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INVESTIGATION OF SEVERE LIGHTNING STRIKE INCIDENTS TO TWO USAF F-106A AIRCRAFT

J. Anderson Plumer

LIGHTNING TECHNOLOGIES, INC.
Pittsfield, Massachusetts 01201

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National Aeronautics and Space Administration

Langley Research Center
Hampton, Virginia 23665

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1.0 Introduction

On 18 December 1978 two USAF F-106A aircraft were struck within a few minutes of each other by separate lightning strikes near Castle AFB, California. Both aircraft had been equipped with the lightning protection modification kit in accordance with USAF T.O. 1F-106-1130 dated 1 February 1976. This modification is described briefly in the Appendix.

One of the aircraft was struck twice and the other one once and the pilot reports indicated that the strikes may have been very severe. The strikes caused extensive damage to the pitot heater harnesses and AWG No. 8 ground wires in each radome, and to the lightning suppressors included with the protection modification kit, although no damage occurred to either aircraft's electrical or avionics systems which this kit is intended to protect.

Because of the apparent severity of these strikes, and the fact that a similar protection modification was being designed for the F-111 radome mounted pitot heater circuit, an investigation was made of these incidents. This investigation consisted of a detailed inspection of the two aircraft and discussions with the pilots of each, conducted on 3 January 1979 at Castle AFB, California. This report presents the results of this investigation and an analysis of the findings. The inspection and pilot interviews were conducted by J.A. Plumer of Lightning Technologies, Inc. and H.M. Bryant of the USAF Sacramento Air Logistics Command, McClellan AFB, California.

2.0 Summary

The two aircraft each sustained severe lightning strikes to the pitot booms, resulting in extensive damage to the pitot heater power harness, No. 8 ground wire, and lightning suppressors, but there was no damage to neither aircraft's electrical or avionic systems.

A simulated lightning current of 226 kA and 3.8×10^6 $A^2 \cdot s$ was required to reproduce the damage sustained by the AWG No. 8 ground wires in the radomes of these aircraft. This is nearly twice the energy of present aircraft lightning current test criteria (200 kA, 2×10^6 $A^2 \cdot s$). If the protection modification had not been in place a surge of major intensity would have entered the aircrafts' electric power distribution systems and the resulting damage to onboard avionics might have been extensive.

3.0 Aircraft Details

The aircraft were inspected and were identified as follows:

Aircraft A: F-106A

Aircraft B: F-106A

4.0 Investigation of Aircraft A

4.1 Pilot Report

This aircraft, which was the lead of a close-in formation of two, sustained two lightning strikes several minutes apart. The first strike occurred at about 4:30 - 4:45 PM while the flight was descending through 1524 m (5000 ft) in the vicinity of some small cumulus clouds and layers of cirrus clouds. It had just entered a heavy rain shower when the first strike occurred. The pilot reported that the strike produced a "big flash" and felt "like someone hit the side of the aircraft with a sledgehammer".

After this strike the aircraft entered a radar pattern (in preparation for landing) and a few minutes later a second strike occurred, producing a "ka-wham" and flash more severe than the first strike. The "Tonotron" radar scope went black and then came on again, with a "snowy" picture. The pilot reported no other instrument malfunctions, flags, circuit breaker pops or blown fuses after either strike. The aircraft proceeded to make an uneventful landing.

4.2 Inspection Findings

4.2.1 External

There was evidence of lightning attachment to the very tip of the pitot tube and swept attachment points appeared every 15 cm (6 in.) or so along the tube and polished aluminum boom. The aft-most lightning strike attachment points were on the adapter unit and glycol ring at the nose of the radome. There was no singeing or thermal discoloration of the radome aft of the adapter, nor were there any attachment points on the fuselage aft of the radome. This indicates a flash of relatively short duration (i.e. 10 milliseconds).

The degree of melting and localized nature of the attachment points along the boom indicate a moderate amount of continuing current and anode attachment points (i.e. negative electrons entered the boom).

The radome was not punctured.

The flash apparently exited the right wing-tip as indicated by an area 5 x 0.3 x 0.6 cm (2 x 0.125 x 0.25 in.) of aluminum eroded away from the trailing edge.

4.2.2 Internal

4.2.2.1 Pitot Tube and Boom Assembly

1. The heater power harness ground wire had been burned away from the splice adjacent to the varistor as illustrated in Figure 1.

Figure 1 - Pitot Heater Ground Wire Burned Away from Splice in Boom of Aircraft A. "Hot" wire was disconnected later).

2. The varistor (S/N: J/C 084) quality was checked in accordance with USAF T.O. 1F-106A-2-10-2-1S-1

case marking:	434 VDC @ 1 mA DC	
+ side to grd:	371 "	"
- side to grd:	328 "	"

USAF T.O. 1F-106A-2-10-2-1S-1 permits a change in varistor voltage of up to 20%. Thus, the (-) reading is beyond tolerance and the varistor should be replaced with a new one.

3. The pitot tube heater tested 20 ohms line-to-line and ∞ line-to-ground, indicating the the pitot tube remains in good condition.

4. There was no other physical damage to the wiring or components inside the boom.

4.2.2.2 Radome

1. The #8 AWG insulated ground wire (Part No. M5086/2-8-9) had been blown away from its terminating lugs and broken and fragmented at numerous places along its length inside the radome. The remains can be seen in Figure 2.

Figure 2 - Remains of AWG No. 8 Ground Wire and Pitot Heater Power Harness of Aircraft A after Two Lightning Strikes.

The outer (cloth) part of its insulation was "browned" and the inner (plastic) layer had been melted (boiled), and resolidified in many places. The tinning on the copper strands had been vaporized and the wire made brittle. The largest remaining section of this ground wire is shown in Figure 3.

Figure 3 - Remnant of No. 8 AWG Ground Wire (P/N M5086/2-8-9) in Radome of Aircraft A.

2. The inside of the radome at each end of the ground wire, and at several places in between was found discolored with metallic deposits from the blown-up ground wire. The forward side of the aluminum rim was bent inward slightly near the ground lug.

3. Fragments from the ground wire were found tightly lodged beneath the static tubes and clamps that run along the top of the radome. Several of these can be seen in Figure 2.

4. The studs at each end of the ground wire were intact and reusable, but the ground-wire terminals there had been melted or broken in two.

5. Not all pieces of the heater power harness and teflon insulating sleeve were available for inspection. Those that were however, (2 pieces over 46 cm long) showed indications of dielectric breakdown at their ends. A portion of the teflon sleeve can be seen in Figure 3.

6. There was evidence of arcing between the ground wire and the ILS localizer antenna tube near the aft-most clamp, and from the localizer tube to the aft ring (across a 2.54 cm air gap). The locations of this arcing are shown in Figure 4.

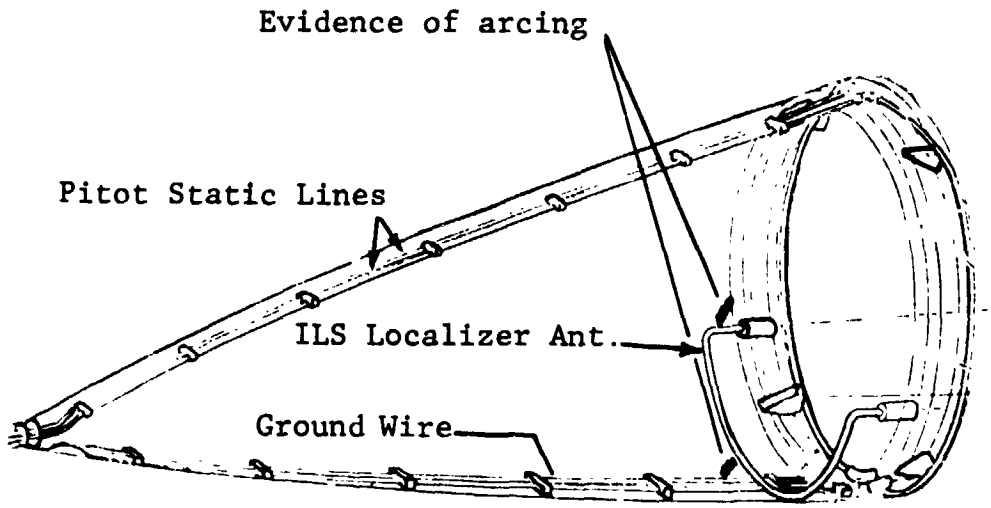

Figure 4 - Locations of Electrical Arcing between the Ground Wire and the Localizer Antenna on Aircraft A.

7. There was evidence of arcing between the heater power harness and the aft ring about 46 cm out from the P/N 3S2060DM185A1 suppressor.

8. The suppressor case had been fractured and blown away around the rectangular L1 and L2 inductors, which had been deformed and rounded by magnetic forces due to excessive current in these inductors. The damaged suppressor can be seen in Figure 5.

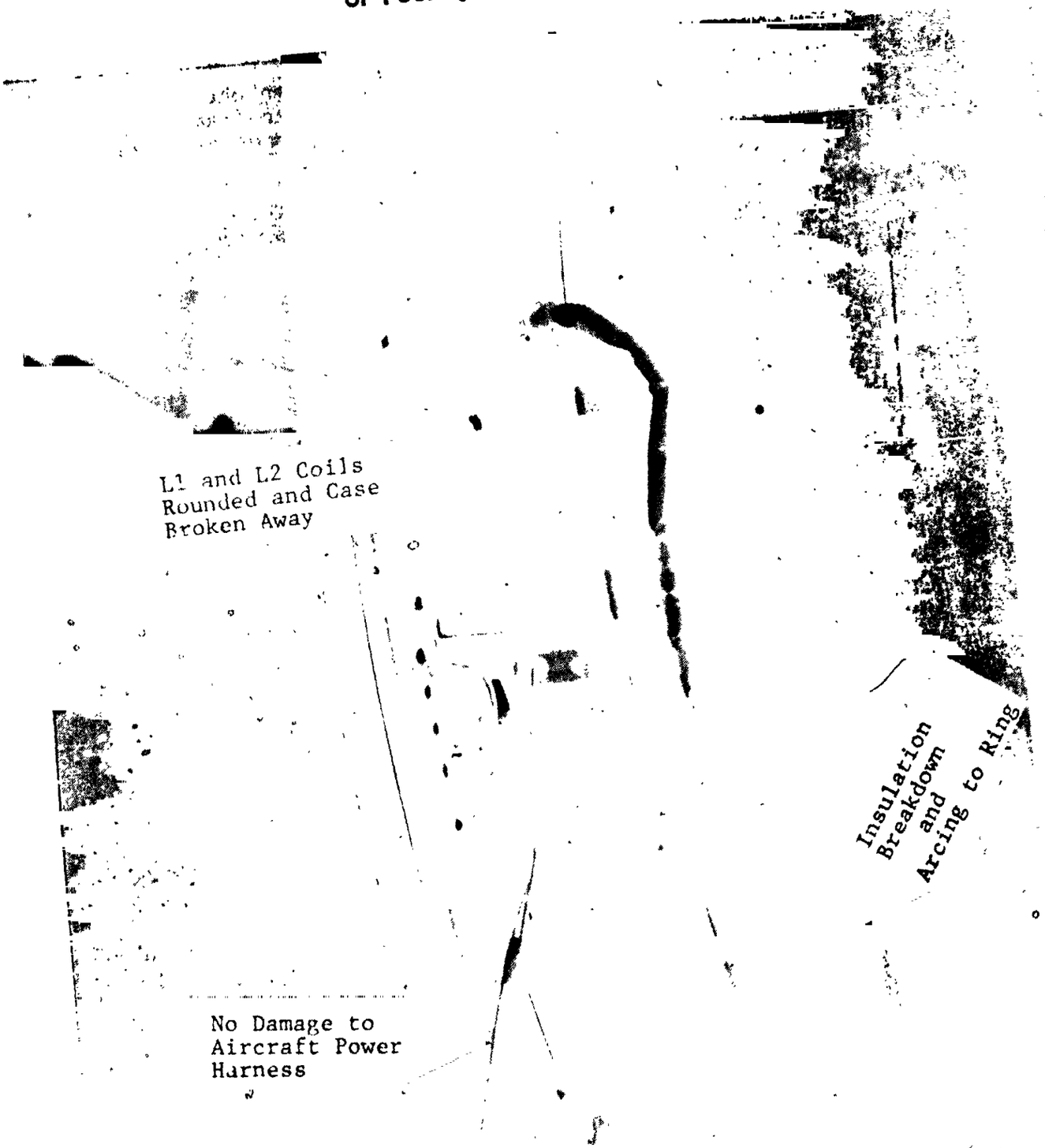

Figure 5 - Damaged P/N 3S2060DM185A1 Lightning Suppressor after Lightning Strikes to Aircraft A.

9. There was evidence of electrical arcing between one turn (each) of L1 and L2 and the suppressor mounting frame several turns out from the ground (aircraft) ends of these inductors. This can be seen in Figure 6.

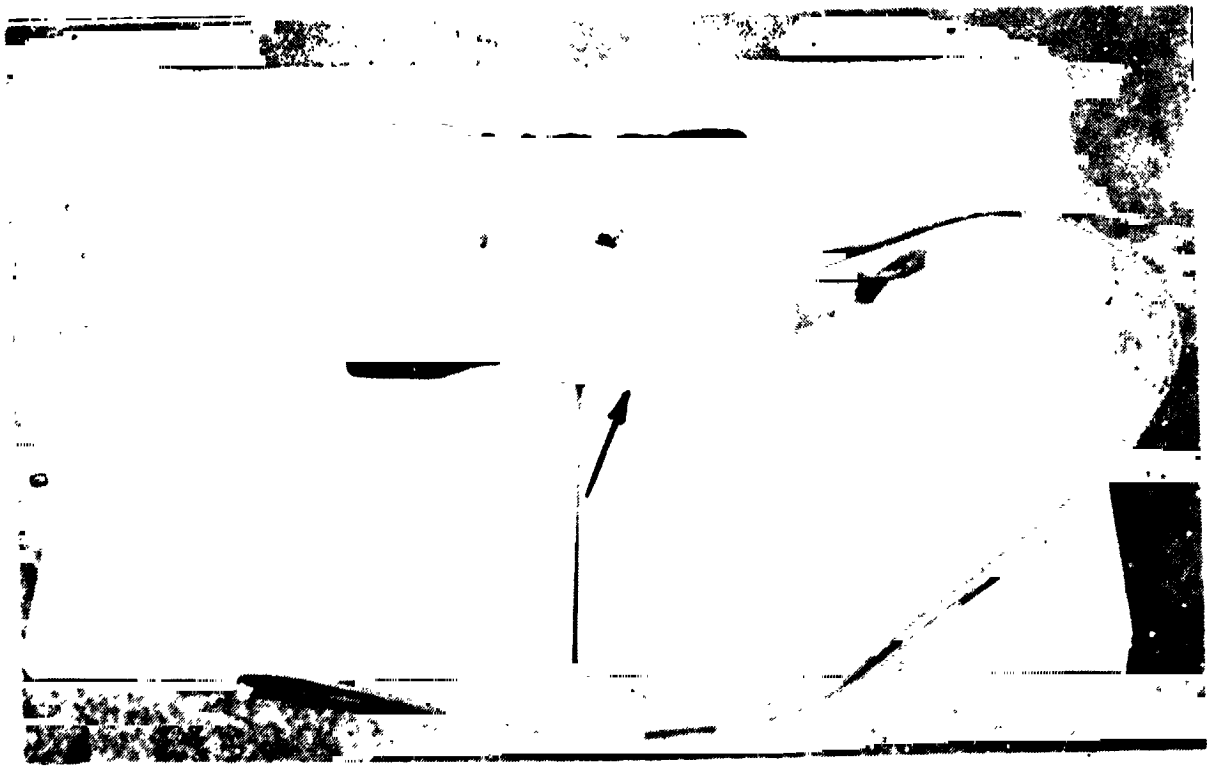

Figure 6 - Evidence of Minor Electrical Arcing between L1 and L2 Windings and the Metal Frame after Potting Material Broke Away (Aircraft A.

10. Results of the suppressor varistor quality check in accordance with USAF T.O. 1F-106A-21-10-2-15-1 were as follows:

case marking:	unavailable for inspection
+ side to ground:	+419 VDC @ 1 mA DC
- side to ground	-351 " "

11. The pitot heater harness aft of the suppressor was undamaged as shown in Figure 5. There was no evidence of electrical arcing at the bulkhead connector.

12. The L2 winding in the suppressor had been burned in two where it arced to the mounting plate. Power circuit continuity through the suppressor was maintained through the high side (L1) of the suppressor.

13. The non-metallic pitot and static lines (that run along the top of the radome) were undamaged.

14. The radar reflector dish had been cracked due to blast forces associated with the electrical arcing that was unleashed inside the radome when the ground wire failed.

4.3 Analysis

1. The evidence reported in the previous paragraph supports the following hypothesis:

The first strike probably left the lightning protection system intact. This conclusion is made because there apparently remained a conductive path for the second strike to follow inside the radome, since the radome was not blown up upon the second strike. Also, the pilot reported that the first strike was not as loud as the second one.

2. The second strike caused the #8 AWG ground wire terminations to fail at each end. This failure was caused by excessive magnetic forces that acted to break the wire at these points, and by thermal stresses that melted and weakened the crimped-on terminals at each end. This strike also caused the ground wire to become very hot; sufficient to melt and discolor the insulation along its entire length.

3. The ground wire terminations failed before all of the lightning current had passed. The balance of the current thus sparked into both conductors of the heater power harness; following, alternately, the harness and broken segments of the No. 8 ground wire to the aft ring. The high temperatures associated with each of these arcs caused the harness and/or ground wire to melt in two at these places. This caused the fragmentation observed in Figure 2.

4. After the aft ground-wire termination failed, the remaining lightning current arced over to the ILS antenna tube and from there to the rim, as was illustrated in Figure 4 and evidenced by melted spots at these places.

5. Also after the ground wire failed, some of the lightning current started to enter the heater harness, following this path into the suppressor. This current, of course, far exceeded the design level of the suppressor, and as it passed through L1 and L2, the magnetic forces it produced caused rounding and deformation of these coils. This in turn burst the potting compound and exposed the coils. Several of the turns touched the suppressor mounting bracket causing the

sparks and melting at the corner of one or two turns of each coil. The "hot" wire (L1) was melted in two and the hot wire (Pin A) of plug P1 was also melted, indicating that most of the lightning current in the harness had chanced to enter this wire. Some of this melting may also have been caused by 400 hertz AC power current arcing to ground through this fault, although the absence of a blown fuse indicates that this was unlikely.

The current that had entered the inductors was limited by them to an amount that could be tolerated by the varistor, which shunted it to ground. The varistor and the series inductor (L3) protected the aircraft's electrical system from any remaining surges.

5.0 Investigation of Aircraft B

5.1 Pilot Report

This aircraft, which was by itself, approximately 74 km (40 miles) away from aircraft A, sustained one lightning strike while flying at 1.7 km (5700 ft) and 275 knots about 28 km (15 miles) west of the field.

The pilot reported that the flight had been flying among layers of stratus clouds, and had just entered an area of very heavy rain when the strike occurred. It produced a "big white flash" that blinded him for about 5 seconds, even though his eyes had been focused on instruments when the strike occurred. The strike also produced a "loud bang", even though the pilot had earphones on at the time, and a "tingling" about the helmet.

The radar scope went black when the strike occurred, but no other effects to avionics or electrical apparatus were noted by the pilot.

The airframe radar had been painting "mostly ground clutter" prior to the strike and the pilot was not aware that he was approaching thunderstorm-type weather. No such storms had been forecast in the area, although the nearby town of Merced experienced a hail storm that same day.

After the strike occurred the aircraft proceeded to land uneventfully.

5.2 Inspection Findings

The lightning strike effects on this aircraft were very similar to those reported in Para. 4.2 for aircraft A as follows:

5.2.1 External

1. There was evidence of lightning attachment to the side of the pitot tube, as indicated by the dendritic patterns left on the stainless steel tube pictured in Figure 7.

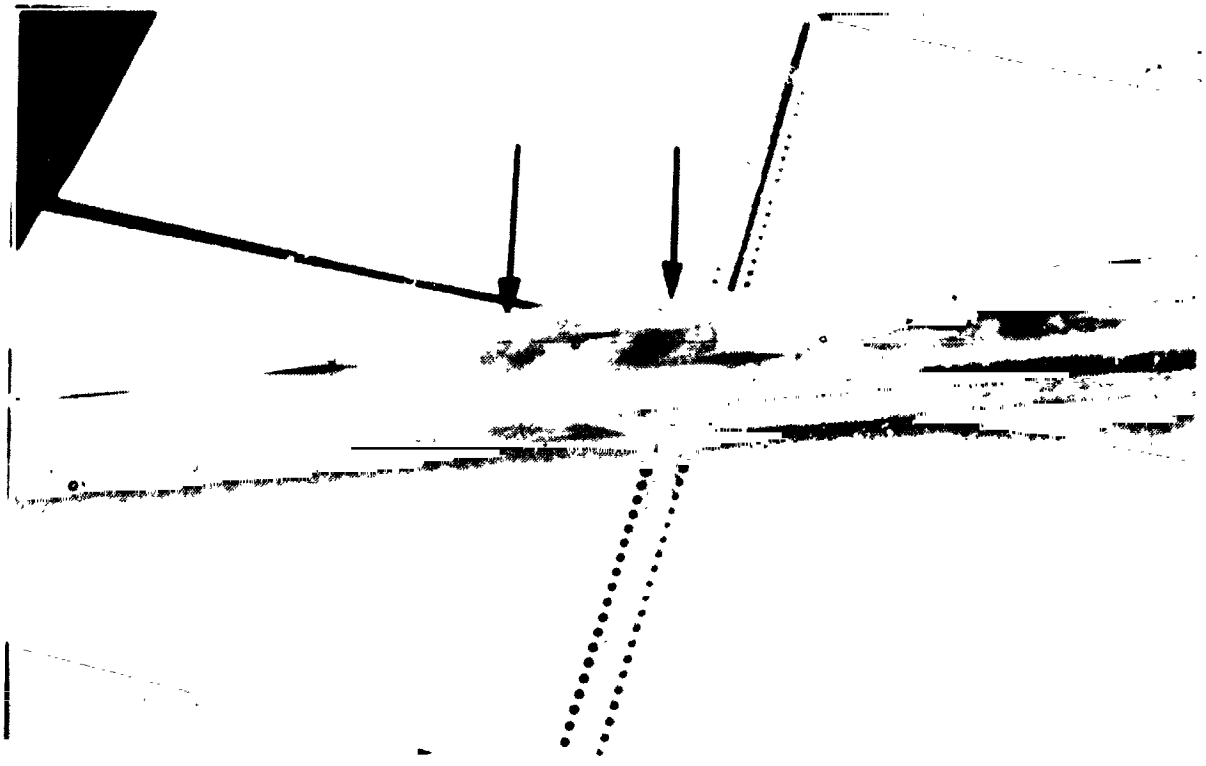

Figure 7 - Dendritic Patterns Left by Lightning Strike Attachment to Pitot Probe of Aircraft B.

2. There was minor damage to the fiberglass cap of the vertical stabilizer, which was the other lightning attachment point.

3. The radome was delaminated for about 6 inches along the bottom.

5.2.2 Internal

1. The No. 8 ground wire and pitot heater power harness had been broken and fragmented between the pitot boom and aft ring. The longest segment of ground wire remaining was 8 cm (3 in.) in length. The inside surface of the radome was covered with deposits of copper near the forward and aft ends, as shown in Figure 8. The largest piece of heater power harness remaining is shown in Figure 9.

Figure 8 - Inside of Radome of Aircraft B Following Lightning Strike, Showing Copper Deposit on Inside Wall at Forward End.

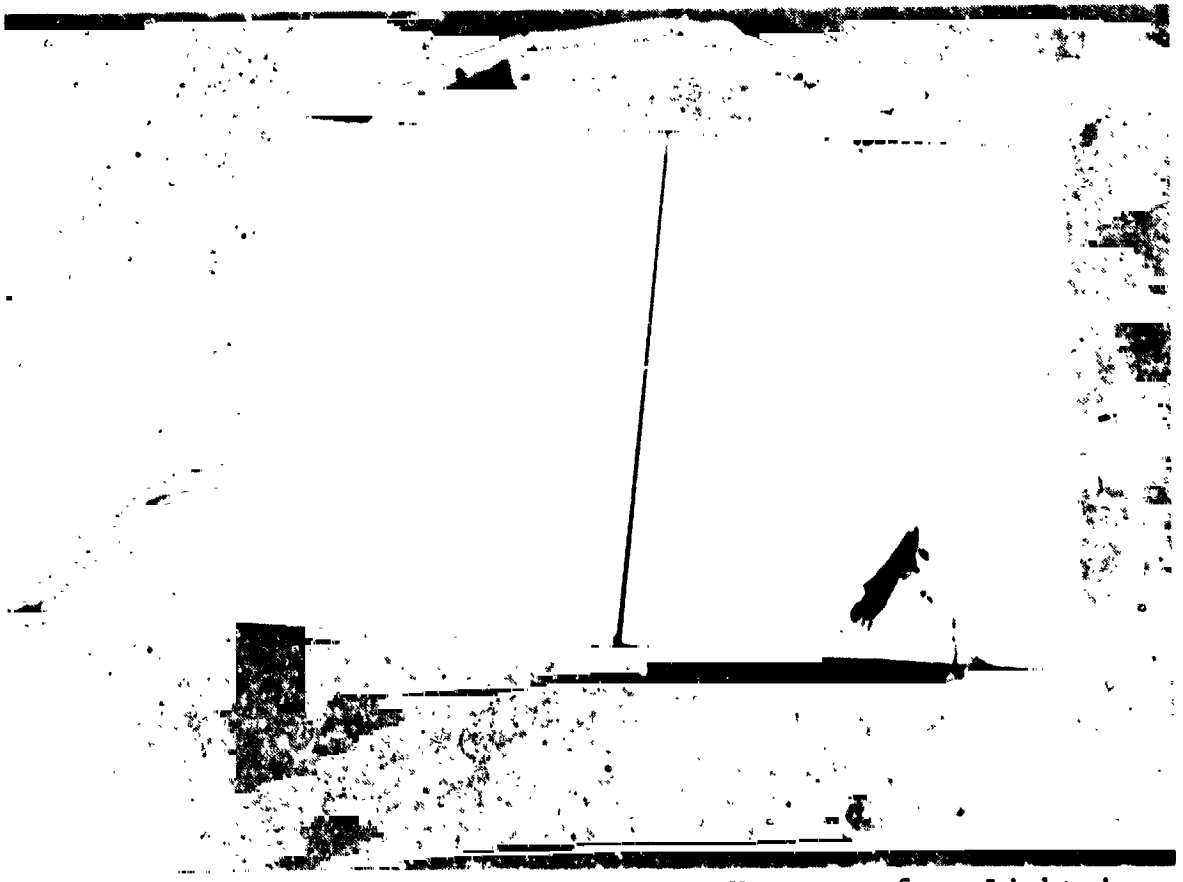

Figure 9 - Remains of Pitot Heater Power Harness after Lightning Strike to Aircraft B.

2. There was physical evidence of electrical arcing between the ground wire and the ILS antenna conduit as had occurred in aircraft A.

3. The P/N 3S2060DM185A1 lightning suppressor case had ruptured in a manner very similar to the one in the other aircraft, as shown in Figure 10.

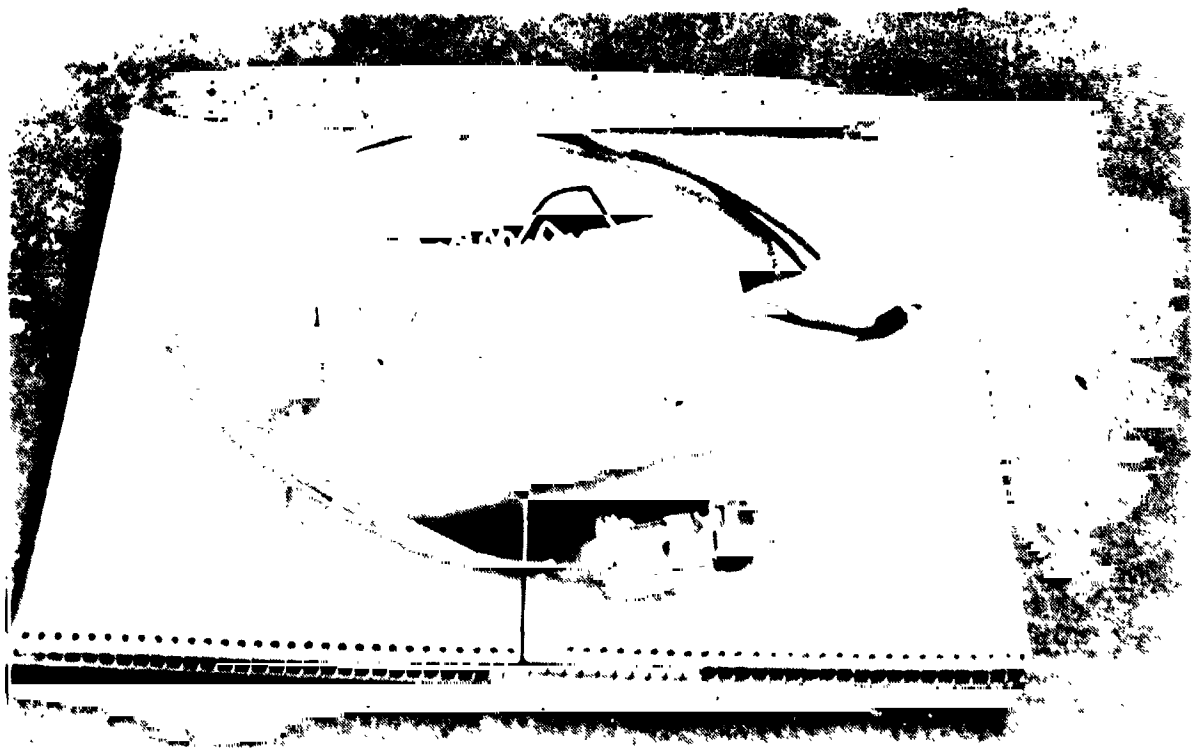

Figure 10 - P/N 3S2060DM185A1 Lightning Suppressor after Lightning Strike to Aircraft B.

The suppressor varistor quality was checked in accordance with USAF T.O. 1F-106A-2-10-2-1S-1, with results as follows:

case marking:	not available for inspection
+ side to ground:	408 VDC @ 1 mA DC
- side to ground:	400 VDC @ 1 mA DC

While the original varistor voltage was not available (the portion of the suppressor case with the stamped label having been fragmented and lost), the voltages of most of the varistors utilized in these suppressors range between 410 and 440 volts. In accordance with USAF T.O. 1F-106A-2-10-2-1S-1 the varistor voltage must remain within 20% of its original level. The varistor in this suppressor, then, appears to be undamaged. The suppressor, of course, must be discarded due to the ruptured case and damaged L1 and L2 windings.

4. There was no damage to the heater power harness between the suppressor and the aircraft.

5. There was no damage to any of the components within the pitot boom. The varistor P/N 164B7290G1 was given a quality check with the following results:

case marking: 423 VDC @ 1 mA DC
+ side to ground: 410 VDC @ 1 mA DC
- Side to ground: 419 VDC @ 1 mA DC

This indicates that the varistor was not overstressed.

5.3 Analysis

The similarity of damage between this aircraft and aircraft A indicates that the same sequence of events occurred (see Para. 4.3). The intensity of the current, measured in terms of action-integral ($A^2 \cdot s$), exceeded the capability of the No. 8 ground wire and the wire failed, forcing some of the current to enter the heater power harness. This damaged the harness conductors, and as it flowed in the suppressor inductors L1 and L2, it caused these coils to round themselves and rupture the case and potting compound. The suppressor, however, succeeded in keeping damaging current and voltage surges out of the aircrafts' power distribution system.

6.0 Concluding Discussion

6.1 Regarding the Lightning Strikes

There are several aspects of these strikes that are worthy of note:

1. Of the three strikes that occurred, two were similar and of an intensity far exceeding the level of presently accepted lightning protection design and test criteria.* An attempt to duplicate the damage to the No. 8 ground wire and the melting of its surrounding insulation required a current whose action integral was 3.8×10^6 $A^2 \cdot s$.

   Because the modification kit was designed for retrofit installation, it was not designed or qualified to the 2×10^6 $A^2 \cdot s$ level. Instead, it was qualification tested to 0.46×10^6 $A^2 \cdot s$ in accordance with San Antonio Air Logistics Command/MME Purchase Description No. 320.

*SAE Committee AE4L Report, "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware", dated June, 1978, Para. 3.2.2.1 (current component A).

2. The occurrence of strokes as high as 2×10^6 $A^2 \cdot s$ is a rarity in itself (approximately 1% of known lightning currents exceed this level) so the occurrence of two of them within a few minutes of each other must be considered a very rare occurrence.

3. The absence of extensive swept-stroke attachment points on either aircraft indicates that the total time duration of each strike was comparatively short, perhaps a few milliseconds. For example, if it is assumed that the strike first attached to the tip of the pitot probe and re-attached successively at points along the 1.83 m (6 ft) long boom (as confirmed by the physical evidence) and also that the aircraft was traveling at 1830 m/sec (600 ft/sec), the duration, T_d, of the flash would be:

$$T_d = \frac{6 \text{ ft}}{600 \text{ ft/sec}} = 0.01 \text{ sec.}$$

This, together with the extent of the damage inflicted upon the ground wires, indicates that the strikes may have been of the positive polarity variety in which most of the energy is transferred in a single stroke.

6.2 Regarding the Lightning Protection Kit

1. The lightning currents in these strikes exceeded the capability of the No. 8 ground wires in the radomes. Failure of the ground wires applied excessive stress to the suppressor, causing the effects noted. If the ground wires had not failed the suppressors would not have ruptured.

2. The possibility of future ground wire failures under unusually severe strokes like this could be minimized by replacement of the No. 8 wire with a longer No. 6 wire. The fact that the system failed safe in these cases, and that severe strokes like this are very rare would indicate that a safety of flight hazard is a remote probability and a fleet-wide modification in the ground wire is not warranted, however.

Appendix

F-106A Lightning Strike Protection Modification

The F-106A lightning protection modification is described in USAF T.O. 1F-106-1130 dated 1 February 1976 and incorporates modification kit identification No. 1560K0150172ABK.

Briefly modification replaces the original AWG No. 12 pitot boom ground wire with a No. 8 wire capable of sustaining more severe lightning currents, and places a lightning suppressor, Part. No. 3S2060DM185A1 in series with the pitot heater power harness to prevent damaging surges from entering the aircraft's power distribution system. A varistor is also placed across the heater power harness at the pitot tube to minimize the possibility of heater burn-out due to a lightning-induced voltage surge in the harness.

The lightning suppressor incorporates a pair of series inductors, L1 and L2, to limit the amount of lightning current that can flow in the heater power harness to safe levels and force most of it to remain in the ground wire. A varistor and single inductor, L3, prevent damaging voltage surges from passing on into the aircraft. The suppressor circuit is shown on Figure 11.

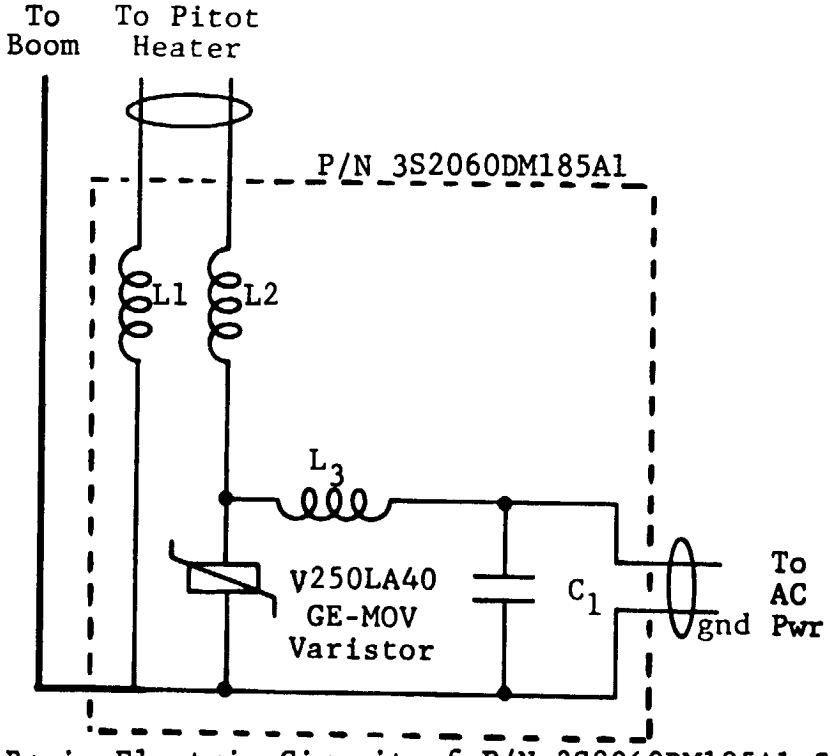

Figure 11 - Basic Electric Circuit of P/N 3S2060DM185A1 Suppressor.