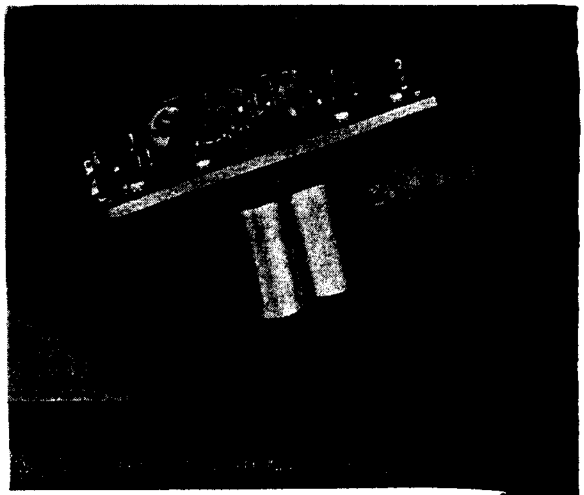

A hidden cause of failure in electronic equipment:

Metal Whiskers

Trouble-making filamentary growth on metal surfaces, particularly on zinc, cadmium and tin, can create shorts and other forms of malfunction. Problem is a real one for design engineers, especially where components are closely spaced.

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METALLIC SURFACES of electrical components have been considered mainly with respect to their corrosion resistance, solderability and, occasionally, magnetic properties. With rapidly increasing demand for lighter and more compact equipment however, spacings between individual parts are being reduced. Consequently there is greater likelihood of trouble from any extraneous conducting particles present on uninsulated metal surfaces. Especially is this true for low-voltage circuits in which equipment is shock mounted and enclosed. Under such conditions there is little to prevent the maximum growth of what are known as "metal whiskers." (*1*)[*]

The metal whiskers are tiny filaments which have been found projecting from the surfaces of certain metals. They are metallic in appearance and highly reflecting. Generally they are about 40-80 millionths of an inch in diameter. Many have been found longer than ⅜ in. While possessing high intrinsic strength, the whiskers are easily moved by a current of air and may be dislodged by mechanical shock. Since the whiskers are metallic they have low electrical resistance. When a projecting whisker makes contact between two circuit elements it will immediately reduce the resistance between them to 300 ohms or less. An applied voltage of 10 volts or more is sufficient to burn off the whiskers but standing potentials are often below this value.

Under such circumstances the possibility of whisker growth must be considered when designing equipment which is electrically sensitive and whose premature operation or failure to operate could result in a serious situation or disaster. As a background it might be well to look at some of the equipment that has failed because of the presence of a few of these microscopic filaments.

Channel-frequency filters (widely used in multichannel transmission lines to maintain the various frequency bands) are very carefully assembled and her-

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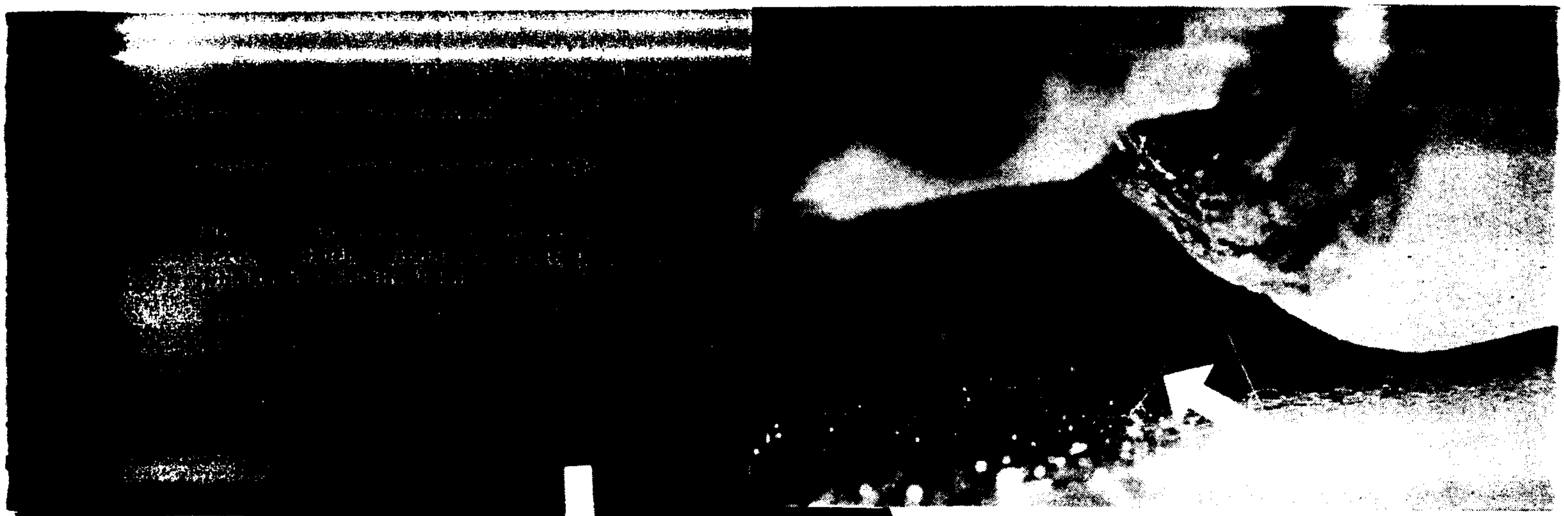
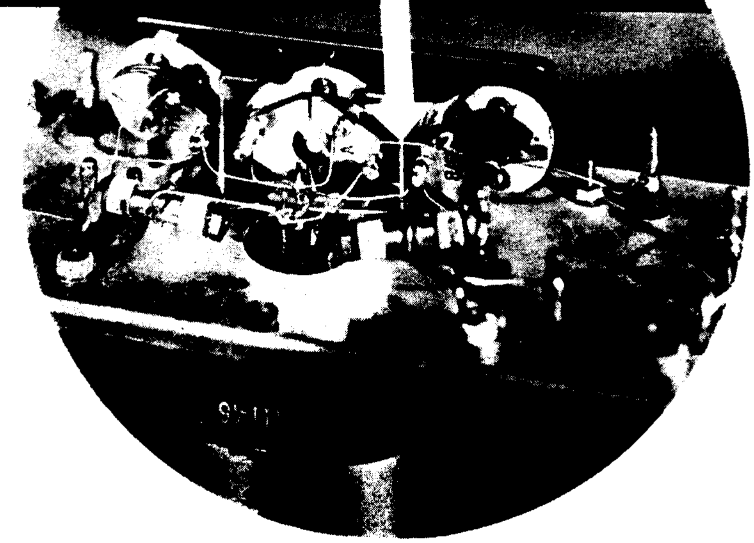
[*] Italic numerals in parentheses apply to Cited References at end of article.





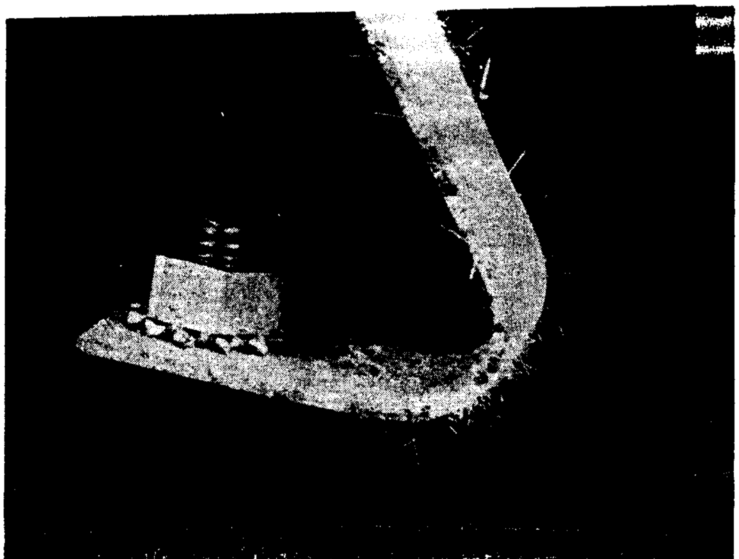
metically solder-sealed (see Fig. 1). Recently some of the filters became inoperative because of low impedance to ground. Removed from service and shipped to the Bell Telephone Laboratories for examination, the fault mysteriously cleared, filters tested satisfactorily and no evidence of trouble could be found. Finally, after numerous attempts to remedy the situation, a few tiny lint-like filaments were noted on the surfaces of a zinc-coated bracket. One or two were long enough to bridge a small gap to the post of an air capacitor, as shown in Figs. 2 and 3. Here then was the first clue to the trouble. Removal of the filaments also removed the low impedance and restored the filter to operating condition. Shipment of the filters first examined had evidently dislodged the trouble-making material.

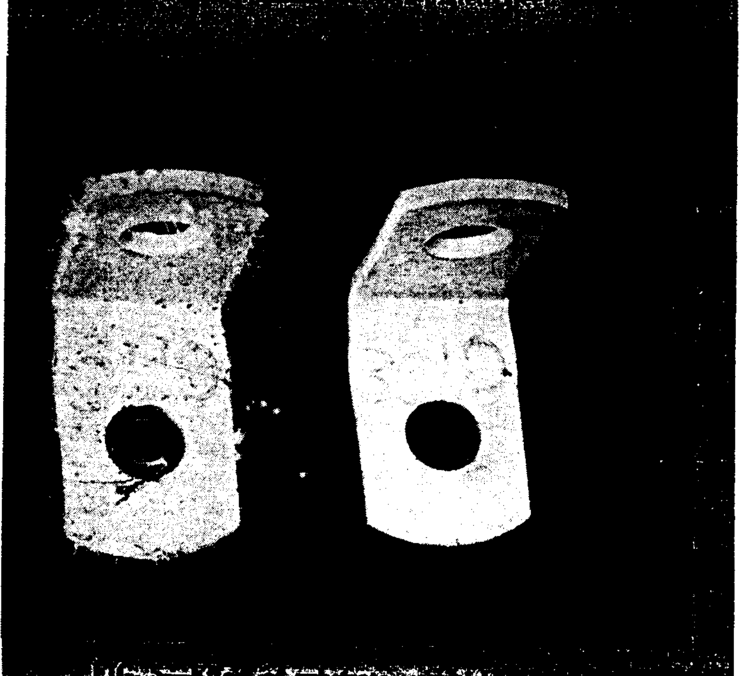
A temporary expedient to clear the whiskers from filters in operating circuits consisted of an electric shock treatment. In some instances, it was possible to burn off the whiskers without other damage by applying a rather high voltage to external connections of the filter. Unfortunately, this treatment affected only the whiskers actually bridging the air gaps between the filter elements. Other whiskers could and often did make contact at a later date. In the case of some filters the dewhiskering process had to be repeated many times. The shock treatment can not be applied to all types of channel-frequency filters because of possible injury to circuit elements. Disassembly is then necessary, a costly and time-consuming process.

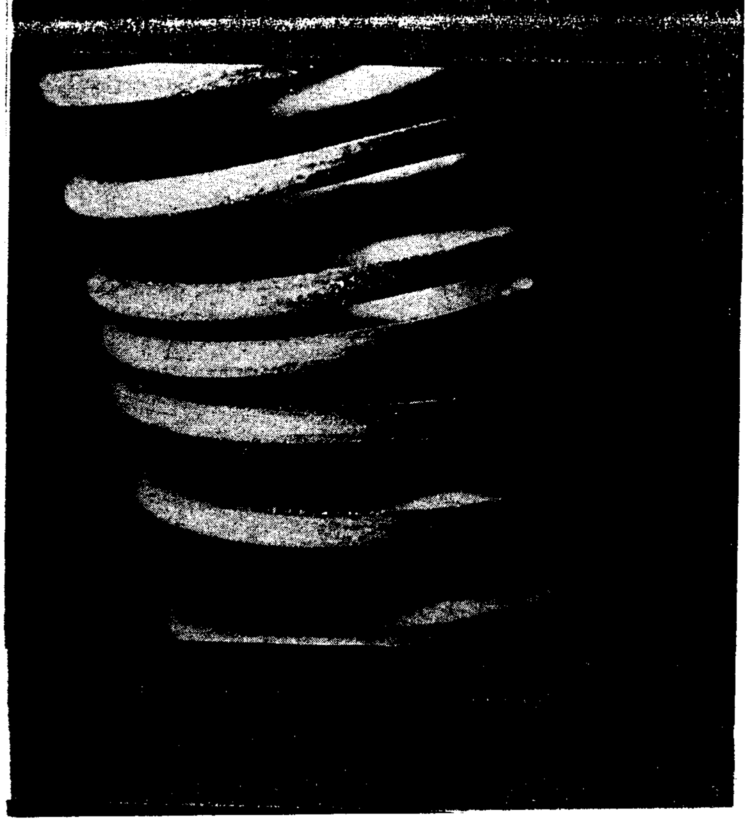
Other types of equipment of our own fabrication and of other manufacturers have subsequently been found supporting whisker growths. Examination of some glass-enclosed quartz-crystal assemblies disclosed whiskers growing from the contact wires. Air capacitors have been observed with whiskers bridging between the plates. The metal end caps of deposited-carbon resistors ant the shells of AN connectors all had whisker deposits. More recently, trouble has been experienced with a critical potentiometer because sections of the winding had been short circuited by whiskers. These had not formed on the potentiometer itself but had been dislodged from the internal tin-coated surfaces of the protecting can.

While temporary methods of treatment were being applied to equipment in trouble, the longer range study of whisker composition and of the mechanism of growth was begun. Approximately 2000 specimens are presently being studied under a variety of conditions and following various pretreatments. Possible methods of growth prevention are being developed and tested. Fig. 4 shows some of the whiskers which developed on a specimen of tin-coated steel. Similar growths have been found on zinc- and cadmium-plated parts.

Preliminary work was carried out under the assumption that the fault lay with the electroplated coatings themselves, and that organic material and high relative humidity were contributing factors. In other words it was thought that a corrosion process was involved. X-ray patterns indicated, however, that the whiskers were metal crystals rather than corrosion products. It was soon found that the whiskers would form at low relative humidities in the complete absence of or-







ganic material. Furthermore, growths developed not only on electroplated coatings but also on metals deposited by hot dipping, spraying, and vacuum evaporating. The possibility of galvanic action between coating and substrate was ruled out when whiskers were grown from metal deposited on paper and on freshly cleaved mica. Finally, whiskers were grown on solid metal.

Environment does not play a decisive role since whiskers have been grown under various conditions of temperature, relative humidity and pressure. There appears to be an optimum temperature for density of growth. In the case of tin, this is in the neighborhood of 125 F. The decrease in growth is marked above 250 F and at 300 F there is little or no evidence of whisker formation. On the other hand, a temperature of −40 F only delays but does not prevent the development of whiskers.

Early in the study the application of a supplementary coating following electroplating was tried as the most obvious possibility for prevention of whisker growth on a metal surface. The whiskers penetrated coatings of hard wax and lacquer with ease. Specimens clad in heavy envelopes of thermosetting plastics (such as those often used for impregnating small unit assemblies) have remained free of whisker growths so long as the coating remained intact. However, where cracks developed, particularly along the edges, whiskers pushed through.

Attempts to prevent whisker growth by alloying the offending metal with another "poisoning" metal lead to some success but a longer observation period for some of the alloys will be required. Coplating a small amount of lead or arsenic with tin, for instance, will not prevent whiskers from forming. Likewise, cadmium-tin and tin-zinc, two electrodeposited coatings sometimes used on electrical equipment, will develop growths. Other possibilities are under investigation.

While whiskers will grow not only on plated but also on solid metal, it has been noted that the thickness of an electroplated coating affects the whisker growth tendency. Wedge-shaped electrodeposits have been made and it was found that maximum growths developed at the thin end of the coating, tapering off as the coating thickness increased.

Likewise, Fig. 5 shows that substrate metal profoundly influences the tendency to grow whiskers. One of the two identical brass specimens was first iron plated and then both specimens were tin plated. After two years whiskers on the tin applied directly over brass are extremely short. In the same period the specimen with a layer of iron interposed between the brass and the tin has developed a luxuriant whisker growth. Similarly, whisker growth on tin applied over copper is reduced but not entirely prevented. Fig. 6 shows some tin-coated copper wire with whiskers in evidence in several places. Thus neither a copper-base material nor copper itself as a substrate will completely eliminate the possibility of growth.

It has been suggested that oil immersion of electrical equipment such as capacitors might be a means of insuring freedom from whisker trouble. Such is not the case however since whiskers have been grown on specimens completely immersed in oil.

Both annealing and cold working of specimen surfaces has been studied as a possible means of preventing whisker growth but in neither case was there any appreciable effect.

Slight preliminary corrosion of the metal surface also has been tried but admittedly this is rather difficult to control. Actually on specimens so treated whiskers have been found growing on scattered areas between more grossly corroded regions.

From X-ray diffraction patterns whiskers appear to be single crystals, although in the tin there is some evidence of twinning. That the whiskers are nearly perfect crystals is borne out by the fact that they will tolerate yield strains of the order of 2-3 per cent without slip. (2) This is a factor of 100 times the maximum strain observed for bulk material.

The rate of growth is being studied at various temperatures. However, there seems to be a wide variation in possible growth rate. After a period of two or three years some whiskers on a specimen surface may be so short as to be hardly visible. Others are several millimeters in length with all sorts of intermediae stages present. This may be due to great differences in growth rate or more likely it may indicate a difference in "induction" period. This is the interval between preparation of the surface and the time when sufficient energy is developed at a particular area to "nucleate" whisker growth. It is possible that the whisker is not born at the exposed surface of the metal but at some lower level to become evident only after an interval of time.

While as yet a specific growth rate cannot be given, some whiskers have been observed to grow approximately 750 microns in a month. This corresponds to a rate of 25 microns or 1 mil per day. Although many have reached a length of more than ⅜ in. it is not yet known to what length a whisker may develop. Many of the longer specimens have been dislodged as a result of a slight air current or mechanical shock.

Zinc, cadmium, tin and several other metals are known to develop whiskers. There are indications that whiskers will form on still other specimens now under study. Some have not been in test for a sufficiently long period. What appears to be the beginnings of whisker growths are still too short to be positively identi-

FIG. 7 — Configuration and growth phenomena in metal whiskers. (Photomicrographs are reproduced in about one-half the size of the original magnification). (A) Stages in growth of a tin whisker (original magnification 2550 X). (B) Observed range in whisker diameters. Left, 5.8 microns. Right, 0.05 microns. (C) Typical tin whisker (original magnification 900 X). (D) Spiral whisker growths (original magnification 2550 X).

fied. However, it may be noted that antimony and some tin-lead and tin-aluminum alloys have developed whiskers.

Copper and silver develop a type of whisker when in the presence of sulfur or sulfur-bearing materials such as hard rubber. These growths are metal sulfides, however. They are not metallic in appearance but are jet black, stiff, spear-shaped and extremely short. Because of their short length there is not much likelihood for trouble from such whiskers. To date, metallic silver whiskers have been grown only under the influence of a standing d-c potential.

To be able to predict with certainty the whisker growth tendency of a metal the mechanism of growth must be understood. Several tentative suggestions have been advanced but as yet none appears to be completely satisfactory. Most of the earlier explanations were based on the assumption that growth took place as a result of deposition of metal at the whisker tip. However, a sequence of electron micrographs has been obtained showing stages in the growth of a whisker over a period of several months. (*3*) As shown in Fig. 7A the initial shape of the tip-end does not change. Furthermore, it has been found that the distance between the tip-end and an index mark on the side of the whisker remains constant. Both of these findings indicate that the material responsible for whisker growth is accreting at its base.

More recently it has been suggested that the whisker develops at the site of a dislocation. (*4, 5, 6*) Frank has advanced the idea that the actual driving force is due to an oxidation reaction occurring over the surface of the whisker. Oxidation of the metal would provide the necessary energy and a screw dislocation persisting at the whisker base would provide a mechanism.

If oxidation is responsible for the continuing growth of a whisker, certainly a gross amount of oxygen is not required. Recent examinations have included specimens that were maintained in a system which first was evacuated and then flushed with hydrogen. Next the specimens were subjected to hydrogen-ion bombardment in an attempt to remove surface oxide. The system was then evacuated to a gas pressure of 10^{-7} mm of mercury, sealed off and gettered. The final pressure was probably of the order of 10^{-8} mm of mercury and whiskers developed under such conditions.

It has been found that application of pressure to the specimen surface will increase the rate of whisker growth. (*7*) A pressure of 3000 to 4000 psi will cause whiskers to develop in a matter of seconds to lengths normally requiring 6 or 8 months when exposed under atmospheric pressure. This is an increase in growth rate of an order of magnitude of 10^6. It suggests that a diffusion process may be involved and may be the actual growth-rate controlling factor. Under normal exposure conditions sufficient oxygen would undoubtedly be present to react with any freshly exposed diffusing metal. Increasing pressure on the specimen may merely increase the diffusion rate of vacancies and hence the travel rate of a dislocation, the slow part of the mechanism suggested by Frank.

Mercury whiskers have been grown by Sears (*8*) who also feels that a screw dislocation is involved. He may be dealing with a somewhat different mechanism, however. In Sear's process, at least in the first stages, a vapor-phase reaction is taking place and filament growth proceeds after mercury has condensed to form a film on the surface of his glass plate. In general, the metals included in our study have very low vapor pressures under the conditions of exposure.

Some thought has been given to the possibility that growths may be associated with effects found at crystal boundries. Whisker growth on single crystals is now being attemped. It is known that a metal crystal substrate is not necessary for growth since whiskers have been grown on thin films of metal evaporated onto paper and freshly-cleaved mica.

During the early work whiskers were found to be about 2 microns in cross section. Examination of many specimens has indicated that under different conditions of growth, Fig. 7A, a considerable size range may be expected. (9) As shown in Fig. 7B a variation in diameter of at least 1 to 100 is possible. Whiskers first observed were quite straight but more recently a few have developed in the form of a spiral. These two types may be seen in Figs. 7C and D. Others have developed into a "dog's leg." In such cases a period of growth is followed by one at an angle and this in turn by further growth parallel to but offset from the original growth direction. Whether or not the angles formed are angles of twinning planes still must be determined. Observed variation in diameters and in spiral-growth forms (Fig. 7D) must be accounted for in any completely satisfactory whisker growth explanation.

In conclusion, it should be emphasized that the presence of tiny whiskers on a metal surface is not merely a matter of interest to the physicist. Their presence on electrical equipment can be a very real problem. Designers and engineers may feel that their particular equipment is not susceptible to whisker growth and that likelihood of trouble is remote. Disregard of this new factor in design considerations can be costly.

When equipment layout requires small spacings between metallic surfaces in a sensitive electrical circuit the possiblility of whisker growth must be considered. If such growth can interfere with proper operation then exposed metal surfaces must be protected by interposed barriers or metals must be specified that do not develop whiskers. □ □ □

Acknowledgment

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