# Relay Failure Caused by Tin Whiskers

Gordon Davy[1]
Northrop Grumman Electronic Systems
Baltimore, MD

## Abstract

Spectacular damage of several relays from high current flowing to the metal case was very likely caused in each instance by a tin whisker growing from the armature, which is bright tin plated, toward a terminal stud. This plating is a nonconformance to the applicable military specification that was in effect at the time of manufacture. The other possible causes, wearout (arcing deposits creating a conductive path between phases) and particles are considered and shown to be unlikely.

## Introduction

This is a report of the spectacular failure of relays used on a military airplane used by the air forces of several countries. Three failures of this kind have been examined (all after more than ten years in the field), and reports have been received of several similar failures, in which a hole in the case is caused by a huge current that was able to flow before control circuitry interrupted it.

Figure 1 shows a failed relay. Soot on all surfaces can be seen through the hole in the case; the end of each terminal stud and the edge of the iron armature below each has melted. Removing the wall revealed that all six contacts[2] had melted open and that the edge of the armature[3] had melted below each of the terminal studs. The discharge presumably initiated between one of the studs and the armature, and once started, it extended to the other studs and the case.

Figure 1 – Failed relay

## Analysis

What could have initiated the current surge to ground after so many years in the field? One possibility is wearout. According to the manufacturer, material from the arc that develops between contacts as they open and close deposits as a film on insulating surfaces. Once the film is continuous, it begins to reduce the insulation resistance between phases. End of life comes when the leakage current through this film grows beyond a threshold so as to initiate an arc between the phases. The manufacturer's engineering data sheet states that this relay is rated for not less than 100,000 operating cycles at 25 percent of rated load (25 amps, three phase, 115 Vac). This relay is used to switch 5 amps (i.e., 20 percent of rated load) an average of four times a day. Thus by the manufacturer's data sheet it should be good for seventy years before wearing out by this mechanism.

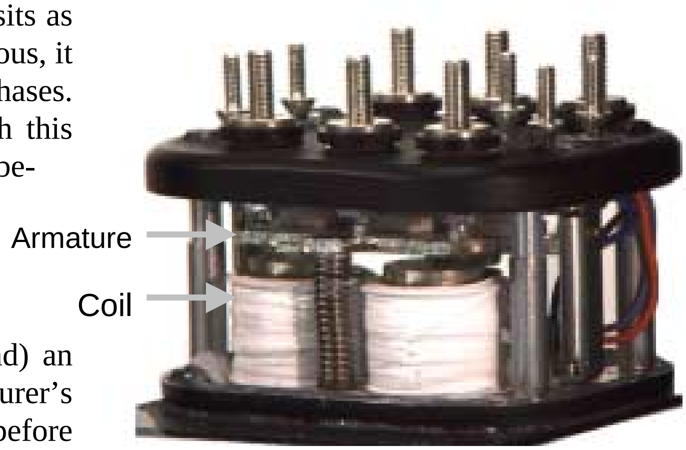


Figure 2 – Opened unfailed relay

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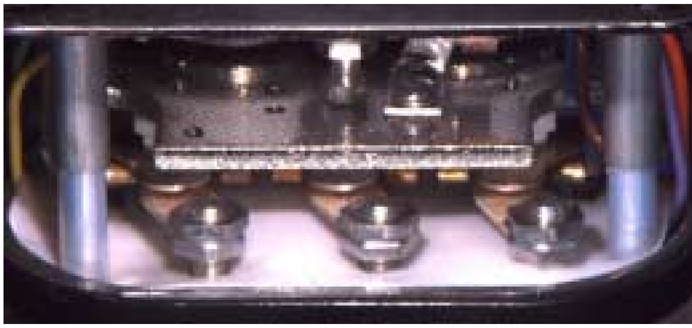
[1] Email address: gordon.davy@northropgrumman.com.

[2] There are two silver-cadmium oxide contacts per phase. The "rupture current" for this relay is specified at 250 amps.

[3] Armature and case are at ground potential.



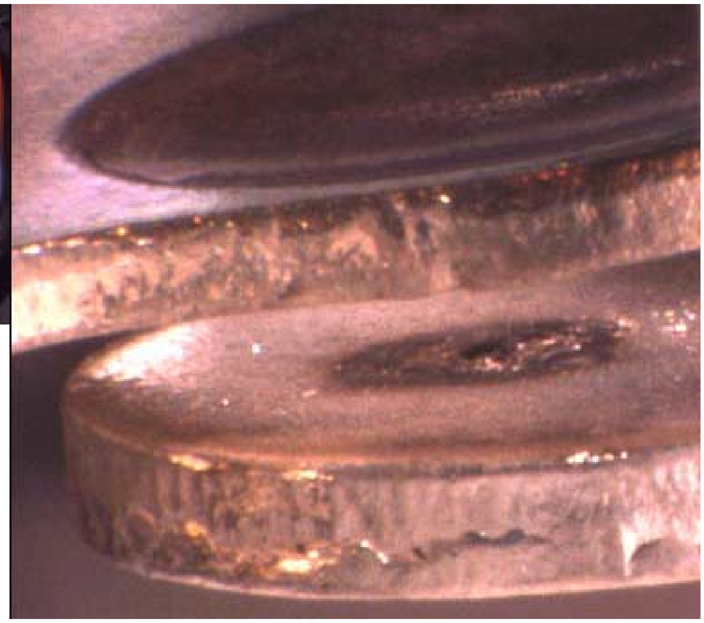


Figure 3 (above) – View of cut-open relay showing three contacts and sheet of Teflon insulation. Three (of six) contact pairs are visible directly below the armature. No evidence of contact arcing deposits can be seen.

Figure 4 (right) –view of contacts showing lack of arcing deposits beyond the center.

Examination of a relay that had served in the same equipment as a failed relay for fourteen years (Fig. 2) but had not failed showed no arcing deposits (Fig. 3) except for slight darkening in the center of the contacts themselves (Fig. 4). The insulation resistance between phases and to ground was found to be far greater than the specified 100-megohm limit.

Another possible arc initiator is a loose particle. When each terminal of the unfailed unit (as removed from the airplane) was tested for isolation, one terminal measured only 3 megohms to ground. When the relay was tapped this value abruptly increased above the limit. This observation would be consistent with a loose particle (but also with a tin whisker, discussed below). PIND[4] testing showed the vibration of the relay contacts (regular pattern on the oscilloscope), but no irregular signal that would have indicated a particle. The wall of the relay was then removed carefully to minimize particle generation[5]. A few particles generated during opening did enter, but no particle large enough to span the gap was seen.

A third possible cause of the relay failure consistent with the observations is that of a tin whisker. According to NASA,

> Tin whiskers are electrically conductive, single crystal structures that can grow from surfaces that use tin (especially electroplated tin) as a final finish. Tin whisker growth is believed to be a purely mechanical phenomenon unlike tin dendrites which require an electromagnetic field and moisture to form. Tin whiskers have been observed to grow to lengths of several millimeters and in rare instances to lengths in excess of 10 mm. Numerous electronic system failures have been attributed to short circuits caused by tin whiskers that bridge circuit elements maintained at different electrical potentials[6].

NASA has a special concern about the use of tin plating because whiskers take time to develop, and a product destined for space will be inaccessible for repair. A NASA survey of relay manufacturers concerning their use of tin plating[7] found that the manufacturer of this relay did not totally eliminate tin plating in its relays until November 1997[8]. NASA has also published a parts advisory that lists GIDEP Alerts relating to tin whiskers[9], including one citing the manufacturer[10] for tin whiskers on external surfaces. The relay discussed in

[4] Particle impact noise detection. A particle would have to be 0.07 inches (1.8 mm) long to span the gap between terminal and armature; PIND detection of such a particle should not be difficult.

[5] Grooves were cut most of the way through the wall at the base and cover, and these grooves were then cut through with a fine chisel. Flange dimensions are approximately 3 by 3½ in. (75 by 90 mm).

[6] For more information on, and many photos of, tin whiskers, see http://nepp.nasa.gov/whisker/background/index.htm.

[7] http://nepp.nasa.gov/whisker/reference/survey/relay_survey.html.

[8] The manufacturer says that for this style, tin plating was replaced about December 1992 by electroless nickel.

[9] http://nepp.nasa.gov/whisker/reference/na-044.pdf.

this report is marked as complying with MS27997, a military standard drawing that has long invoked MIL-R-6106 as the procurement specification[11]. As stated in the GIDEP Alert, MIL-R-6106 was revised in 1981 (seven years before these relays were built) to prohibit the internal use of tin plating[12].

What became apparent upon opening the unfailed relay was the bright tin plating on the armature, including many long whiskers. X-ray fluorescence confirms that the armature plating is pure tin[13]. The wall plating is tin-lead[14] and does not have whiskers.

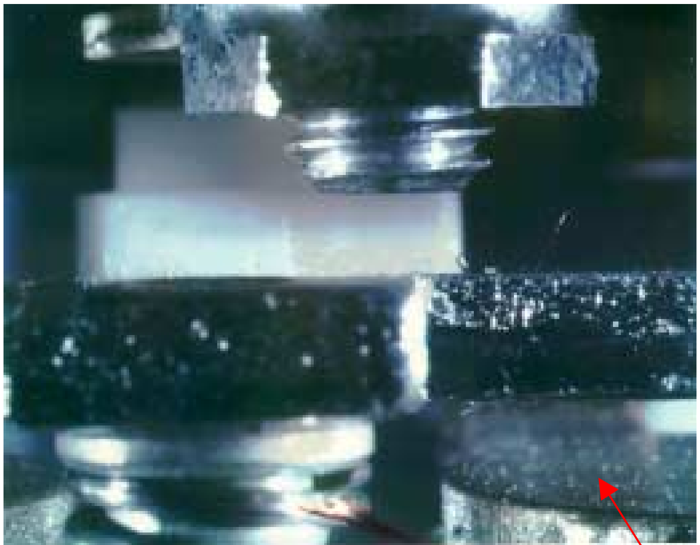


Figure 5A – Edge view of armature with pole piece

Although with suitable lighting the whiskers can be seen without magnification, photographing them is difficult[15]. Figure 5 shows an edge view of the armature. A terminal stud is seen at the top, and the return spring at the bottom. Not visible in the photo is a whisker that spans about 75 percent of the gap to this stud. Many flattened whiskers can be seen as spots on the pole piece of the coil (see red arrow, Fig. 5A). For judging dimensions, the gap in Fig. 5B between armature and terminal stud is 0.07 inch (1.8 mm). Many whiskers longer than 0.1 inch (2.5 mm) can be observed, but (as to be expected) only at locations where the gap is larger. Figure 6 shows another view of whiskers.

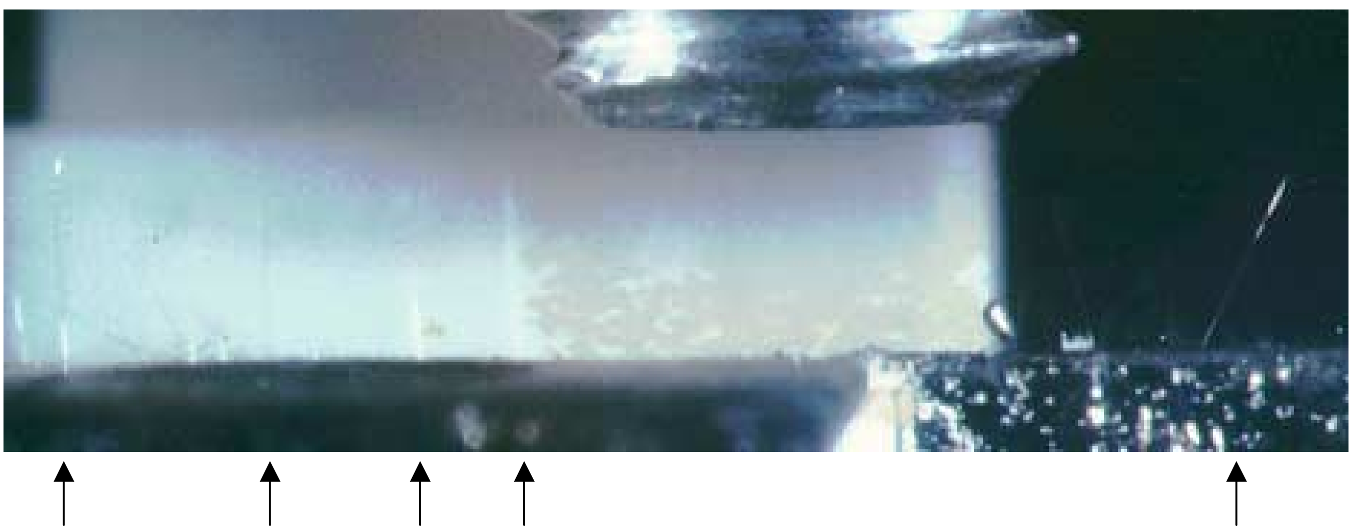


Figure 5B – Close-up view from Fig. 5A. Arrows show location of prominent whiskers

[10] Alert No. C6-A-91-03, prepared by Floyd Moore of Boeing Aerospace & Electronics, April 1991.

[11] At least since Rev. A, dated 1970. This military specification is titled “Relays, Electromagnetic, General Specification for” (now MIL-PRF-6106). A representative for the manufacturer stated that the relay is evacuated and backfilled with dry nitrogen, plus a small amount of oxygen to prevent cold welding.

[12] In Rev. J, 2 Nov. 1981, para. 3.3.1 was added: “Zinc plating, cadmium plating, or unfused pure tin plating shall not be used on internal parts of hermetically sealed relays.” The current requirement (Rev. L, 10 Nov. 2000) is 3.4.1.1a: “Pure tin plating is prohibited internally and externally. Tin-lead finish is acceptable, provided that the minimum lead content is 3 percent.” Lead in tin plating is known to suppress whisker formation.

[13] One edge showed about 80 µin (2 µm), the opposite edge, 260 µin (6.5 µm) of tin.

[14] Approximately 70 percent tin, 400 µin (10 µm) thick. The wall material is aluminum.

[15] Although long, a typical whisker is slender – just a few µm.

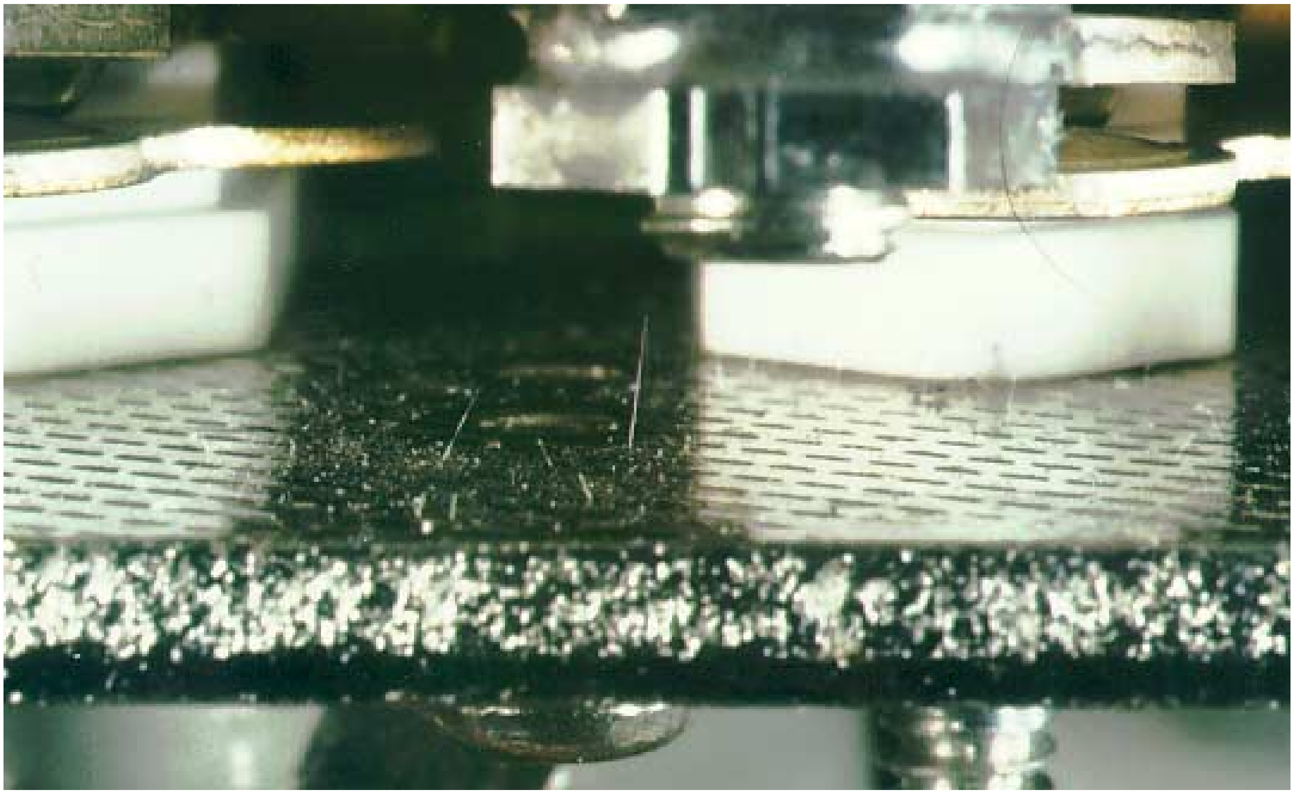


Figure 6 – Oblique view of armature showing whiskers

Some additional facts about tin whiskers are worth reporting here[6].

> Experimenters report the incubation period [before whisker growth begins] may range from days to years. This attribute of whisker growth is particularly concerning because meaningful experiments to determine the propensity for a particular process to form whiskers may need to span very long periods of time. Growth rates from 0.03 to 0.9 mm/yr have been reported. Growth is highly variable and is likely to be determined by a complex relationship of factors including plating chemistry, plating thickness, substrate materials, grain structure and environmental storage conditions… Some experimenters report that ambient temperatures of approximately 50°C are optimal for whisker formation, while others observe that room temperatures (22°C to 25°C) grow whiskers faster. Reportedly, whisker growth ceases at temperatures above 150°C.

Tin whiskers, some long enough to cause a short circuit with appropriate location, are present in unfailed fielded relays. However, given that the internal pressure is one atmosphere, it might seem surprising that a tiny whisker could initiate a high-current case-rupturing discharge instead of just melting open. Indeed, the NASA parts advisory[9] states

> At atmospheric pressure, if the available current exceeds the fusing current of the whisker, the circuit only experiences a transient glitch as the whisker opens. ***In space vacuum*** however, a much more destructive phenomenon can occur. If currents of above a few amps are available, the whisker will fuse open but ***the vaporized tin may initiate a plasma that can conduct over 200 amps!*** [Emphasis in original] An adequate supply of tin from the plated surface is necessary to sustain the arc.

However, the failure mode demonstrates that it is quite possible to have a self-sustaining arc at atmospheric pressure and the kind of voltage and current available to this relay. Arc welders operate at similar voltages (with no tin). For an arc, the relationship between voltage and current is not linear but partially inverse, as expressed by the Ayrton equation[16]:

$$E_a = a + bx + \frac{c + dx}{i} \tag{1}$$

where $E_a$ is the arc voltage, *a, b, c*, and *d* are empirical constants that depend on the electrode material and surrounding gas, *x* is the gap between electrodes, and *i* is the current. Thus, the voltage needed to sustain an arc actually drops as the current rises.

As an example, for iron electrodes in air and with the gap expressed in mm, the equation is

$$E_a = 15.0 + 9.4x + \frac{15.7 + 2.5x}{i} \tag{2}$$

Assuming a 2-mm gap and 115 volts, the initial current is only 250 mA; the high-current limiting value for $E_a$ is 34 volts[17]. It seems clear that adequate voltage is present in these relays as installed in military airplanes to sustain the kind of arc that has been observed.

It is interesting to note that the current density in an arc is practically independent of the current, and most of the current is carried by electrons[18], not gas ions. The characteristic temperature is 5000 to 6000 K[19] – well above the boiling temperature of all the metals involved (e.g., 2736 K for aluminum, 3148 K for iron, 2891 K for tin[20]). This is consistent with the observed partial melting of the armature. Thus, while tin initiates the arc, contrary to the NASA assertion above neither its presence nor reduced pressure is necessary to sustain it[21].

## Conclusion

Any relay containing tin plating inside is at risk of having tin whiskers. A whisker almost long enough to cause failure was observed in the unfailed relay. One whisker, if it gets long enough and is appropriately located, and if adequate voltage and current are available, can cause a damaging event of the kind shown in Fig. 1, even at atmospheric pressure.


## Acknowledgements

The author is grateful for help from Pete Espersen, Tom Andersen, Deas Brown, Ken Radford, Vic Velelli, George Forrester, Gary Vriesema, and Ken McCue.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[16] J. D. Cobine, *Gaseous Conductors*. New York: Dover Publications Inc., 1958, p. 294. My thanks to Lyon Mandelcorn, formerly with Westinghouse Electric Corporation, for providing the reference and for helpful conversations. According to Dr. Mandelcorn, special efforts are needed in the design of high-current circuit breakers to ensure that opening the breaker contacts actually does interrupt the current.

[17] The calculated gap for 115 volts at high current is more than 10 mm. This is complicated by the oscillation of the voltage and the presence of three phases. Tabulated values for a, b, c, and d for other combinations of electrode material and gases are mostly within a factor of three of the values used in Equation 2.

[18] Cobine, *op. cit.*, p.292.

[19] Cobine, *op. cit.*, p.291.

[20] R. E. Honig, “Vapor Pressure Data for the Solid and Liquid Elements”, *RCA Review*, **23** (4), 1962, 567-586. Note that while tin’s melting temperature (505 K) is well below that of aluminum (933 K), its boiling temperature is higher.

[21] Hertha Ayrton developed Equation (1) in 1902 while studying how to make arc lamps perform better. The arcs she studied ranged from 2-25 amps and 35-85 VDC. Atmospheric-pressure arcs may be unfamiliar to NASA because of the rarity of its use of voltages and current sources able to sustain them.