TIN WHISKER EXPERIENCE - ROCKET MOTOR INITIATOR Failure Analysis

Problem Description:	**Charge wire shorted to case**
Problem History:	**During assembly-level testing, the rocket motor initiators were showing an ohmic short from the charge wires to the case. These parts passed initial testing at supplier. The shorts on a few devices, measuring less than 50 ohms, were duplicated after part removal. The short was not duplicated on a few other devices.**

Problem Title: **Rocket motor initiator failure**

Summary:
The failure mechanism was determined to be tin whiskers emanating from the tin plating on the internal pins. The high conductivity, pure tin crystalline whiskers bridged the 10-mil spark gap to cause the test failures. The fusing current of the whiskers was in the range of the source current of the test equipment. This caused inconsistencies during problem identification and verification at the various test facilities. The following is the chronology of events in the investigation of the initiator test failures.

Xray Exam:
No anomalies were detected within the case or along the shield braid. The shield braid was removed on a previously fired unit to facilitate inspection. No features were detected to suggest a shorting mechanism.

Electrical Test and Evaluation at Supplier 1:
Three shorted devices were sent back to Supplier 1 for electrical test. When measured with a Valhalla low resistance meter none showed evidence of shorting. The three devices were tested for insulation resistance at 500vdc with a Hipotronix hi-pot meter. The meter was set at the highest sensitivity. One of the devices caused the meter to indicate a failure the instant the "test" button was depressed. Subsequent testing did not duplicate this failure. No reasonable explanation was provided for this transient response other than it could be attributable to "moisture burn-off" or other foreign material in the spark-gap.

Assembly Audit:
A review of the piecepart drawings and assembly processes identified a few areas that are potential contributors to this failure mode.

1. The two pins which are within the glass seal are tin plated. A well documented phenomenon with pure electrodeposited tin is the formation of "whiskers". These filaments of pure tin from the plating can be as long as 100mils, and are attributable to compressive stress in the plating. The spark gap is a 10mil clearance around the pins.
2. There is no specific call-out for a final clean or visual inspection of the spark gap. Residual process chemicals could provide a source of ionic contamination and moisture. This may result in latent defects due to dendritic growth across the surface of the glass seal.
3. Loose conductive debris may intermittently bridge the spark gap during vibration.

Destructive Analysis:

Eight fired initiators were supplied for analysis. There were no previous indications of electrical anomalies with these devices. The shield braid crimp band was pulled off. The case surrounding the encapsulation was removed with a combination of lathe and end mill. The Viton elastomeric gasket was removed. Both surfaces of the gasket had a texture similar to a woven fabric. Some filaments, likely fibers, were observed attached to the bottom side of the gasket. A gasket was measured for conductivity up to 50 volts dc, and no leakage was detected.

Scanning Electron Microscopy/Elemental Dispersive Xray Spectroscopy (SEM/EDS):

A few slightly reflective features were barely detectable on some of the pins using optical microscopy. One was examined by SEM/EDS and appeared to be a tin whisker extruded from the surface down in the spark gap area. EDS returns were weak from this area but iron, nickel, cobalt (Kovar), and tin were detected. The relative amount of nickel detected suggested a nickel plating under the tin. The diameter of the whisker was ~14 microns, and it was ~30 microns long. A cursory examination of this and two other fired initiators did not reveal evidence of additional whiskers.

Inspection of Assemblies at Customer:

The rocket motor assemblies with failed initiators were evaluated at the assembly facility. Valhalla resistance meters were brought in from supplier to confirm the failures. The shorted initiators were measuring between 10 and 24 ohms from leads to case. The test set and cabling into the explosion-safe room where the motors are tested were inspected and verified with resistors of known value. The Valhalla meter used in th assembly facility was a battery-powered fail safe model, with a 10mA current limit. Failed initiators were then measured with the other two Valhallas and the short appeared to clear. They subsequently measured open with all meters. The source current of the other Valhalla models was specified as up to 100mA.

A curve tracer was used to characterize the V-I characteristic of a shorted initiator. The response was essentially linear, which is typical of an inherently conductive material, rather than an ionic contaminant. The slope of the response indicated a resistance of ~12 ohms up to ~15mA of applied current. The short then cleared, and no conduction was observed with up to 30V applied. A second failed initiator was tested and exhibited an almost identical response. To dispel the theory of a shield braid strand shorting to the lead, a small strand was removed and tested with the curve tracer. The response indicated a resistance of <1ohm. The power was increased in an attempt to measure the fusing current. The strand withstood more than 5 amps and remained intact. The two initiators used in this test were returned to the vendor to download the charge. These devices were then sent for destructive analysis.

Destructive Analysis of Failed Initiators:

The two initiators, S/N's 756 and 949 were deprocessed in the Model shop, using a lathe. A plunge cut was made into the housing surrounding the leads. This caused the epoxy encapsulation around the leads to separate from the internal elastomeric gasket. The pins were subsequently bent by this process. Optical examination of the spark gap area revealed numerous whiskers emanating from the leads.

Evaluation by SEM/EDS revealed the following:
S/N 756 - Approximately 5-10 whiskers per pin were identified.
S/N 949 - Approximately 20-30 whiskers per pin were identified.

In both cases, the whiskers were growing from the tin surface at various angles, and reached various lengths. They were 2-3 microns in diameter. None could be conclusively identified as fused from the curve tracer test.

EDS dot maps were produced of the whiskers. A dot map shows the elemental composition of the sample, and the location on the sample where the detection originated for each element. Two dot maps are included in this report. The top images on the dot maps are the secondary (SE) and backscatter (BSE) electron images of the sample, in this case a single whisker. The other images are the elemental maps of the sample, each map for a specific (labelled) element. Tin, iron, nickel, and cobalt were mapped. The first dot map was generated from a whisker still intact, suspended in the spark gap. Significant detections of Fe, Ni, and Co were identified in the whisker. A subsequent dot map was generated with whiskers removed from the initiator. No trace elements were detected - only tin. This indicates that scattered xray photons from the background created spurious detections in the field of view. Other reports have suggested that whisker growth is influenced by impurity diffusion in the tin, based on elemental maps of the test samples. The validity of this diffusion theory will be determined by the accuracy of the elemental data.

Process Audit at Supplier 2:

An audit was conducted at the second-source supplier, to assess possible areas of risk in their assembly and test flow. One note of coincidence, they had test failures in 1989 which resulted in an extensive investigation. The result of this identified tin whiskers growing out of tin-plated pins, extending across the spark-gap. These whiskers appeared to support more than 25 mA of current. The pins are presently tin/lead plated, with no evidence of whisker growth. Their spark-gap is designed to be 7-10mils, but there is no callout for concentricity. All devices are tested at least twice at 500Vdc, and an ESD test at 25kV.

Supplier 2 has more documented procedures for visual inspection, aqueous and ultrasonic cleaning of their subassemblies. This appears to be sufficient for eliminating ionic and particulate contaminants. With respect to their electrical tests, it is unlikely that they would have detected the shorts that are presently being observed on the Supplier 1 devices. The specific sequence of events during the automated hi-pot test was requested. Their investigation revealed that the current through the device under test is not monitored until 1 second after the application of test voltage (500vdc). This is sufficient time to clear the short, resulting is a test "good" indication.

The general opinion of the audit team was that Supplier 2 was a mature organization, with dedication and competence demonstrated by the production, engineering, and manufacturing organizations.

Deprocessing of Initiator from Flight Failure:

A Supplier 1 initiator from a prior flight test failure was submitted for analysis. The failure was due to a delay in the firing of the launch motor, although the initiator did not appear to be a contributor. The spark gap area was exposed and the pins examined optically under darkfield and brightfield illumination, up to 200x. There was no evidence of whisker growth.

Conclusion:

The electrical test anomaly identified with the fail-safe low current Valhalla ohmmeter and the curve tracer was due to the growth of tin whiskers, which bridged the spark gap internal to the initiators.

Discussion:

There have been many reports of the tin whisker phenomenon dating back to at least the 1950's. Although the consensus on the growth mechanism is residual or applied compressive stress on the tin plating, there is still disagreement over accelerating factors and the physics of the nucleation and diffusion mechanisms which drive the whisker population. The following are the recurring opinions in the literature on potential sources of compressive stress.

- Electrodeposited pure tin, especially bright tin with organic additives, tends to result in a fine-grained structure with high residual stress. This is conducive to whisker growth. Plated and reflowed, or hot tin dip coatings result in a stress-relieved, large-grained structure. This will not support whisker growth, although one report claims whiskers were induced with an externally applied mechanical stress at elevated temperature. If, during assembly at Supplier 1, the operator soldering the wires to the pins had heated the entire pin sufficiently to reflow the tin plating this failure may never have occurred. Both alloying the tin with at least 1% lead, as well as plating thickness greater than 10 microns are reported to inhibit whisker formation.

- The base metal or under plating can influence whisker growth. It has been shown that tin over copper or copper alloys will promote whisker growth. The volumetric change during the formation of Sn/Cu intermetallic compounds will develop compressive stress in the tin. Thermal cycling may also contribute to compressive stress due to the mismatch in coefficient of thermal expansion.

- Exposing the plated parts to elevated temperatures (~50 deg C) has been claimed to accelerate whisker growth, it has also been disputed. Exposing the plated parts to higher temperatures (~150 deg C) has been claimed to allow grain growth (annealing) in the tin to relieve residual stress and eliminate whisker growth. This too has been disputed.

- Externally applied mechanical (compressive) stress can cause whisker formation. There may be additional stress on the pins due to case distortion from the installation torque of 75-90 in/lbs. Although this is not a likely contributor, it is included to illustrate the number of variables which must be considered, making analytical solutions to this problem difficult.

The effect of tin whiskers in low power circuits has been extensively documented. The launch/flight motor initiator current is sourced by a low impedance battery. The risk in this high power application is if a sufficient number of whiskers bridge the spark gap and are able to support enough current to affect the timing of the initiator current pulse, or cause a premature ignition if the "fire" FET fails. Curve trace testing of two failed parts indicates less than 15mA will fuse the whiskers. The circuit appears to be able to tolerate an additional 1.5 amps of loading without significant effects. This implies that over 100 whiskers are required to grow across the spark gap and make ohmic contact with the case before circuit interruptions begin to become a possibility. The highest whisker count on the failed units that were analyzed was 30 per pin, very few of which had progressed across more than 75% of the spark gap.

Published reports have indicated a time dependence, and possible incubation periods associated with whisker growth. The present lot of initiators have been identified as over two years old. Every initiator has been electrically tested for isolation to the case, during various stages of fabrication and integration. The current threshold which would allow detection during electrical test is much lower than that required to begin to pose a risk during launch or flight. There have been no known cases of initiator shorts which have not cleared using conventional measurement techniques.

The question which remains to be answered is "when will the whisker growth terminate". This requires knowledge of plating variables, thermal history, and other initial conditions that cannot be determined at this point. The compressive stress in the plating must be relieved. One possible approach would be to determine future growth potential empirically. Samples of initiators could be inspected, then stored in an environment most favorable for whisker growth. The actual growth rate could be documented by periodic inspections of the spark gap area.

1. Six initiators were submitted for evaluation and documentation of whisker activity in the spark gap areas. It was claimed that these initiators were determined to be shorted. They were sent to Supplier 1 for downloading of the charge. The epoxy encapsulation and outer case were removed mechanically. The following is a summary of the results:

Internal Exam:
The spark gap area was examined with an optical microscope to 100x magnification.

S/N	Observation
LM 0689	many whiskers observed, with more than 3 per pin that had progressed across more than 50% of the spark gap.
1273	similar to 0689
0953	similar to 0689. The pins were slightly damaged during deprocessing
140	similar to 0689
854	no whiskers were identified
1203	whisker activity not as pronounced as 0689

SEM Exam:
Inspection of the spark gap areas of the above devices confirmed the visual exam. The whiskers measured approximately 1 - 4 microns in diameter. This measurement variation is likely due to the measurement orientation, since the whiskers are not perfect cylinders. No whiskers were identified on device 854.

In general, the whiskers were uniformly distributed around the pins. One theory suggests that the process of forming the J-hook may add residual compressive stress to the pin resulting in whisker growth. If the stress was in unidirectional bending, it would place one side of the pin under tensile stress, and the opposite side under compressive stress. There was no whisker growth pattern around the pins to suggest a preferred orientation.

2. S/N 756 was microsectioned to measure plating thickness on the pins. This sample was from the original analysis.

Microsection/SEM:
Three measurements were taken of the tin plating on each pin, one at the bottom of the spark gap near the glass seal, one at the midpoint, and one at the opening of the spark gap. There was considerable roughness in the base metal, and non-uniformity in the plating, so the thickness is presented as an approximate average.

	Tin Thickness, microinches		
Measurement Point	pin 1	pin 2	Nickel Thickness
A - near glass seal	43	85	none detected (or less than 1 microinch)
B - midpoint	87	67	"
C - at opening	83	91	"

The thickness for the tin appears to be slightly below the 100 - 250 microinches as specified by Supplier 1. One source in the literature recommended a minimum thickness of 400 microinches to achieve a plating with low residual stress. A layer of nickel plating was not detected under the tin.

3. Whisker fusing test. An electrical evaluation was performed by the project on eight shorted initiators to measure the fusing current of the short (whisker). The ESAF circuit was used with a 30v power supply to simulate the thermal battery. The charge wire was in series with the short path, and the current during the event was monitored with a storage scope. The short in initiator # FM 0886 appeared to sustain a 2.2 amp current for >20 microseconds (offscale) which caused the initiator to fire.

The initiator was deprocessed to examine the spark gap area. An arc had clearly been sustained across the spark gap, from one of the pins to the case. The size and duration of the arc could have been influenced by factors other than the amount of tin in the whisker. The test leads used to connect to the initiator in the safety box were significantly longer than in the system. The stray inductance may have provided the additional energy to sustain the arc after the whisker fused. The polarity of the applied voltage was opposite the system configuration.

The metal transfer during a D/C arc will tend to follow the electron flow. The tin on the pins has a much lower melting temperature than the nickel on the case. Locally high temperatures at the arc would reflow the electrodes. It is possible that the electron flow from the pin allowed the reflowed tin to be consumed to sustain the arc. Both of these variables may be eliminated in subsequent testing.

SEM/EDS Examination:

An attempt was made to identify the composition of the disruption in the metals from the arc, and to determine the direction of metal transfer. The results were inconclusive. The area of interest was in a recessed location that caused spurious indications in the EDS x-ray returns.

One other observation resulting from this test is that the mechanical shock of firing the initiator did not appear to affect the whisker population. In fact, one whisker grew outside of the spark gap to a length of ~15 mils, and remained intact. This indicates that the initiators that did not exhibit whisker growth after being fired likely never had whiskers.