provided by the SEM facilitated topographical examination of the whisker growths. The general appearances of these whiskers are seen in Figures 7 to 15. Frequently the whiskers are noted to have a uniform direction of growth. Whisker diameters vary from 1 to 4 microns and their surfaces are characterised by the presence of longitudinal striations which run parallel to the direction of growth. Occasional whiskers, as in Figure 9, were noted to have very irregular growth directions. The change in growth direction or kinks, were usually associated with an angular displacement of about 45 degrees. The variation in whisker diameter is seen to be similar to the average size of the nodular-like grain pattern seen on the plating surface in Figures 9, 14 and 15. The incipient whisker seen in Figure 9 has a rounded end, quite different from the "stepped" end of the whisker seen in Figure 13 which has the appearance of a fractured surface. The change in diameter of a whiskers' shaft, as in Figure 11, appears from its surface morphology to be due to the presence of an edge dislocation.

The X-ray energy dispersive analyser attachment to the SEM was used to make point analyses of the plating and at several positions along the length of individual whiskers. The resultant characteristic X-ray peaks revealed only the presence of tin, other elements present in excess of about 50 parts per million were not observed.

Measurement of Whiskers' Current Carrying Capacity

Several whiskers having lengths of more than 1.5 mm were carefully plucked from the tin plated box and attached at their ends

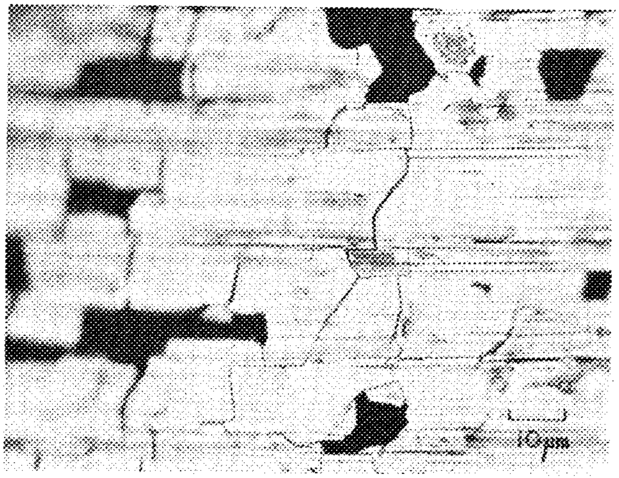

FIG. 6. *Underside of thin tin plating following its detachment from steel plate during adhesion test.*

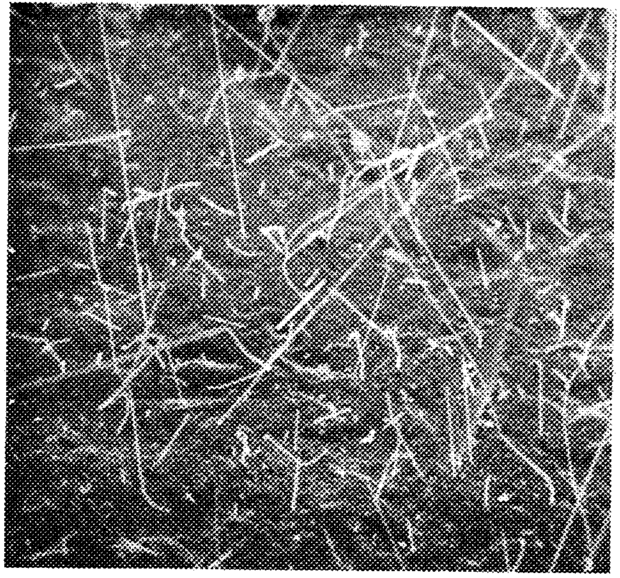

FIG. 7. *Scanning Electron Micrograph showing general appearance of growing whiskers.*

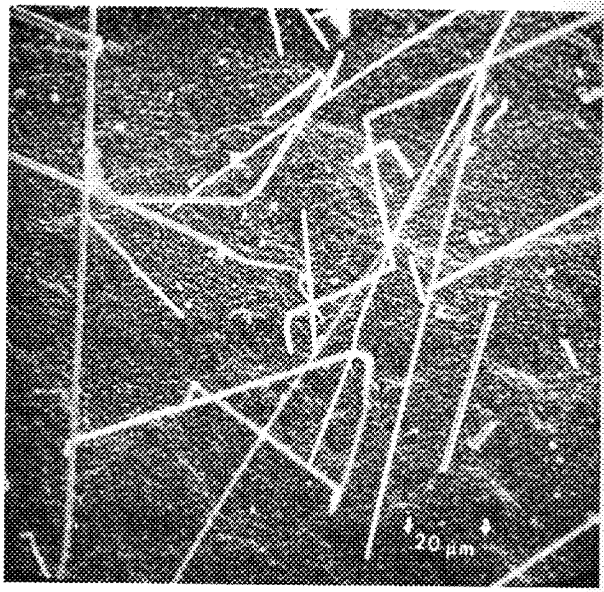

FIG. 8. *SEM view of whiskers showing uniform diameters along their lengths.*

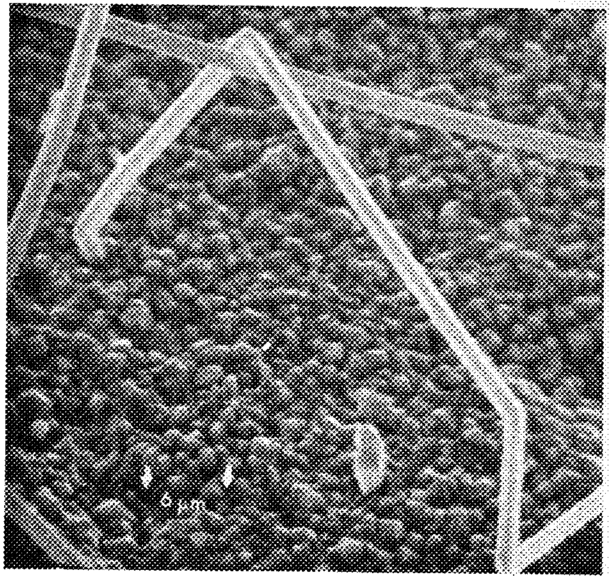

FIG. 9. *Detail of a whisker with a very irregular growth direction and an incipient whisker.*

to clean glass microscope slides with small deposits of silver-loaded epoxy resin, all under a high power stereo microscope and by means of hand-held microtools. The diameter of the whiskers were at, or below the resolution of this microscope and with the unavoidable transmission of vibrations from one's hand to the tweezers many attempts had to be made in order to produce four ideally mounted samples (see Figure 16). Each glass slide was placed on to a microprobe station. Two probes were manipulated on to the silver loaded epoxy patches but this composite material had insufficient conductance for any sensible current carrying measurements to be made on the Tektronix 576 visual display unit. Instead, the thoroughly cleaned probes were slowly positioned to rest on the whisker surface at a separation distance of approximately 0.8 mm. Successful current carrying measurements were obtained for two whiskers. The following results refer to the moment just prior to the burning out of each whisker:

Whisker	Measured Diameter (microns)	Measured Current mA	Measured Voltage V	Current Carrying Capacity (approx.) A/mm^2
1	3.0	32	3.0	4500
2	2.8	22	1.5	3500

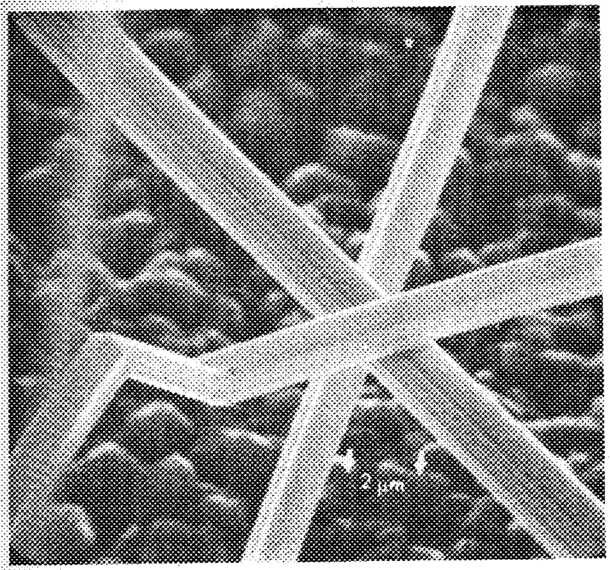

FIG. 10. *An unusual view of whiskers—note the uniform longitudinal striations along their lengths.*

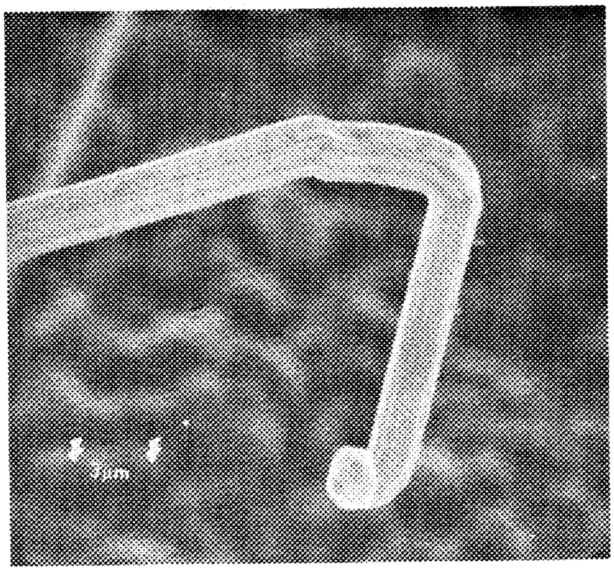

FIG. 12. *Whisker showing pronounced change in direction during its initial growth.*

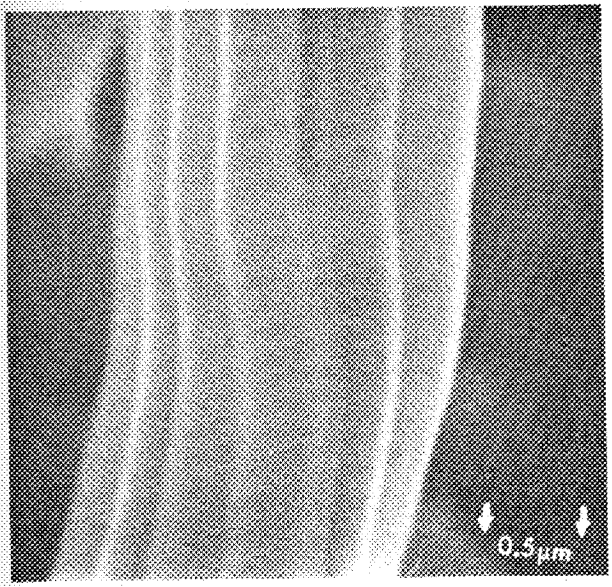

FIG. 11. *The rare occurrence of a whisker changing its shaft diameter.*

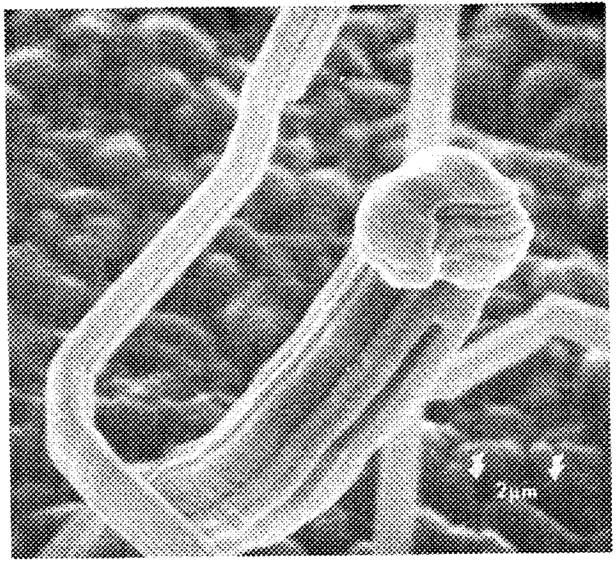

Fig. 13. *This appears to be the fracture surface of a large diameter (approx. 4 microns) whisker. The nearside thin whisker has a diameter of approx. 1.5 microns.*

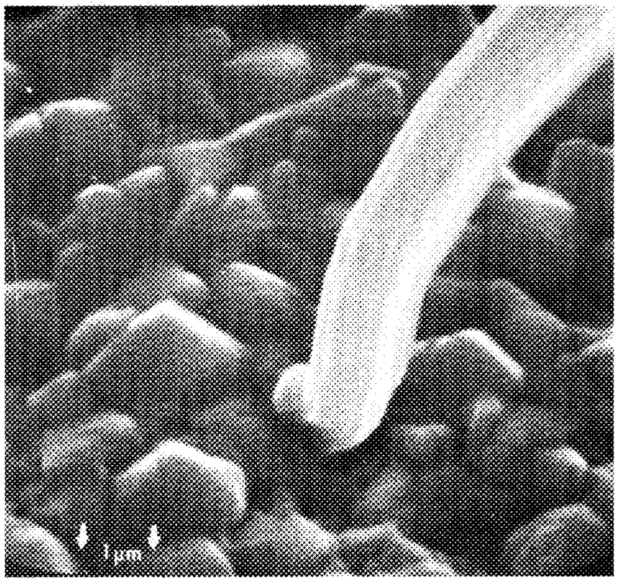

FIG. 14. *Base of whisker has roughly the same diameter as the nodules on the tin plating. Although volume of tin whisker is quite considerable there is no signs of local subsidence on plating surface.*

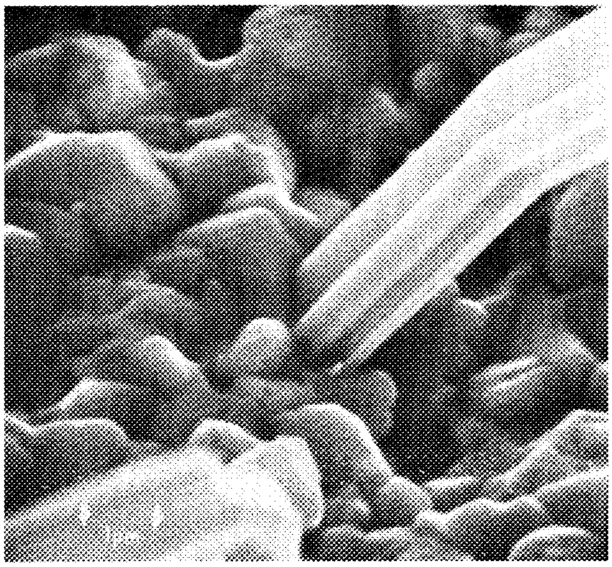

FIG. 15. *As figure 14.*

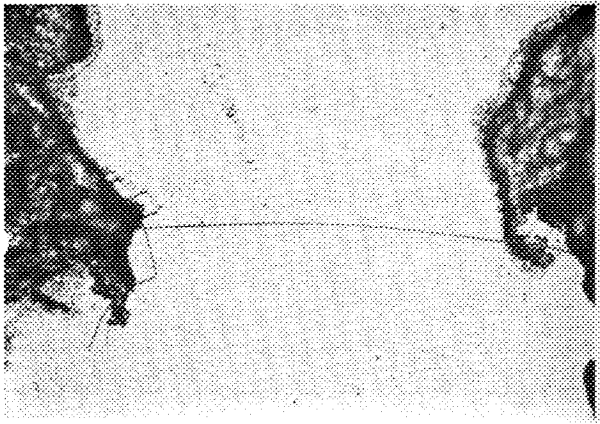

FIG. 16. *Single whisker attached to glass plate by silver epoxy.*

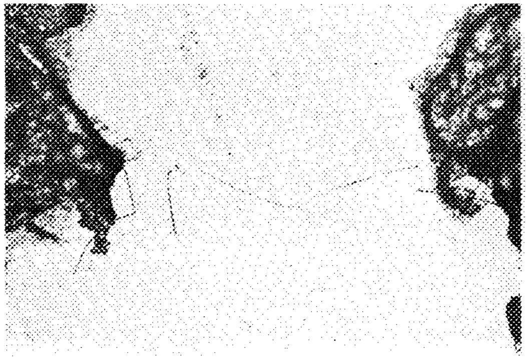

FIG. 17. *Burnt out whisker after probing.*

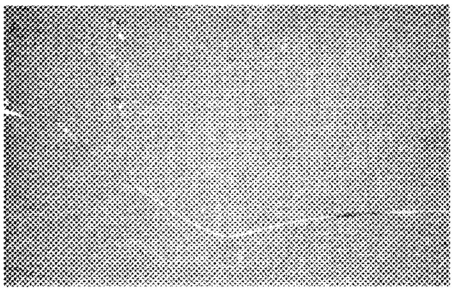

FIG. 18. *Detail of whisker from Fig. 17.*

Metallography

A small part of the steel container was carefully removed with a jeweller's saw. This was transversely mounted in a room temperature curing resin and then ground and polished to a one micron diamond paste finish. The mount was lightly etched, then viewed with a Reichert projection microscope. The tin plated steel surfaces are seen in cross-section in Figures 21 and 22 at a magnification of × 1000. The section reveals that a thin strike of copper had been applied to the steel before the final tin plating. The thicknesses of the various plated layers are as tabulated in the next column.

Several cross-sectioned whiskers can be seen embedded in the mount material photographed in Figure 21; they have diameters in the order of 2 microns. No voids are seen within the bulk of the tin plate which would account for the exhumed volume of tin material making up these whiskers.

Steel Box	Plating Thickness (microns)	
	Copper Strike	Tin Finish
Inside surface seen to be whisker forming	< 1	< 10, but generally 8
Outside surface supporting no whiskers	1–2	18–20

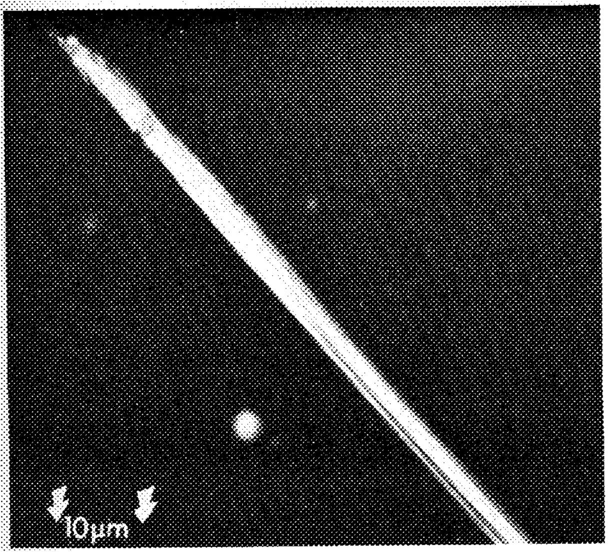

FIG. 19. *Location of whisker fracture beneath probe.*

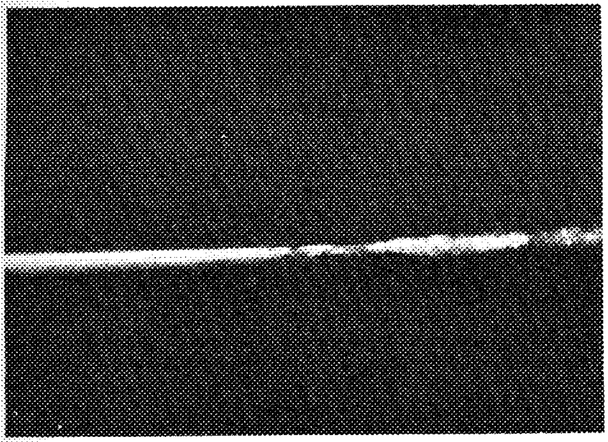

FIG. 20. *Portion of overheated whisker—surface oxidation has replaced longitudinal striations.*

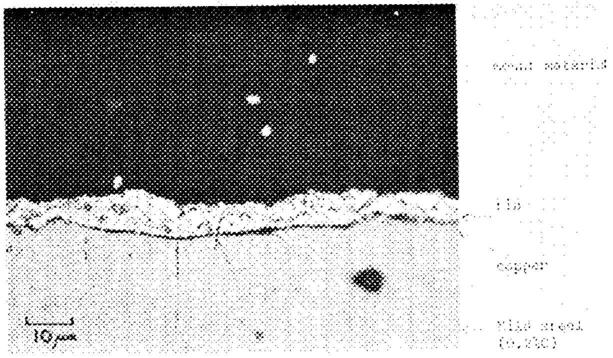

FIG. 21. *Cross-section of surface supporting whisker growth. Several whiskers can be seen within the mount material.*

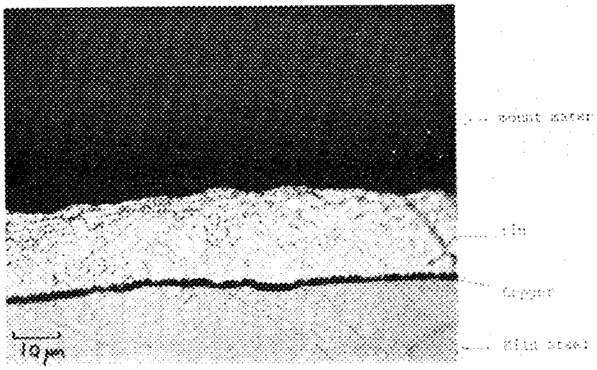

FIG. 22. *Cross-section of barren surface.*

DISCUSSION

The Process of Whisker Nucleation from Vapour or Liquid Phases

One model[10] for nucleation of whiskers on a perfect crystal surface considers the presence of impurity trace atoms which have been adsorbed by the crystal structure. These adsorbed atoms have atomic radii below a critical size in order that they may diffuse considerable distances within the crystal before emerging to the crystal surface and evaporating again.

At this moment the crystal is assumed to be in equilibrium with its vapour pressure. If the vapour pressure above the surface is then increased, thereby affecting an increase in the number of adsorbed atoms, at some point it will be possible for two or more of these atoms to be positioned together on the crystal surface. The atomic steps, or ledges, surrounding such atoms will have a high binding energy and therefore would act as preferential sites for the desposition of further atoms. These nucleation sites on the surface of a substrate could initiate the growth of whiskers from a surrounding liquid or vapour phase. It is probable that this nucleation mechanism will precede the growth of metallic whiskers from the reduction of various volatile salts. In particular Fe, Cu, Ag, Ni, Co, Pt and Au were seen to be readily reduced from their halides to form whiskers which grew from their tips by the condensation of freshly formed metal vapour.[11] The formation of silver whiskers on the surface of pressed α-silver sulphide have recently been studied.[12] Silver atoms were initially directed onto the silver sulphide substrate from a vapour phase. These probably formed incipient whiskers by a mechanism analogous to the aforementioned nucleation model. When whiskers were grown from those nucleation sites by an additional electrochemical process (i.e., migration of silver ions through an iodide solution to the tips and sides of the whiskers) there was no initial drop in potential of the cell due to any nucleation stage and a steady state was immediately attained at a potential which was dependent on the magnitude of the current used for growing whiskers.

The Process of Stress-Induced Whisker Nucleation

Tin and possibly cadmium and zinc whiskers will nucleate and grow spontaneously from electroplated surfaces regardless of their surrounding environment.[1–5] Growth is most likely induced by stresses within the electroplated layer such as those resulting from:

a) impurity atoms which have codeposited;
b) residual stresses due to plating conditions (e.g., high current density);
c) residual stresses from mechanical working of surface after plating (e.g., tumble drying or abrasive cleaning of components);
d) stresses due to mechanical loading of plating by bolting or spring fixtures;
e) stresses caused by differences in thermal expansion between the plating and its substrate;
f) particle irradiation;
g) stresses formed by internal oxidation.

Whisker nucleation sites may become conducive for whisker growth depending on the intensity and direction of any of the aforementioned stresses. These sites will occur at positions of defects within the lattice structure of the electrodeposit. Emergent screw dislocations are sources capable of instigating the continuous growth of whiskers. In crystallographic terms compressive microstresses within the deposit may be relieved by the outward diffusion of material in a direction perpendicular to the screw dislocation. Such mass transfer is likely to involve dislocation mechanisms, such as cross-slip and climb, which will facilitate tranfer of material from the bulk of the deposit to the vicinity of activated screw dislocations.

This mechanism of growth assumes that whiskers grow from their roots upwards with the gradual feeding of new atoms to the whisker base. Experiments using radioactive tracers have investigated material self-diffusion and growth of tin whiskers.[13] It was found that tin deposits containing oxygen promote rapid diffusion of tin into the whisker from directly underneath the whisker but that oxygen also tended to inhibit large scale diffusion of tin from directions parallel to the substrate surface.

Tests using X-ray diffraction techniques on zinc and cadmium whiskers have shown them to be single crystals with the "C" axis of their close packed hexagonal structure lying parallel to the direction of growth of the whiskers. Tin whiskers were shown to have a tetragonal structure.[14]

Results of the laboratory investigation already outlined in the text show that the tin whiskers are very pure, have a uniform growth direction and are highly conductive, thereby indicating that their crystal structure is virtually perfect, particularly with respect to line defects such as edge dislocations which are thought to be characterised by the observed longitudinal surface striations. The poor adherence and rather brittle nature of the tin plate seen in Figure 6 indicate that residual microstresses were available and probably played the major part in promoting tin whisker growth. The regions surrounding solder joints made to this tin plate did not support whiskers presumably because of the cancellation of microstresses, or stress-relief, in the tin by the heat dissipated from the soldering tool.

The tin plating on the inside of the electronic box is noted to be half as thick as the outside deposit. This results from the poor throwing power of the electroplating solution. It would appear that under these conditions, the critical thickness of tin which will initiate whisker growth lies around 10 microns. It is interesting to note that there has been no local surface subsidence in the base region of whiskers (Figures 14 and 15) and the cross-sectioned whisker surface (Figure 21) shows no microscopic voids or pores likely to account for the volume of tin making up the whiskers. This indicates that there has been extensive tin diffusion from directions parallel to the surface of the steel substrate.

The Danger of Whiskers to Spacecraft Electronic Systems

During the past five years laboratory work at ESTEC in the field of component failure analysis has shown conclusively that whisker growth will, under many conditions, jeopardize the reliability of spacecraft electronics. The following modes of whisker growth have been observed:

a) The growth of molybdenum whiskers in a high humidity or liquid environment as seen in Figure 23. Failed integrated circuits were electrically tested, leak tested and decapped. SEM inspection and energy-dispersive X-ray analysis revealed that molybdenum whiskers had grown from the metallisation pattern on the chip causing internal short circuits.[15] Although the package was still hermetic, surface stains strongly indicated that some residual liquid was present in the device when it was sealed.

b) Tungsten whiskers were observed to be growing on the surfaces of heater coils situated within vacuum tubes.[16] They are thought to have grown from the vapour phase resulting from

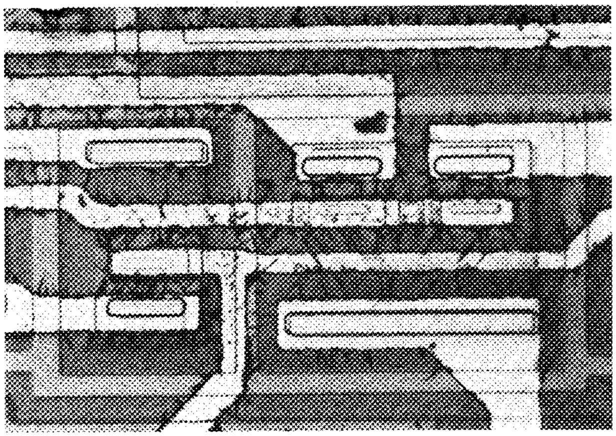

FIG. 23A.

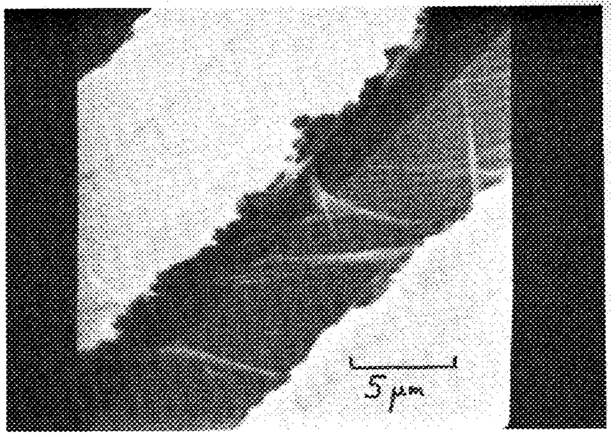

FIG. 23C.

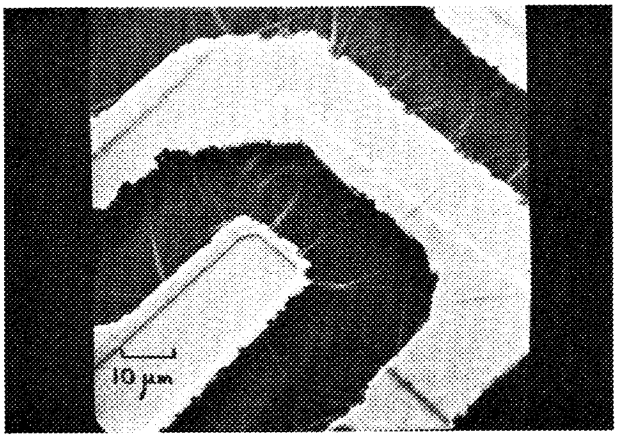

FIG. 23B.

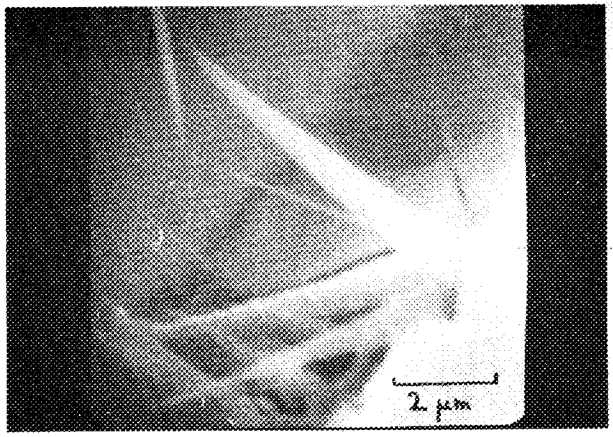

FIG. 23D.

FIG. 23A–D. *Short circuits caused by molybdenum whiskers growing from the metallisation pattern on an integrated circuit.*

non-uniform heating and sublimation of the tungsten heater coil. Some whiskers had grown to a length of 46 microns. One short whisker shown in Figure 24 had a diameter of approximately 2 microns.

c) Glass-rich oxide whiskers have been revealed within the insulation glass windows of integrated circuit flat-packs.[17] Figure 25 shows the gap between a Kovar lead and the package wall frame. Prior to glass-sealing the metal parts were initially oxidised. During sealing glass preforms are melted and flown around the oxidised metal pieces. At this stage metal oxide is dissolved into the glass to form a hard oxide-rich glass layer and a strong glass-to-metal seal. On cooling, the volume of liquid glass between the lead and the wall frame of this device has become super-saturated with metal oxide. Glass-rich oxide whiskers have then nucleated on the metal surfaces and grown into the glass. Such whiskers have a far greater electrical conductivity than glass and, as seen in Figure 25, they constitute a leakage current path between component lead and case.

d) Tin whiskers have been seen growing from the plated-through holes of a printed circuit board having a bright tin finish on the conductor paths.[18] Figure 26 shows such a whisker. Whiskers have also been initiated on commercially available tin plated pcb's having an epoxy/glass fibre base laminate (type G10). The thermal expansion characteristics of this laminate have been studied.[19] In the direction perpendicular to the laminate the glass weave does not restrict the resin expansion and in this Z-direction (i.e., in the board thickness) the coefficient of expansion is an order of magnitude greater than in the X and Y directions (i.e., along the width or length of the board). Type G10 boards with a thickness of 1.5 mm were seen to increase in thickness between 35 to 40 microns when cycled through the temperature range from 20°C to 160°C. In the case of pcb's or multilayer boards with plated through holes and a final finish of pure tin plating the problem of whisker growth during thermal cycling should not be minimised. In this instance, owing to the great thermal mismatch between tin and epoxy, plated through holes will be subjected to tensile and compressive forces which may cause tin whisker growth by spontaneous extrusion.

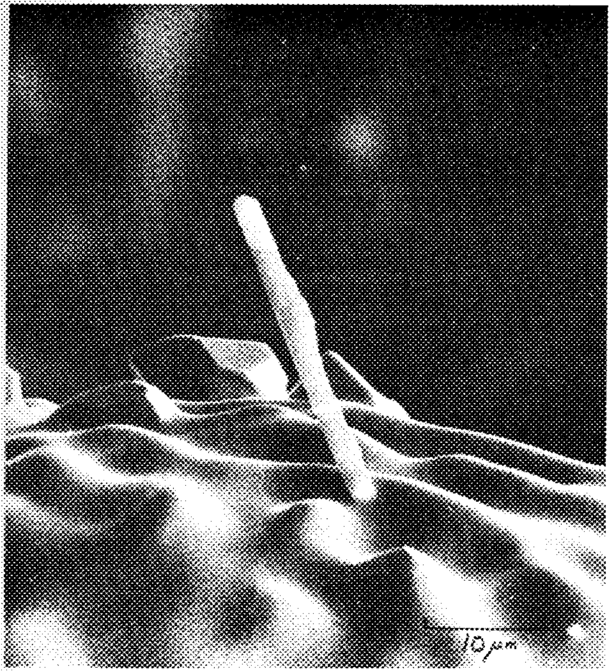

FIG. 24. *Tungsten whisker growth on a tungsten heater coil.*

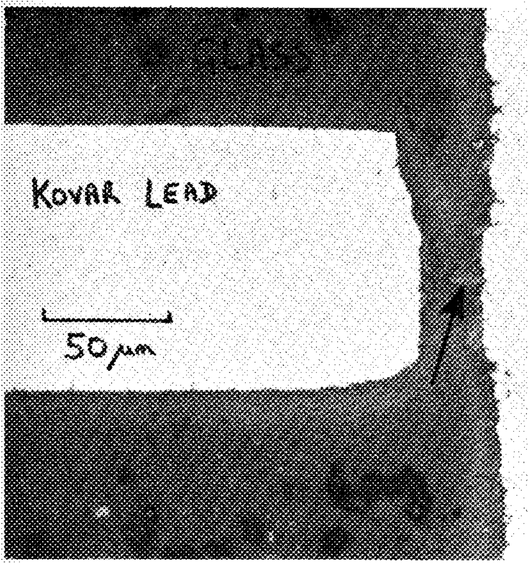

FIG. 25. *Excessive glass-rich oxide whiskers (arrowed) within glass insulation of flat pack windows.*

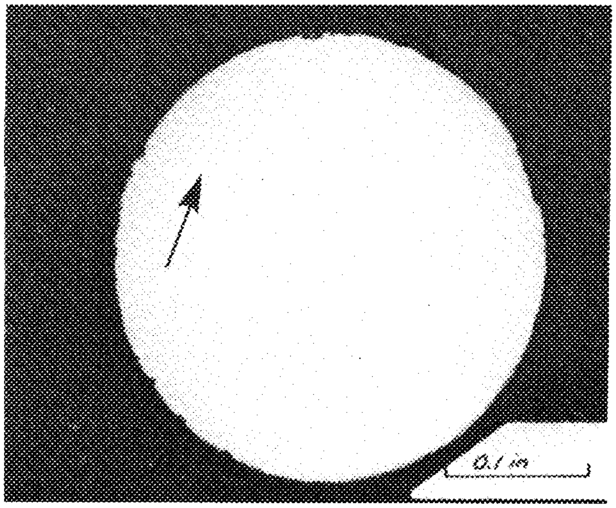

FIG. 26. *Whisker growth (arrowed) in the plated-through hole of a printed circuit board having a bright tin finish* (18).

CONCLUSIONS

- The literature survey (see references) and the findings from the laboratory analyses detailed earlier in the text show that spontaneous growths of conductive whiskers can cause extensive damage to spacecraft electronics. This is particularly exemplified when using miniature circuits which progressively employ closer spacings between conductors.
- Whisker growth does not depend on the existence of an electric field. Undetected whiskers which may have grown during the manufacture, integration or testing of the spacecraft could become detached during the launch phase as a result of the large release of mechanical energy (thermed vibration, shock and acoustic noise). Once detached, they may float under zero gravity on to electrically conductive surfaces. Short circuits may be caused by whiskers bridging gaps on printed circuit boards or solar arrays. They may also be caused by whiskers falling on components themselves. Paints and enamels are ineffective in preventing this phenomenon.
- In view of the long mission requirements of recent ESA space projects there is also the danger that surfaces prone to whisker growth may nucleate and form whiskers as a result of exposure to the space environment.[20] Thermal cycling of the spacecraft when localised stresses are imposed on adjacent materials with

different coefficients of thermal expansion and the effect of irradiation, are likely to accelerate whisker growth.

- Tin whiskers have been found to carry currents of 22–32 mA before burning out. They will be particularly troublesome in low voltage electronic equipment due to their low resistivity. High voltage equipment may not be subjected to catastrophic short circuit as it is likely that the whiskers will burn-out.

RECOMMENDATIONS

- It is strongly recommended that surfaces which may support stress-induced whisker growth, such as tin, cadmium and zinc, are excluded from spacecraft design.
- An alternative finish[21] which has not been seen to support whisker growth is 60/40 tin-lead. This solder alloy can be electroplated and then fused onto most metallic substrates and such a finish is an ESA mandatory requirement for printed circuit boards and terminations which are intended to support solder-mounted components.[20,22] A solder coating is also preferable to a tin coating for retention of solderability during long term storage.[23]

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BIOGRAPHY

B. D. Dunn has been employed at the European Space Agency in Noordwijk, Holland since 1969 as Metallurgy Group Leader in the Materials Section of the Product Assurance Division which provides functional support to the ESA satellite projects and Spacelab in the form of materials selection, mechanical testing, metallurgical examination, quality control, etc., of spacecraft hardware.

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