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SUMMARY

As part of the NASA Langley Research Center Storm Hazards Program, 69 thunderstorm penetrations were made in 1980 with an F-106B airplane in order to record direct-strike lightning data and the associated flight conditions. Ground-based weather radar measurements in conjunction with these penetrations were made by the National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory (NSSL) in Oklahoma and by the NASA Wallops Flight Center in Virginia. In 1980, lightning transients were recorded from 10 direct lightning strikes and from 6 nearby flashes for a total of 16 lightning events. Following each flight, the airplane was thoroughly inspected for evidence of lightning attachment, and the individual lightning attachment spots were plotted on isometric projections of the airplane to identify swept-flash patterns.

This study provides further insight into the way in which an airplane interacts with a lightning flash channel, especially the manner in which flashes sweep aft from initial lightning attachment points. This paper presents pilot descriptions of the direct lightning strikes to the airplane, shows the strike attachment patterns that were found, and discusses the implications of these patterns with respect to aircraft protection design. The flight conditions during which the lightning events occurred are also included. Finally, brief descriptions of the lightning strikes on three U.S. Air Force F-106A airplanes which were struck during routine operations are given in the appendix.

INTRODUCTION

The NASA Langley Research Center (LaRC) Storm Hazards Program originated in 1977 in response to a National Transportation Safety Board review calling for "more sophisticated measurement of thunderstorm hazards and turbulence" and to an Airline Pilots Association call for "realistic policies for flight operations in severe storm areas." Although hazards such as turbulence and wind shear are being studied, the primary emphasis of the Storm Hazards Program is being placed on lightning hazard research. Lightning is of special interest because the projected use of digital avionics systems and composite aircraft structures will require incorporating lightning-related design features.

The flight program began in 1978 when a Twin Otter airplane equipped with an airborne lightning locator system was flown on the periphery of thunderstorms in Oklahoma and Virginia (ref. 1). The program continued in 1979 when operations began with an F-106B airplane, which was flown on the periphery of thunderstorms in Virginia (ref. 2). In 1980, the third year of the research effort, 69 thunderstorm penetrations were made with the F-106B in Oklahoma and Virginia during which lightning transients were recorded. Preliminary results from all the 1980 experiments are reported in references 3 to 6.

Although lightning protection for aircraft is available, it must be applied only where needed if the performance gains afforded by new digital avionics systems and composite materials are to be realized. This requires improved knowledge of the susceptibility of various parts of the aircraft surface to lightning strikes, that is, the lightning strike zones. A large number of reports exist on lightning strike attachments to civil and military airplanes (for example, refs. 7 to 11), but these do not sufficiently develop the complete lightning attachment scenario or identify all the initial- and swept-flash attachment points. For the purpose of establishing surfaces of different susceptibility to lightning strikes on such aircraft, the Federal Aviation Administration has defined lightning strike zones in reference 12. These definitions were later expanded by Society of Automotive Engineers Committee AE4L (ref. 13) to accommodate the different lightning environments at forward and trailing-edge regions of the airplane. These definitions, however, do not establish the actual locations of the various zones on a particular airplane. At present this is accomplished by comparing new designs with actual experience (when available) of similar-shaped airplanes, or by simulating lightning strikes in scale-model tests. Uncertainties still exist, and the purpose of the Storm Hazards Program is to clarify some of the more questionable aspects of establishing lightning strike zones. The purpose of this paper is to report the complete results of the Storm Hazards '80 lightning-attachment-point analysis.

TEST EQUIPMENT AND PROCEDURES

The nine airborne experiments on the F-106B in 1980 are described in references 1, 3, 5, and 14 to 29. Table I summarizes the experiments performed.

Test Equipment

F-106B research airplane.- The F-106B, a two-seat, delta-wing interceptor with 60° leading-edge sweep, is shown in figure 1 and the basic characteristics are given in table II. The two-seat cockpit and large internal weapons bay for carrying the research instrumentation systems make it well suited for thunderstorm research. The canopy provides a metal structure above the crew to minimize the possibility of canopy puncture or of electric shocks to the crew from lightning. The U.S. Air Force inventory of F-106 airplanes has been relatively free from lightning strike damage compared with other aircraft in the U.S. military inventory, and the engine has proven resistant to flameout from ingestion of lightning flash pressure fluctuations or ingestion of large amounts of precipitation.

The criteria used in choosing this airplane for thunderstorm research are given in reference 30. Based on these criteria and on discussions with other thunderstorm researchers, an extensive "lightning hardening" program was carried out on the airplane and the data systems (refs. 2, 5, and 6). Prior to each thunderstorm season, the lightning hardening procedures were verified by ground tests (ref. 5) in which simulated lightning currents and voltages of greater-than-average intensity were conducted through the airplane with the airplane manned and all systems operating.

Airborne direct-strike lightning instrumentation (DLite) system.- The DLite system (ref. 14) documents the electromagnetic characteristics of direct lightning strikes and nearby lightning flashes at normal airplane flight altitudes. It consists of seven electromagnetic sensors (ref. 16) mounted on the surface of the airplane, a shielded recording system in the weapons bay, and a control panel in the aft cockpit.

Although seven sensors were installed, only three sensors were chosen to record data for 1980. The time rate of change of electric flux density $\dot{D}$ was detected by the flat-plate dipole antenna, or $\dot{D}$ sensor, mounted beneath the nose of the airplane. The time rate of change of the total attachment current to the nose boom

$\dot{I}$ was detected by an inductive-current probe, or $\dot{I}$ sensor, installed inside the fiberglass radome attached to the metal nose boom. Finally, the time rate of change of magnetic flux density $\dot{B}$ from longitudinal (nose to tail) strikes was detected by a multigap loop antenna, or $\dot{B}$ sensor, located on the right side of the fuselage. The locations of these three sensors are shown in figure 1.

The recording system consists of 2 digital, expanded-memory, wide-band, transient-waveform recorders (ref. 15) coupled to a 14-track analog tape recorder, and 1 wide-band (6-MHz), 2-channel, analog tape recorder. The outputs of the $\dot{D}$ sensor and $\dot{B}$ sensor were recorded by the digital transient-waveform recorders, which have augmented memory capacity for 10-nsec time resolution during the specific times of interest. The output of the $\dot{I}$ sensor was recorded by the wide-band analog tape recorder. These three sensors transmitted their data to the shielded recorders via shielded cables. Inter-Range-Instrumentation Group (IRIG) B time (an international standard for coding time) was transmitted to the recorders by fiber optics from a battery-operated time-code generator in the Aircraft Instrumentation System (AIS). Commands from the control panel were transmitted via fiber optics.

Other airborne data systems.- The outputs of the AIS and the weapons-bay-mounted Inertial Navigation System (INS) were used to determine the flight conditions associated with the lightning events. The AIS measured the following parameters: static pressure, dynamic pressure, angles of attack and sideslip, total air temperature, the three angular rates, the three linear accelerations, rudder pedal positions, and stick positions. Interphone conversations and VHF radio transmissions were recorded on a separate track. The separate AIS 14-track analog tape recorder also recorded the outputs of the INS, which included latitude, longitude, pitch and bank angles, true heading, vertical acceleration, and the inertial components of airplane ground speed. The IRIG B time was provided by the same battery-operated time-code generator which provided time to the DLite system. The descriptions of the lightning flashes by the crew and contacts with the mission controllers were recorded on an aft-cockpit voice recorder which ran continually throughout the flight.

The airplane was also equipped with a commercially available digital X-band color weather radar to supplement the radar guidance provided by the National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory (NSSL) or by NASA Wallops Flight Center (WFC). The radar was modified to show a green contour for precipitation reflectivity values of 30 to 40 dBZ, a yellow contour for values of 40 to 50 dBZ, and red contours for values greater than 50 dBz. (Unmodified units present the three colors at values of precipitation reflectivity which are 10 dBZ less.) When ground-based-radar data were not available, the contour levels from this radar, as described on the voice tape, were used to document the precipitation environment.

NSSL ground-based radars.- For the research flights in Oklahoma, the NSSL Norman Doppler radar, described in reference 31, was used to measure the precipitation reflectivity data. Additionally, an incoherent 10-cm-wavelength surveillance radar (ref. 31) was used to provide air traffic control guidance to the airplane.

WFC ground-based radars.- For those flights which occurred in Virginia, three separate radars were used. First, precipitation reflectivity was measured with the WFC Space Range Radar (SPANDAR). Second, an FPS-16 tracking radar at WFC was used to track the C-band transponder mounted on the airplane fuselage in order to provide the SPANDAR crew with real-time information on the location of the airplane. On those occasions when the INS was not used onboard the airplane, the FPS-16 data were used to produce plots of the airplane ground track. Third, the precipitation data from the National Weather Service WSR-57 radar at Patuxent River, Md., were transmitted in real time to a color video display in the SPANDAR control room to assist the SPANDAR crew in providing real-time airplane-penetration guidance. Details of the WFC ground equipment can be found in reference 32. The slow electric-field changes and radio frequency (RF) radiation from lightning activity were measured at WFC by the equipment described in reference 33.

Test Procedures

Flight procedures.- The thunderstorm penetration procedures, given in detail in references 4 to 6, are outlined briefly in this section. Two guidelines adopted from previous thunderstorm programs were that all flights be limited to daylight hours to minimize the threat of flash blindness, and that penetrations not be made through storm areas having precipitation reflectivity contours over 50 dBZ to minimize the chances of encountering hail. Whenever possible, the freezing level was chosen as the altitude for penetration. The pilot set power and airspeed prior to storm entry and maintained a constant pitch attitude during the penetration, accepting the resulting altitude excursions. This procedure was the best technique for flight control and provided a more accurate measurement of turbulence. The desired indicated airspeed for penetration was 300 knots. The flight observer operated all the data systems from the rear cockpit, allowing the pilot to give his undivided attention to flying the airplane. At any time during the mission, the pilot could elect to terminate a penetration by using a predetermined escape vector.

Reduction of precipitation reflectivity radar contours and airplane ground tracks.- The combined plots of radar precipitation reflectivity radar contours and airplane ground tracks were made by superimposing the two independent data sets. For flights in Oklahoma, the precipitation reflectivity data from the NSSL Norman Doppler radar were interpolated to a flat plane from data taken from adjacent sweeps at different tilt (elevation) angles to produce a single plot of reflectivity factor in range-normalized decibels (dBZ) for each thunderstorm penetration of interest. The interpolated altitude approximated the penetration altitude of the airplane, and the reflectivity factor was plotted as constant contours at 10-dBZ increments. Although this scheme introduced some errors because of averaging across time and variations in airplane altitude, these errors are believed to be small because of the relatively short duration of the penetrations. More details on the Doppler radar data reduction procedure can be found in reference 1.

For flights in Virginia, the precipitation reflectivity data from the WFC SPANDAR were plotted at a constant tilt angle of 0°. The data were contoured in 10-dBZ increments using the techniques described in references 1 and 2. Because the data were not interpolated to the airplane altitude, larger differences in radar sample height and airplane penetration altitude exist in the WFC data than in the NSSL data. For flights at either location, the airplane ground track was computed with the equations given in reference 1 by using the latitude and longitude measured by the onboard INS and recorded by the AIS. When INS data were not available for those flights made with WFC support, FPS-16 C-band radar data were substituted to produce computer plots of the airplane ground track. (See refs. 1 and 2.)

Determination of lightning attachment points.- After an airplane has become part of a completed flash channel, the ensuing stroke and continuing currents which flow through the channel may persist for more than 1 sec. Essentially, the channel remains in its original location but the airplane moves forward a significant distance during the life of the flash. The mechanisms of initial entry and exit points of the channel on the airplane are described in reference 11. These points, which occur simultaneously, are typically located at airplane extremities. In the example shown in figure 2, the initial entry point is shown at the tip of the nose boom and the initial exit point at the trailing edge of the left wing tip, which are typical entry and exit points for a delta-wing airplane. Besides the initial entry and exit points, there may be other subsequent attachment points that are caused by the motion of the airplane through the relatively stationary flash channel. For example, when a forward extremity, such as a nose boom, becomes an initial attachment point, its surface moves through the lightning channel, and thus the channel appears to sweep back over the airplane surface, as illustrated in figure 2. This occurrence is known as the swept-stroke phenomenon. The flash channel will continue to sweep back along the airplane surface until the flash dies or the airplane flies out of the flash channel. In the example shown in figure 2, the final entry point is located on the speed brake. The exit portion of the flash continues to trail back from the left wing tip throughout the flash. More details on the swept-stroke phenomenon may be found in reference 11.

Following each flight in which there were direct lightning strikes, the lightning attachment points were located by careful inspection of the airplane surface. The procedure was as follows:

1. Inspect each airplane extremity for evidence of lightning attachment. The evidence was usually manifested by spots of molten and resolidified metal ranging in diameter from 0.01 to 1.00 cm (0.004 to 0.400 in.),[1] usually surrounded by a region of discolored paint.

2. Closely inspect all surfaces that lie aft of the nose boom for additional lightning attachment points that indicate the swept-flash path(s) taken following initial attachments to the nose boom. This often required the use of a 4× magnifying glass because the diameters of some of the swept-flash attachment points were very small and the points were hard to distinguish from other blemishes on the airplane surface.

3. Record the location of each attachment point and plot the points on isometric drawings of the airplane.

4. Calculate the dwell time t that elapsed between attachment points, assuming the airplane was travelling at a constant velocity V of 182.9 m/sec (600 ft/sec), with the expression $t = d/V$, where d is the distance between successive attachment points.

5. Review and correlate findings with the pilot's and observer's observations. This step was particularly important in separating the attachment points produced by each strike after a flight in which more than one strike was received.

6. Postulate, based on the attachment points and flight crew observations, the probable direction from which the strike initially approached the airplane, the initial and final attachment points, the swept-flash path(s), and the point(s) and direction(s) from which the flash exited the airplane.

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[1]Dimensional quantities are presented in both the International System of Units (SI) and U.S. Customary Units. Measurements and calculations were made in U.S. Customary Units.

DESCRIPTIONS OF DIRECT LIGHTNING STRIKES AND NEARBY FLASHES

Overview

The 1980 lightning transient data summary is given in table III. The summary shows that 22 lightning transients were measured during the 16 lightning events which occurred. The flight conditions for each lightning event are summarized in table IV. The data in table IV are cross-referenced to the figures in reference 3, in which the corresponding lightning waveforms are plotted. Preliminary approximations of the lightning attachment paths are also given in reference 3, and estimates of the ambient temperatures and altitudes at which the lightning events occurred are given in reference 18.

Descriptions of Lightning Strikes

Strike 1, flight 80-018, June 17, 1980.- The synoptic weather situation for June 17, 1980, on which two research flights were made, is given in reference 31. On the first flight a direct lightning strike to the nose boom occurred. The pilot estimated the visibility as about 152 m (500 ft) with heavy rain and moderate turbulence. The estimated diameter of the lightning channel was 15 to 20 cm (6 to 8 in.). The pilot saw the flash strike the nose boom and spiral down the left side of the airplane. A "zap, crackle" was heard during the event, but there was no radio noise to warn of the impending strike.

Following the strike, the pilot terminated the mission and returned directly to base. The postflight inspection revealed the lightning attachment points shown in figure 3. The initial entry point was the angle-of-attack vane on the left side of the nose boom. The metal spindle to which the balsa wood vane was glued was pitted and a small smoke streak was left on the vane. (See fig. 4(a).) The stroke then reattached at the top of the nose boom at the radome junction, then at a rivet on the left side of the fiberglass radome (fig. 4(b)), at several places along the left side of the fuselage including the trailing edges of two fuselage-mounted probes, and at several points on the top of the left wing near the root. One of these points (fig. 4(c)) was in the middle of a wing panel and not at a panel edge or on a fastener. The location of this point, which was the deepest lightning penetration found in 1980, is shown in figure 3. Exit points were found on the trailing edge of the left wing tip (figs. 4(d) and 4(e)) and the trailing tip of the vertical-fin cap (fig. 4(f)).

Based on the attachment point locations and the pilot comments, the strike scenario shown schematically in figure 5 was developed. It is believed that the strike entered from above and to the left of the airplane and exited to the right and downward.

The relative location of the airplane in the thunderstorm at the time of the direct strike is shown in figure 6, in which the airplane ground track has been superimposed on a contour map of precipitation reflectivity factor measured by the NSSL Doppler radar at Norman, Okla. The reflectivity data have been interpolated to a constant altitude of 4.5 km (14 800 ft), whereas the airplane altitude at the time of the strike was 5 km (16 400 ft). The time of the strike and the accompanying $\dot{D}$ measurement are indicated by a lightning symbol and circle on the ground track. As can be seen, the airplane was in an area indicating 20 dBZ of reflectivity.

Strikes 2 and 3, flight 80-019, June 17, 1980.- Two direct lightning strikes occurred during the second flight on June 17, 1980. During a turn 180° to the right to begin a penetration, a direct strike to the nose boom occurred. The pilot reported that the strike hit the nose boom and the streamer swept down both sides of the airplane. Because the lightning produced no adverse effects, the flight continued. The direct-strike-lightning instrumentation system did not respond to this strike. On a subsequent penetration, a second direct lightning strike occurred. The pilot reported a direct strike to the nose boom which "ducked under" the nose of the aircraft. The $\dot{D}$ sensor recorded a transient simultaneous with the pilot's call on the radio.

The lightning attachment point locations are shown in figure 7. Based on the pilot comments, the attachment points plotted in figure 8 were ascribed to strike 2. The small "x" symbols in figures 7 and 8 denote attachment points on the underside of the wing, and the small, solid symbols denote points on the near side of the airplane. Some of the cosmetic damage is shown in the photographs of figure 9. The spindle of the sideslip vane, which was mounted in the vertical plane beneath the nose boom, was pitted (fig. 9(a)). The burn marks on the trailing edge of the left elevon and the left wing tip are shown in figures 9(b) and 9(c). The lightning strike scenario for strike 2 is given in figure 10. For this strike, the initial entry and exit points are presumed to have occurred on the nose boom. Although the sideslip vane may have actually been involved in strike 3 rather than in strike 2, the initial entry and exit points for strike 2 probably still occurred somewhere on the nose boom because of the geometry of the points. In this strike, as the airplane moved forward, the entry point swept down the right side of the fuselage and beneath the right wing across the midspan area (fig. 8). The exit point, on the other hand, swept back to the left wing, where the flash branched. One branch swept down the leading edge to the wing tip and the other branch swept across the top of the wing in the midspan area. The general orientation of the channel (fig. 10) gave an entry from below and to the right of the airplane, with an exit off the extremities upwards to the left. The exit points were presumed to be on the left wing because more severe damage was found on the left elevon and the left wing tip than was found on the trailing edge of the right elevon. These factors, in conjunction with pilot comments for strikes 2 and 3, make this and the following scenario for strike 3 the most probable scenarios for resolving the two sets of attachment point data given in figure 7. Precipitation reflectivity contours from ground-based radars were not available for this penetration; however, the airborne radar showed precipitation reflectivity values less than 45 dBZ.

Those points believed to have been caused by strike 3 are shown in figure 11. These points included those found on the under-nose pitot-static head and on the VHF radio antenna on the bottom of the fuselage beneath the cockpit. The resulting lightning scenario is shown in figure 12. The initial entry and exit points occurred on the nose boom, with the entry point sweeping back along the fuselage just below the right canopy rail and the exit point sweeping underneath the fuselage to the two probes under the nose. The channel was oriented from upper right to lower left.

Photographs of the attachment points at the junction between the metal nose boom and the fiberglass radome and at the VHF radio antenna are presented in figures 13(a) and 13(b). The radome damage consisted of a vaporized area about 2.0 cm (0.8 in.) in diameter just aft of the nose-boom fitting. No puncture occurred, however. The VHF radio antenna (fig. 13(b)) had a burn mark on the leading edge and a burn on the side of the antenna 4.1 cm (1.6 in.) aft of the leading edge. The thermal discoloration on the black paint is visible. (The extensive erosion of the black paint along the leading edge was caused by rain.)

The airplane ground track and the precipitation reflectivity contours for the second penetration of flight 80-019 are shown in figure 14. For this penetration, the reflectivity data have been interpolated to a constant altitude of 4.5 km (14 800 ft). (Airplane altitude at the time of the strike was 4.8 km (15 900 ft).) At the time of the strike, denoted by the lightning symbol and circle, the airplane was on the edge of a 20-dBZ contour. During the penetration, the airplane flew within about 4 to 13 km (2 to 7 n.mi.) of two 40-dBZ contours.

Nearby flashes 1 to 4, flight 80-023, July 22, 1980.- On the second penetration of this flight, three lightning transients were recorded onboard the airplane, although no direct lightning strikes occurred. The airplane ground track during the second penetration is shown in figure 15 superimposed on the precipitation reflectivity contours measured by the WFC SPANDAR. The reflectivity values approximate those at the nominal penetration altitude of 4.6 km (15 000 ft) because the SPANDAR was at a tilt angle of 0°. Accounting for curvature of the Earth, the reflectivity data were sampled at a height of 305 m (1000 ft) in the middle of the storm shown in figure 15. The three nearby flashes are indicated by the symbols on the ground track in figure 15. On the first flash, the $\dot{B}$ sensor recorded a waveform, whereas the $\dot{D}$ sensor recorded a waveform on each of the next two flashes. At cloud entry (20:34:08 Greenwich mean time (GMT)), the pilot reported "downdraft, heavy rain." At 20:34:33 GMT the pilot reported "audible and visible lightning, turbulence, rain, good turbulence, good rain, 2500 ft/min updraft." At 20:34:55 GMT, "lots of rain, flashes all around" was reported. At the end of the penetration, the pilot summarized the run as "no direct strikes, but heavy rain." According to the approximate reflectivity values given in figure 15, the first two nearby flashes occurred in the core of the storm in 30 to 40 dBZ of reflectivity, and the third nearby flash occurred on the fringes of the storm in less than 10 dBZ of reflectivity.

At the beginning of the seventh penetration on flight 80-023, the fourth nearby flash was recorded by the $\dot{D}$ sensor. The airplane ground track and WFC SPANDAR reflectivity contours for this penetration are shown in figure 16. The waveform was recorded coincident with the pilot report "just going into cloud, starting to rain." No mention was made of lightning, however. According to the data in figure 16, the airplane was in less than 10 dBZ of reflectivity at the time of the flash.

This storm was within range of the slow-electric-field-change system operated by NASA Goddard Space Flight Center at WFC, and records of slow electric-field changes and RF radiation were obtained for this storm. These data are presented in reference 33, where the identifiable lightning events in 1-minute intervals were counted. The number of events was plotted as a function of time and was used to determine a flashing rate for this storm. Nearby flashes 1 to 3 occurred during a peak in the activity, and nearby flash 4 occurred after the peak, probably during the decaying phase of this particular cell. The waveforms of the slow electric-field data measured at the ground were suggestive of intracloud lightning at the times of nearby flashes 1, 2, and 4, and of cloud-to-ground lightning at the time of nearby flash 3. In addition, at 20:34:33 GMT (when the pilot reported "audible and visible lightning"), a field change suggestive of an intracloud discharge was recorded. It should be noted that nearby flash 1 showed relatively poor correlation with an electric-field change measured on the ground, as described in reference 33. A thorough postflight inspection of the airplane did not reveal any evidence of a direct lightning strike during this flight.

Strike 4 and nearby flash 5, flight 80-029, August 12, 1980.- The storm of interest on August 12, 1980, was imbedded within a widespread area of precipitation over the Atlantic Ocean east of Virginia Beach, Va. The storm was too far from the

WFC SPANDAR to record the reflectivity data, and the AIS and the INS had been removed for repair; however, the DLite system was operational, and altitude was taken from the pilot's notes. While reversing course at an estimated altitude of 5.2 km (17 000 ft), a visually spectacular strike occurred. The flight observer described the strike as follows: "... a flash of lightning appeared overhead, moving from right to left. The channel seemed to dip down in the middle towards the aircraft. As the aircraft moved forward, the channel seemed to break up in slow motion, leaving chunks of wispy yellow plasma suspended in the air, drifting by the cockpit. Prior to breakup, the channel was yellow and appeared to be a tight helix. At first, we weren't sure the channel had actually struck the airplane. Although we had just come through an area of turbulence, rain, and visible lightning, the ride was quite smooth, with only light rain at the time of the strike." The lightning attachment point locations are shown in figure 17, and the corresponding lightning scenario is shown in figure 18. No lightning exit point could be found for strike 4. Although no attachment points were found on the nose boom, it is believed that the initial entry point could have been on the nose boom because of the low probability of an initial entry occurring on the canopy overhead rail, where there are no protuberances. The main lightning channel overhead was very bright and could have shielded a smaller leader to the nose. Referring to table IV, one can see that this was the second direct lightning strike in which no lightning waveforms were measured.

During the second penetration, the $\dot{D}$ sensor recorded a waveform (nearby flash 5) at an estimated altitude of 5.8 km (19 000 ft). At 21:07:00 GMT, the pilot had called "good lightning - real close." At 21:09:00 GMT, the pilot said "lots of lightning, more turbulence, 3000 ft/min downdraft."

Nearby flash 6, flight 80-030, August 15, 1980.- The storm of interest on August 15, 1980, was located over eastern North Carolina approximately 50 km (27 n.mi.) west and 100 km (54 n.mi.) south of WFC. The extreme distance from WFC necessitated a nominal penetration altitude of 6.4 km (21 000 ft) to provide line-of-sight communications to project control at LaRC and to the SPANDAR crew. The SPANDAR provided some real-time guidance to the flight crew, but the pilot relied mostly on the onboard weather radar and visual cloud references. As was the case with flight 80-029, the storm was too distant for recording reflectivity data by the SPANDAR and the INS was not used; therefore, pitch and bank angles were not recorded. (See table IV.)

During the fourth penetration at an altitude of 6.4 km (21 000 ft), the $\dot{B}$ sensor recorded a transient. Thirty seconds prior to the flash, the pilot had reported a "little glow" in the clouds. Right after the nearby flash, he reported heavy rain and moderate turbulence. Significantly, the pilot also said "still no significant lightning to speak of" in describing the flight up to that time. Although areas of reflectivity in excess of 50 dBZ were identified in the storm by the SPANDAR and by the onboard radar, the airplane was never in an area exceeding 50 dBZ.

Strike 5, flight 80-036, September 1, 1980.- On September 1, 1980, the airplane flew into a "perfect, isolated storm" approximately 160 km (86 n.mi.) west and 230 km (124 n.mi.) south of WFC. A nominal penetration altitude of 6.4 km (21 000 ft) was again chosen for communications purposes. The WFC SPANDAR was not able to provide postflight contour data because of the extreme range. A direct strike to the nose of the airplane occurred which simultaneously triggered the $\dot{D}$ and $\dot{B}$ sensors. This was the first lightning event in which two sensors had recorded simultaneous data during the Storm Hazards '80 Program. The pilot stated that he "was looking right at the nose - a small one [strike]." A series of soft crackles can be heard on the voice tape at the time of the strike. The penetration only lasted 41 sec from cloud entry to cloud exit, with the strike occurring 2 sec after cloud entry. Immediately prior to cloud exit, the pilot reported "lots of turbulence, not much precipitation." All that could be determined from the airborne weather radar was that the airplane was in precipitation reflectivities less than 50 dBZ throughout the penetration, although the actual reflectivity values must have been much less.

The lightning strike attachment points and the lightning strike scenario for strike 5 are given in figures 19 and 20. No exit point could be identified for this strike. Although no entry point could be found on the nose boom, the initial entry point probably occurred here because of the geometry of the points and the pilot's comments. As the airplane moved forward, the entry point jumped back to the leading edge of the left wing and to the underside of the wing across the midspan area. The entry channel hung onto the trailing edge of the left elevon until the flash was over. The geometry of the points indicates the flash struck the airplane from below and to the left. This was the second strike occurring during 1980 in which the flash swept back across the midspan of the wing with no upstream attracting point. The flash would normally be expected to sweep back along the wing leading edge to the wing tip. (See ref. 34.)

Strikes 6 to 10, flight 80-038, September 3, 1980.- Five of the ten direct lightning strikes to the airplane in 1980 occurred during a single thunderstorm penetration through two adjacent cells on September 3, 1980. The storm was approximately 170 km (92 n.mi.) west and 180 km (97 n.mi.) south of WFC over North Carolina. Because of the distance from the storm, the WFC ground-based radars could not be used; therefore, penetration guidance was provided by the airborne weather radar. To maintain voice communications with LaRC, an altitude of 10.1 km (33 000 ft) was necessary. The airborne weather radar indicated two levels of reflectivity (30 to 40 and 40 to 50 dBZ) along the airplane flight path.

Before the precipitation started, the first direct strike (strike 6) occurred, with both the $\dot{B}$ and $\dot{I}$ sensors recording waveforms. Two seconds later (20:27:55.4 GMT) the $\dot{D}$ and $\dot{I}$ sensors recorded waveforms. The pilot counted this second set of waveforms (strike 7) as part of the first strike. At 20:28:04 GMT the pilot said "maybe hit again," and the $\dot{B}$ and $\dot{I}$ sensors were triggered at this time (strike 8). His next comment was "a lot of lightning and a lot of turbulence, lot of precipitation, here comes heavy rain." By 20:29:20 GMT the ride had smoothed out and the airplane was between the two cells, although still in the clouds. The airborne radar showed a distance between cells of 18.5 km (10 n.mi.). The turbulence and rain were both light. Just prior to penetrating the second cell, the fourth strike of the penetration (strike 9) occurred, with the $\dot{D}$, $\dot{B}$, and $\dot{I}$ sensors all responding. Immediately afterward, the airplane flew into heavy rain and "lots of turbulence." In the middle of this cell, the fifth strike of the penetration (strike 10) occurred with the same three quantities measured as in strike 9. The pilot then elected to terminate the penetration, turning north to exit the storm. The airborne radar showed two levels of reflectivity (30 to 40 and 40 to 50 dBZ) during the penetration.

The lightning attachment points for strikes 6 to 10 are shown in figure 21. The pilot comments were too sparse to assign the points to a particular strike. The flight observer thought all the strikes occurred at the nose, favoring the left side. The pilot, on the other hand, did not believe the strikes favored either side. Note that there is a string of points beneath the right wing near the wing-fuselage juncture. Unlike the attachment points from strikes 2 and 5 on flights 80-019 and 80-036, attachment points in this area of the wing are not unexpected because of their proximity to the airplane centerline. (See ref. 34.)

DISCUSSION OF RESULTS

Altitude and Temperature

The penetrations, strikes, and nearby flashes are plotted as a function of altitude in 0.3-km (1000-ft) altitude bands in figure 22. The penetrations generally are divided into two groups centered at approximately 4.6 and 6.4 km (15 000 and 21 000 ft), with a single penetration at about 10.1 km (33 000 ft). The penetrations centered around 4.6 km reflect the procedure of conducting thunderstorm operations at or near the freezing level, where lightning strikes to operational aircraft are expected to be prevalent. (See ref. 11.) Most of the penetrations centered at about 6.4 and 10.1 km were made during those flights in which higher altitudes were required for communications purposes. Five direct lightning strikes, representing one-half of the 1980 lightning strikes, occurred during the single penetration between 9.9 and 10.2 km (32 500 and 33 500 ft). With so little data, this penetration naturally resulted in the highest strike rate of 5 strikes per penetration. The next highest value was 0.32 strike per penetration in the altitude band from 4.7 to 5.0 km (15 500 to 16 500 ft).

A total of 233.03 minutes was spent inside the clouds (cloud entry to cloud exit) during the Storm Hazards '80 Program. The distribution of penetration time with altitude is shown in figure 22. As would be expected, the distribution of time with altitude is very similar to the altitude distribution of the penetrations. The single high-altitude penetration lasted 4.27 minutes. When the ratios of strikes per minute are computed, the strike rates range from a high of 1.2 strikes per minute for the high-altitude penetration to about 0.1 strike per minute for the other three altitude bands in which strikes occurred.

The distribution of lightning events with ambient temperature is plotted in figure 23. Six of the ten direct lightning strikes occurred at temperatures colder than -20°C, whereas published aircraft lightning strike statistics (ref. 11) indicate that most reported lightning strikes to aircraft have occurred at or near the freezing level. Only two direct lightning strikes and five nearby flashes occurred at temperatures between 0°C and -10°C. The lightning strike trend shown by these data is in general agreement, however, with the results of references 35 and 36, in which the maximum lightning activity in thunderstorms was found to occur near 9.1 km (30 000 ft) at about -40°C. The differences between statistics such as those in reference 11 and the data in references 35 and 36 were related to three features of normal operations of commercial aircraft: avoidance of obvious thunderstorm areas; the duration of lower altitude holding patterns in bad terminal weather; and frequency of instrument flight rules (IFR) altitude assignments. Therefore, the lightning event distribution with temperature found in the Storm Hazards Program may be the result of the higher percentage of flight time spent by the research airplane at altitudes above the freezing level compared with the low percentage of time spent at these altitudes by commercial aircraft during weather penetrations in routine operations. These findings indicate that future Storm Hazards Program missions should concentrate on thunderstorm penetrations at higher altitudes and colder temperatures to maximize the airplane lightning strike rate.

Turbulence and Precipitation

In general, the lightning events occurred in areas of the thunderstorms in which the pilots characterized the turbulence as light to moderate and the rainfall as moderate. However, some of the lightning events took place with no turbulence and no precipitation, and still others took place in heavy rain and heavy turbulence. All the lightning events occurred inside the cloud boundaries, although one direct lightning strike (strike 5) occurred only 2 sec after cloud entry. These data indicate a poor correlation of lightning strikes with turbulence and precipitation. The results of the Storm Hazards '80 Program support the following conclusions made in the Storm Hazards '78 Program (ref. 1): the presence and location of lightning do not necessarily indicate the presence and location of hazardous precipitation and turbulence.

Strike Patterns

In addition to the lightning studies using the NASA F-106B airplane, lightning attachment points were also located on three U.S. Air Force F-106A airplanes that were struck during missions, as described in the appendix. The lightning-attachment-point patterns on the three U.S. Air Force airplanes were similar to those found on the NASA airplane. This study provides further insights into the way in which an airplane interacts with a lightning strike channel, especially the manner in which flashes sweep aft from initial lightning attachment points. These data confirm that initial entry and exit points frequently occur at airplane extremities, in this case the nose boom, the wing tips, and the vertical-fin cap. However, only 3 of 10 strikes actually had confirmed initial entries at the nose boom. Swept-flash attachment points were observed along the full length of the fuselage, as is common in other airplanes of this general size, following initial strikes at the nose. Unexpectedly, 20 percent of the flashes swept aft across the midspan surfaces of the delta wing (strikes 2 and 5, figs. 8 and 19). Swept-stroke attachments across unswept wings on airplanes without upstream attachment points such as engine nacelles or drop tanks are extremely rare (see ref. 34), and only a few midspan strikes to other delta-wing airplanes have been reported.

Lightning Dwell Times

Dwell times were computed for the individual swept-flash attachment points for strikes 1 to 5, which were the strikes for which the lightning attachment points could be individually identified. A typical set of dwell-time computations is shown in table V, in which the dwell times for each of the points for strike 1, flight 80-018, are given. The corresponding lightning attachment points, plotted in figure 3, are numbered in table V in sequence from the tip of the nose boom aft along the airplane. For the five strikes analyzed, dwell times at individual adjacent swept-flash attachment points ranged from 1 to 6 msec on painted metal surfaces. Higher dwell times occurred, however, where the swept flashes jumped across the fiberglass radome or jumped from the fuselage to a wing. This effect can be seen at points 2 and 13 in table V (12.6 and 10.3 msec, respectively). Points 2 and 3 bracket the radome, and points 13 and 14 bracket the jump of the flash across the engine inlet from the fuselage to the left wing.

The maximum depth of penetration into a painted aluminum skin was approximately 0.06 cm (0.025 in.) in a skin 0.15 cm (0.059 in.) thick. A photograph of this point is given in figure 4(c), and the location of the point is shown in figure 3. The penetration depths on unpainted surfaces should be less than on painted surfaces for the reasons given in reference 11. The dwell-time data presented in reference 11 show that bare metallic external finishes have the lowest dwell times, since most paints and other coatings act to concentrate the attachment at more widely separated points for correspondingly longer times than does a bare surface. Although the point shown in figure 4(c) occurred in the middle of a smooth wing panel, most of the swept-flash attachments occurred either at the edges of flush rivets or fasteners (even when these were coated with paint and invisible to the eye) or at external antennas and probes.

The swept-flash attachment paths and burn marks found in this program indicate that the midspan areas of swept-wing airplanes may be more susceptible to lightning attachment than is currently believed. If so, greater attention to lightning protection may be required for the internal structure and the external wing surfaces of integral wing fuel tanks in swept-wing airplanes now being designed, especially when composite materials and adhesive bonding will be used.

Because of the absence of well-defined evidence of return-stroke flash attachments on the airplane for the 10 strikes, it was not possible to determine the distance swept by the lightning leader prior to return-stroke arrival at the airplane. However, in strike 2 (fig. 8), the appearance of a localized "splatter" of attachment points at the right-wing leading edge suggests a possible return-stroke attachment, or current peak, at this location. The physical marks left by all the strikes indicate they were of low intensity, insufficient to produce noticeable damage to the surfaces of a metal aircraft.

Lightning Protection

There were no adverse effects to the airplane or the flight crew from any of the direct lightning strikes or nearby flashes. There were no discernible lightning transients induced in any electrical system, there were no blown circuit breakers or fuses in the airplane, and there were no data dropouts on any of the instrumentation systems. The Storm Hazards '80 lightning strike experiences, along with those described in the appendix and reference 8, indicate that aircraft with metallic structures and with avionics of current design can be protected from the direct or indirect effects of lightning by careful attention to proper design and bonding of all metal structural components and by suitable isolation, routing, and physical restraint of the electrical systems.

SUMMARY OF RESULTS

As part of the NASA Langley Research Center Storm Hazards Program, 69 thunderstorm penetrations were made in 1980 with an F-106B airplane in order to record direct lightning strike data and the associated flight conditions. This study produced the following results:

1. Six of the ten direct lightning strikes occurred at temperatures colder than -20°C, whereas published aircraft lightning strike statistics indicate most reported strikes have occurred at or near the freezing level (0°C).

2. The data indicate a poor correlation of lightning strikes with turbulence and precipitation. The 1980 results support the conclusions made from the 1978 results,

that the presence and location of lightning do not necessarily indicate the presence and location of hazardous precipitation and turbulence.

3. The data confirm that initial entry and exit points of strikes frequently occur at airplane extremities, in this case the nose boom, the wing tips, and the vertical-fin cap. However, only 3 of 10 strikes actually had confirmed initial entries at the nose boom. Swept-flash attachment points were observed along the full length of the fuselage, as is common in other airplanes of this general size, following initial strikes to the nose. Unexpectedly, 20 percent of the flashes swept aft across the midspan surface of the delta wing.

4. The maximum depth of penetration of any lightning attachment point into a painted aluminum skin was approximately 0.06 cm (0.025 in.) into a skin thickness of 0.15 cm (0.059 in.). Although the point of deepest penetration occurred in the middle of a smooth wing panel, most of the swept-flash attachment points occurred either at the edges of flush rivets or fasteners (even when these were coated with paint and invisible to the eye) or at external antennas and probes.

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October 20, 1982

APPENDIX

LIGHTNING STRIKE REPORTS FOR THREE F-106A AIRPLANES IN ROUTINE OPERATIONS

Background

During the NASA Langley Research Center Storm Hazards '80 Program, NASA researchers were provided the opportunity to inspect three U.S. Air Force F-106A airplanes following direct lightning strikes which occurred during routine operations. The NASA researchers also interviewed the pilots, whose comments are the basis of the descriptions which follow. Study of these incidents expands the Storm Hazards Program data base.

Pair of Lightning Strikes to Two F-106A Airplanes Flying in Formation

Two F-106A airplanes were flying in close formation with about 1.2 to 1.8 m (4 to 6 ft) between wing tips as shown in figure 24. The two were located about 185 to 204 km (100 to 110 n.mi.) east of the Capes of Virginia. The two airplanes were at an altitude of 7.6 km (25 000 ft) at an indicated airspeed of 400 knots (Mach 0.88) in light cirrus clouds with no turbulence and no precipitation. A lightning flash came straight at the formation from head-on at the same altitude as the airplanes. The wingman saw the channel divide and simultaneously strike the nose booms of both airplanes. This portion of the channel was yellowish-white in color. The wingman could also see a blue-green haze extending down the left side of the nose of the lead airplane and down the leading edge of that airplane's left wing towards its wing tip during the strike. Peripherally, the wingman could see numerous streamers extending towards his right wing tip. The wingman could not see if the streamers were actually attached to his airplane, however. At the time of the strike, the wingman received a small electrical shock to both hands, which were gloved. His left hand was on the throttle and his right hand was on the right horn of the control stick. Both of his feet were on the rudder pedals. The wingman estimated that the shock was like one receives from an electrostatic discharge for shuffling one's feet across a carpet. The wingman stated that the light intensity of the entire lightning channel fluctuated during the event.

The lead pilot compared the flash to flying through a wispy yellow-white ribbon which extended from 30° left to 40° right of centerline and 5° above the horizon. The lead pilot did not experience an electrical shock.

Following the strike, the two airplanes separated to approximately two wing spans between wing tips, as shown in figure 25, and climbed to an altitude of 7.9 km (26 000 ft). Once again the two airplanes were struck by lightning. The pilot descriptions of this second strike were similar to those of the first, including the electrical shock to the wingman's two gloved hands. Neither pilot experienced flash blindness, nor did they hear any audible reports or electrical radio static. Neither airplane experienced any disturbances to the electrical systems. Following the second strike, the two airplanes climbed out of the cirrus clouds and returned to base without further incident. During the postflight inspections, the lightning suppressor kit (see ref. 8) in each airplane was tested and found to be within specifications.

The lightning attachment points found on the two airplanes following the pair of strikes are shown in figure 26. The following lightning damage was found on the lead airplane: burn marks on the pitot head and along the nose boom; weld-like marks at the fore and aft seams of the glycol ring on the nose boom; evaporated material from the fiberglass radome just aft of the metal nose-boom adapter; considerable erosion on left wing tip; and burns at the top and bottom of the vertical-fin cap at the trailing edge. On the wing airplane, the lightning attachment points were at the following locations: along the nose boom; several at the boom-radome juncture; two points on the right side of the radome several centimeters (inches) aft of the metal boom adapter; one on the right side of the radome high and ahead of the mounting ring; one on the load ring seam; both latches on the right-side nose door and two in between the latches; one on the seam under the windshield; one in the middle of the star in the emblem; numerous along the top of the fuselage; numerous along the leading edge of the vertical fin; several along the left side of the vertical fin; one large burn on the trailing edge of the rudder; one on the top of the right wing near the fuselage juncture; two on the bottom of the end of the right pylon tank and two on the back of the tank; and two on the left wing tip and three on the right wing tip.

The lightning attachment points and the scenario developed for the first lightning strike (with the two airplanes in close formation, fig. 24) are shown in figure 27. The lightning channel is shown divided into two branches, with the initial entry point of each branch at the nose-boom pitot head on the airplanes. The initial entry point for branch 1 then jumped back to the left wing tip of the lead airplane, and then across the gap between the wing tips of the two airplanes to the right wing tip and right external fuel tank on the wing airplane. A probable reattachment point was the leading edge of the external tank, but no attachment points were found there in the postflight inspection. Branch 1 exited from the vertical fin of the lead airplane. The entry point for branch 2 jumped back from the nose boom to the right wing near the fuselage on the wing airplane. Branch 2 exited from the left wing tip of the wing airplane.

The lightning attachment points and the corresponding strike scenario conjectured for the second strike are shown in figure 28. As was the case for the first strike, the lightning channel divided into two branches, with initial attachments to each airplane on the nose booms. The entry point for branch 1 then swept back along the nose boom to the radome of the lead airplane, where the flash ended. The exit point for branch 1 was on the vertical fin of the lead airplane. The entry point of branch 2 swept back along the entire length of the airplane, with the final entry point streaming off the rudder. The initial exit point for branch 2 occurred on the left wing tip of the wing airplane. Unlike the first strike, the lightning channel is not shown jumping across the gap between the wing tips of the two airplanes, as it is believed that the distance between the two airplanes was too large for such an arc to have taken place during the second strike.

Multiple Strikes to a Single F-106A Airplane

During a cross-country flight, a single F-106A penetrated a line of thunderstorms at an altitude of 13.7 km (45 000 ft) en route to Tinker Air Force Base, Okla. For several minutes the pilot flew through heavy precipitation and turbulence. The precipitation caused considerable airframe noise, and the turbulence produced airplane normal acceleration response from -1.2g to 3.7g. Suddenly, the precipitation and turbulence rapidly decreased to zero, and the airplane flew into a cavern-like area with visibility of 1.9 km (1 n.mi.). At this time, a lightning bolt hit the nose boom from head-on. The pilot felt a tingle in his right hand which he described as being no more than a buzz. The pilot's hands were gloved; his right hand was on the stick, his left hand was on the throttle, and both feet were on the pedals.

Shortly afterwards, the pilot saw a double (forked) channel 305 m (1000 ft) ahead of the airplane passing from right to left. The airplane flew through both forks in succession. The pilot could not tell if the two forks were oriented above or behind one another. Following a nearby flash to the left of the airplane, the pilot climbed to 14.3 km (47 000 ft) and broke out of the weather.

Following each of the strikes, the pilot noticed fluctuations in airspeed and Mach number which seemed excessive even for the weather situation. In about 1 minute, the fluctuations would clear up. No electrical disturbances were noted, although a crackle in the VHF communications was noted at the time of each strike. During the postflight inspection, the lightning suppressor kit was inspected and found to be within specifications. (See ref. 8.)

The lightning attachment points found on the airplane are shown in figure 29. The geometry of the points indicates the airplane was struck twice during the flight, with the points ascribed to each strike shown in figures 30 and 31.

The lightning attachment points in figure 30 are believed to have been caused by the first (head-on) strike described by the pilot. The lightning scenario developed for this strike is shown in figure 32. The initial entry point was the nose boom, with the flash entry sweeping back along the left side of the nose boom, jumping back to the radome-fuselage juncture and then to the angle-of-attack sensor, and finally jumping to the leading edge of the inlet lip. The initial exit point was the right wing tip. The flash channel entered from above and to the left of the airplane flight path and exited downward and to the right.

The second strike, figures 31 and 33, was produced by one of the branches of the forked lightning flash. Initial entry is presumed to have occurred on the nose boom, with the entry point jumping back to the nose-boom/radome juncture, then back to the inlet, and finally back to the right wing tip, hanging on there until the flash ended. The initial exit point was the left wing tip. This point geometry implies that the flash entered from above and from the right of the flight path and exited downward and to the left. This orientation is in agreement with the pilot's description of the flash orientation of the forked flash.

CONCLUDING COMMENTS

The only significant difference between the effects of the direct lightning strikes to the Storm Hazards Program F-106B and the three operational airplanes discussed in this appendix are the reported minor electrical shocks to two of the U.S. Air Force pilots. It should be noted that neither the lead pilot in the formation of two F-106A airplanes nor the two pilots involved in the severe lightning strikes reported in reference 8 reported crew shocks. In response to the crew shock reports, the lightning safety consultant for the Storm Hazards Program, Mr. J. Anderson Plumer of Lightning Technologies, Inc., inspected the different designs of the F-106A canopy and the F-106B canopy. He found that the F-106A canopy is heated and defogged by blown hot air. The F-106B canopy, on the other hand, has gold mesh wiring imbedded in and around the glass for these purposes. In addition, the F-106B canopy has a center overhead rail running the length of the canopy (see fig. 1), whereas all

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F-106A canopies have been upgraded to a new design in which a single sheet of stretched acrylic is used and the overhead rail has been deleted. Mr. Plumer believes that because of the two differences outlined above, the F-106A canopy provides a larger aperture for lightning coupling into the cockpit, and hence a higher probability of receiving a minor electric shock from lightning in an F-106A than in an F-106B.

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TABLE I.- SUMMARY OF NINE AIRBORNE EXPERIMENTS IN 1980

Experiment	Data system	Organization	References
Direct-strike lightning measurements	DLite system	NASA	3, 14 to 20
Direct-strike lightning measurements	Data Logger	Boeing Commercial Airplane Co.	21
Effect of lightning on composite materials	Fiberglass vertical-fin cap flame sprayed with aluminum	NASA	5
Measurement of lightning optical waveforms	Lightning optical signature sensor	NOAA-NSSL	None
Measurement of lightning X-ray emissions	Lightning X-ray detector	Univ. of Washington	5, 22, 23
Measurement of trace gases from lightning - Atmospheric Chemistry Experiment	Atmospheric chemistry air sampler system	NASA	5, 24 to 28
Lightning attachment point determination	F-106B	NASA	5
Turbulence and wind shear measurements	Aircraft Instrumentation System (AIS) Inertial Navigation System (INS)	NASA	29
Storm hazards correlation	Airborne lightning locator Airborne X-band radar Cockpit voice recorder Outside-air temperature gauge AIS INS	NASA	1

TABLE II.- CHARACTERISTICS OF F-106B RESEARCH AIRPLANE

Length, m (ft)	21.54 (70.67)
Height, m (ft)	6.17 (20.25)
Wing span, m (ft)	8.62 (28.29)
Wing area (gross), m^2 (ft^2)	64.83 (697.83)
Wing chord at root, m (ft)	9.07 (29.77)
Aspect ratio	2.198
Wing sweepback angle	60°6'13"
Empty weight, N (lbf)	116 543 (26 200)
Gross take-off weight, N (lbf)	160 710 (36 129)
Engine	J75-P-17 axial flow turbojet
Thrust (military) at sea level, N (lbf)	71 616 (16 100)
Maximum thrust, N (lbf)	108 981 (24 500)

TABLE III.- 1980 LIGHTNING TRANSIENT DATA SUMMARY

["X" indicates recorded transient]

Flight	Event	Event recorded by -		
		$\dot{D}$ sensor[a]	$\dot{B}$ sensor[a]	$\dot{I}$ sensor[b]
80-018	Strike 1	X		
80-019	Strike 2			
80-019	Strike 3	X		
[c]80-023	Nearby flash 1		X	
↓	Nearby flash 2	X		
↓	Nearby flash 3	X		
↓	Nearby flash 4	X		
80-029	Strike 4			
80-029	Nearby flash 5	X		
80-030	Nearby flash 6		X	
80-036	Strike 5	X	X	
80-038	Strike 6		X	X
↓	Strike 7	X		X
↓	Strike 8		X	X
↓	Strike 9	X	X	X
↓	Strike 10	X	X	X
Totals	10 strikes	10	7	5
	6 nearby flashes	22 transients		

[a]Digital, expanded-memory, wide-band transient-waveform recorder with 10-nsec time resolution.

[b]Wide-band (6-MHz), 2-channel analog tape recorder (100-nsec step response).

[c]Sensitivity of $\dot{B}$ and $\dot{I}$ sensors increased 10 times and 100 times, respectively, for all subsequent flights.

TABLE IV.- AIRPLANE FLIGHT CONDITIONS DURING DIRECT STRIKES AND NEARBY FLASHES IN 1980

Event	Flight	Date	Time, GMT	Research site	Attachment point figure	Scenario figure	Figure from ref. 3 for -		
							$\dot{D}$	$\dot{B}$	$\dot{I}$
Strike 1	80-018	June 17	17:23:24.0	NSSL	3	5	1, 9		
Strike 2	80-019	June 17	22:28:36.0	NSSL	8	10			
Strike 3	80-019	June 17	22:33:50.0	NSSL	11	12	2, 10		
Nearby flash 1	80-023	July 22	20:34:28.5	WFC	NA	NA		11	
Nearby flash 2	↓	↓	20:34:40.6	↓	NA	NA	12		
Nearby flash 3	↓	↓	20:35:01.0	↓	NA	NA	13		
Nearby flash 4	↓	↓	20:54:21.9	↓	NA	NA	14		
Strike 4	80-029	Aug. 12	20:54:50.0	↓	17	18			
Nearby flash 5	80-029	Aug. 12	21:08:47.0	↓	NA	NA	15		
Nearby flash 6	80-030	Aug. 15	20:40:50.0	↓	NA	NA		16	
Strike 5	80-036	Sept. 1	21:06:02.0	↓	19	20	3, 18	3, 17	
Strike 6	80-038	Sept. 3	20:27:53.4	↓	21	(a)		4, 19	20
Strike 7	↓	↓	20:27:55.4	↓	↓	(a)	5, 21		22
Strike 8	↓	↓	20:28:04.1	↓	↓	(a)		6, 23, 24	25
Strike 9	↓	↓	20:30:28.8	↓	↓	(a)	7, 27	7 ,26	28
Strike 10	↓	↓	20:30:54.7	↓	↓	(a)	8, 30	8, 29	31

[a]Insufficient information to formulate scenario.

TABLE IV.- Concluded

Event	Pressure altitude		Temperature, °C	True airspeed		Pitch angle, deg (a)	Bank angle, deg (b)	Precipitation reflectivity, dBZ	Penetration no. of event
	km	ft		m/sec	knots				
Strike 1	5.0	16 400	-20.1	212.3	412.7	5.1	7.4	20	3rd of 3
Strike 2	4.8	15 750	-1.0	191.3	371.9	6.6	29.3	[c]<45	1st of 4
Strike 3	4.8	15 900	-.4	201.6	391.9	3.5	2.2	20	2nd of 4
Nearby flash 1	4.6	15 200	-1.3	220.9	429.4	6.1	3.3	30 to 40	2nd of 8
Nearby flash 2	4.9	16 000	-3.9	224.4	436.2	4.8	3.0	30 to 40	2nd of 8
Nearby flash 3	5.0	16 250	-4.1	227.1	441.4	2.2	-1.1	<10	2nd of 8
Nearby flash 4	4.7	15 350	-.7	212.0	412.1	2.0	-.3	<10	7th of 8
Strike 4	[d]5.2	[d]17 000	(e)	(e)	(e)	(e)	(e)	[c]<50	1st of 2
Nearby flash 5	[d]5.8	[d]19 000	(e)	(e)	(e)	(e)	(e)	↓	2nd of 2
Nearby flash 6	6.4	20 850	-7.7	222.2	431.9	(e)	(e)	↓	4th of 6
Strike 5	6.4	21 100	-11.2	222.7	432.9	1.1	1.4	↓	4th of 8
Strike 6	10.1	33 150	-38.8	240.2	486.3	4.5	13.1	↓	1st of 1
Strike 7	10.1	33 250	-39.6	250.9	487.7	3.8	4.0	↓	↓
Strike 8	10.2	33 300	-35.6	255.9	497.4	.8	-12.2	↓	↓
Strike 9	10.2	33 500	-43.7	269.3	523.5	1.8	16.5	↓	↓
Strike 10	10.2	33 400	-43.8	274.2	533.0	8.0	-2.5	↓	↓

[a]Positive for nose up.
[b]Positive for right wing down.
[c]Reflectivity indicated by onboard X-band weather radar.
[d]Estimated.
[e]Not available.

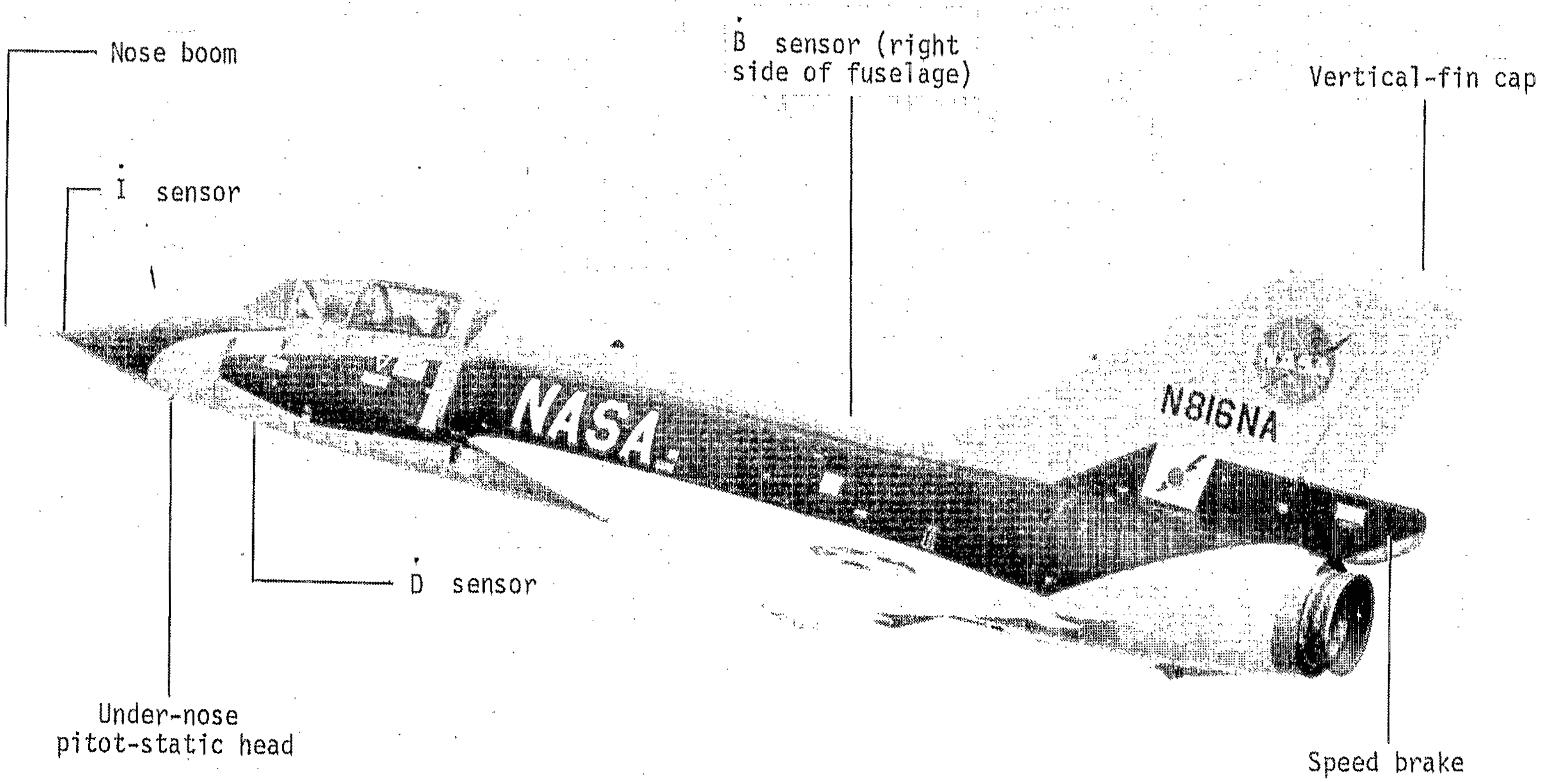
TABLE V.- TYPICAL DWELL-TIME DATA FOR LIGHTNING STRIKE 1 TO THE F-106B AIRPLANE

[Flight 80-018, June 17, 1980]

Attachment point sequence	Distance to next point		Dwell time, msec	Remarks
	m	ft	(a)	
1	1.65	5.42	9.0	Nose boom (initial entry point)
2	2.31	7.58	12.6	Boom attachment fitting
3	.79	2.58	4.3	Radome attachment bolt
4	1.01	3.33	5.6	Fuselage
5	.74	2.42	4.0	↓
6	.53	1.75	2.9	↓
7	.63	2.08	3.5	↓
8	.30	1.00	1.7	↓
9	.46	1.50	2.5	↓
10	.20	.67	1.1	↓
11	.23	.75	1.3	↓
12	.48	1.58	2.6	↓
13	1.88	6.17	10.3	Inlet
14	.20	.67	1.1	Wing
15	.28	.92	1.5	↓
16	.41	1.33	2.2	↓
17	.23	.75	1.3	↓
18	.36	1.17	2.0	↓
19	.30	1.00	1.7	↓
20	.34	1.08	1.8	↓
21	.43	1.42	2.4	↓
22	(b)	(b)	(b)	Wing (final entry point)
23	(b)	(b)	(b)	Wing tip (initial exit point)
24	(b)	(b)	(b)	Vertical-fin cap (initial exit point)
Total			75.4	

[a]Dwell time is distance to next point divided by 182.9 m/sec (600 ft/sec).

[b]Not possible to compute distance or dwell time - flash hung on trailing edge.



L-79-7204.1

Figure 1.- NASA F-106B research airplane used in Storm Hazards Program.

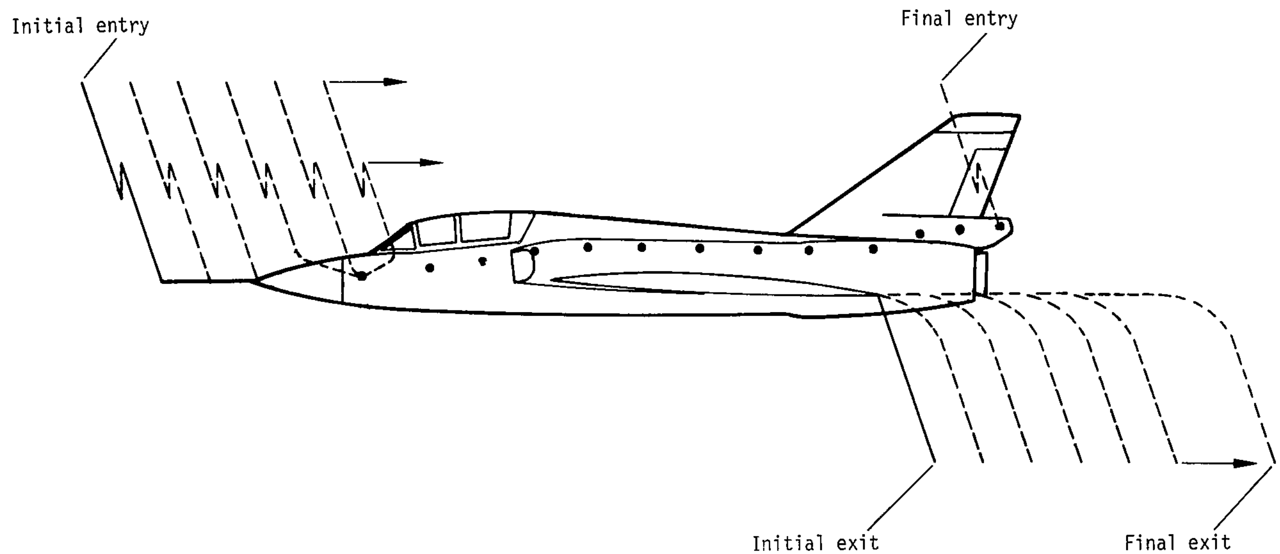


Figure 2.- Typical path of swept-flash attachment points.

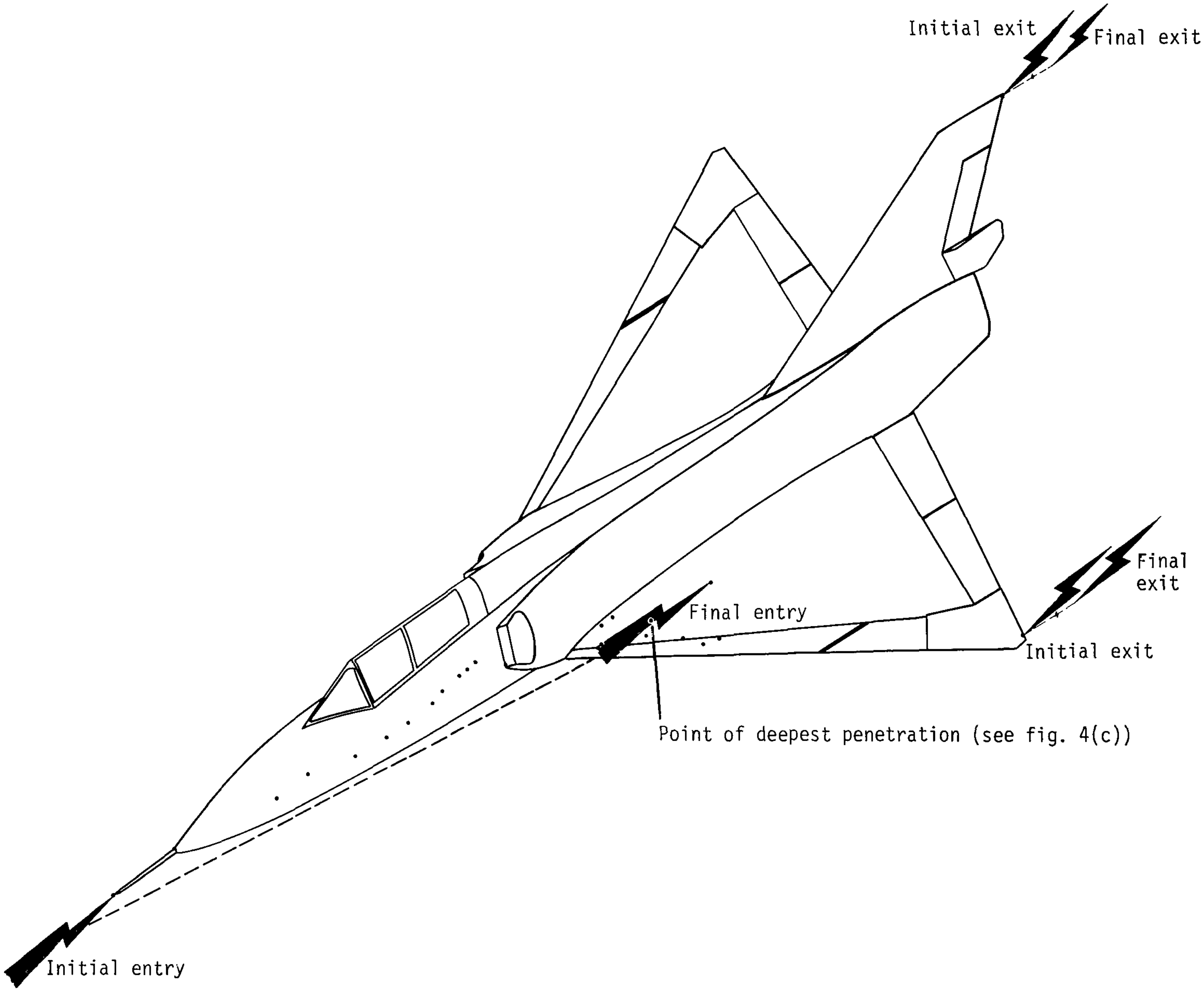
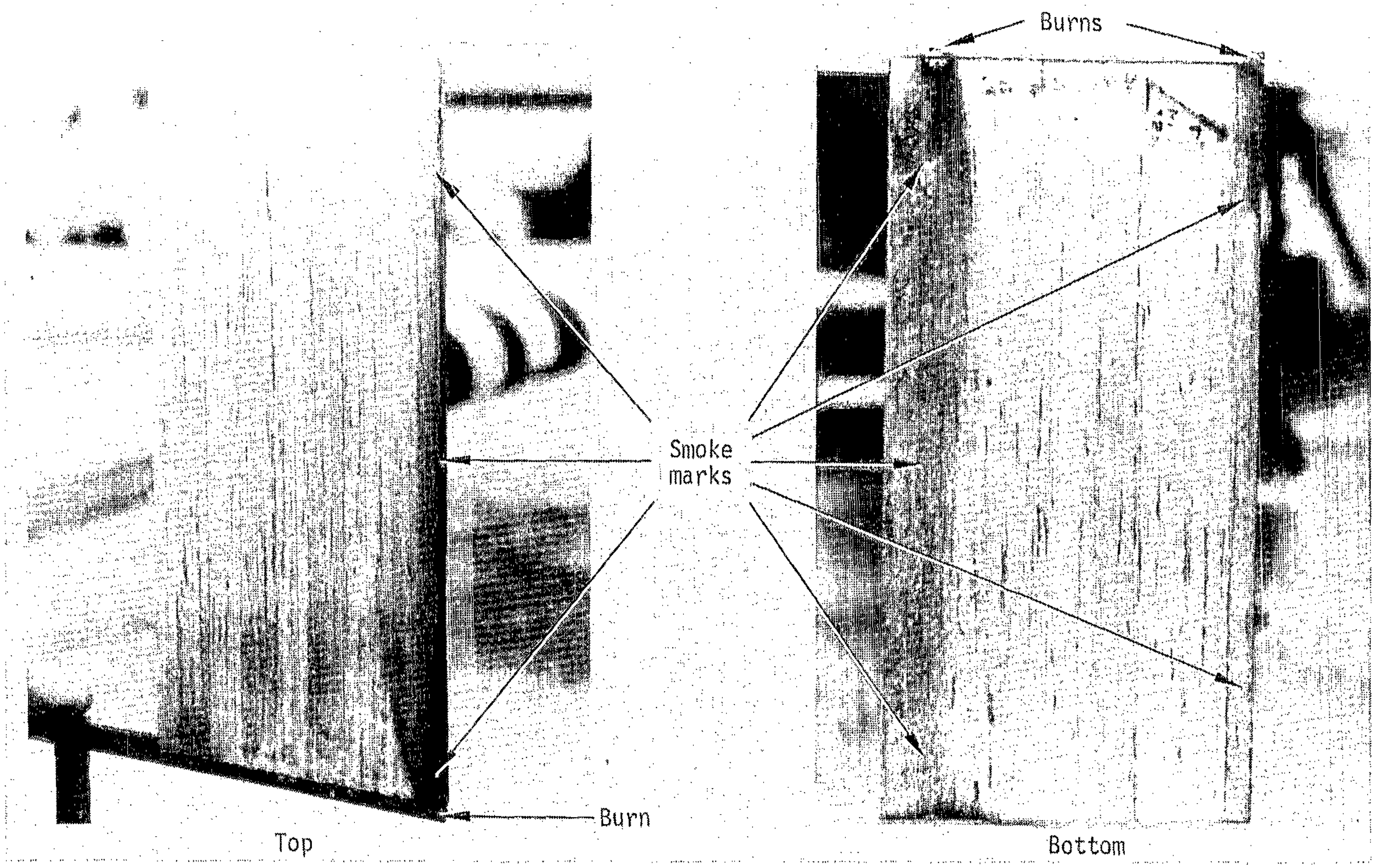
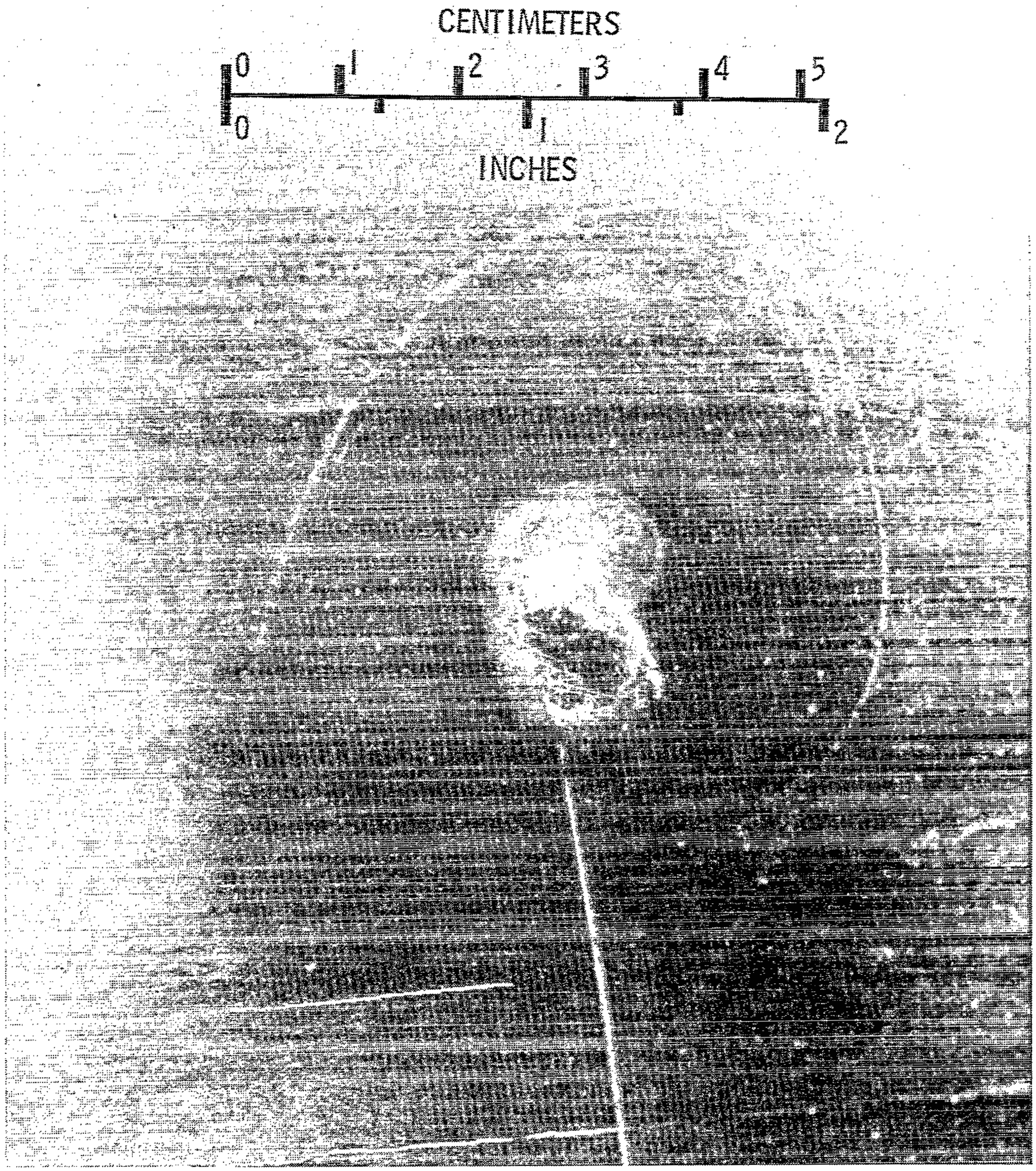


Figure 3.- Lightning attachment points for lightning strike 1, flight 80-018, June 17, 1980.



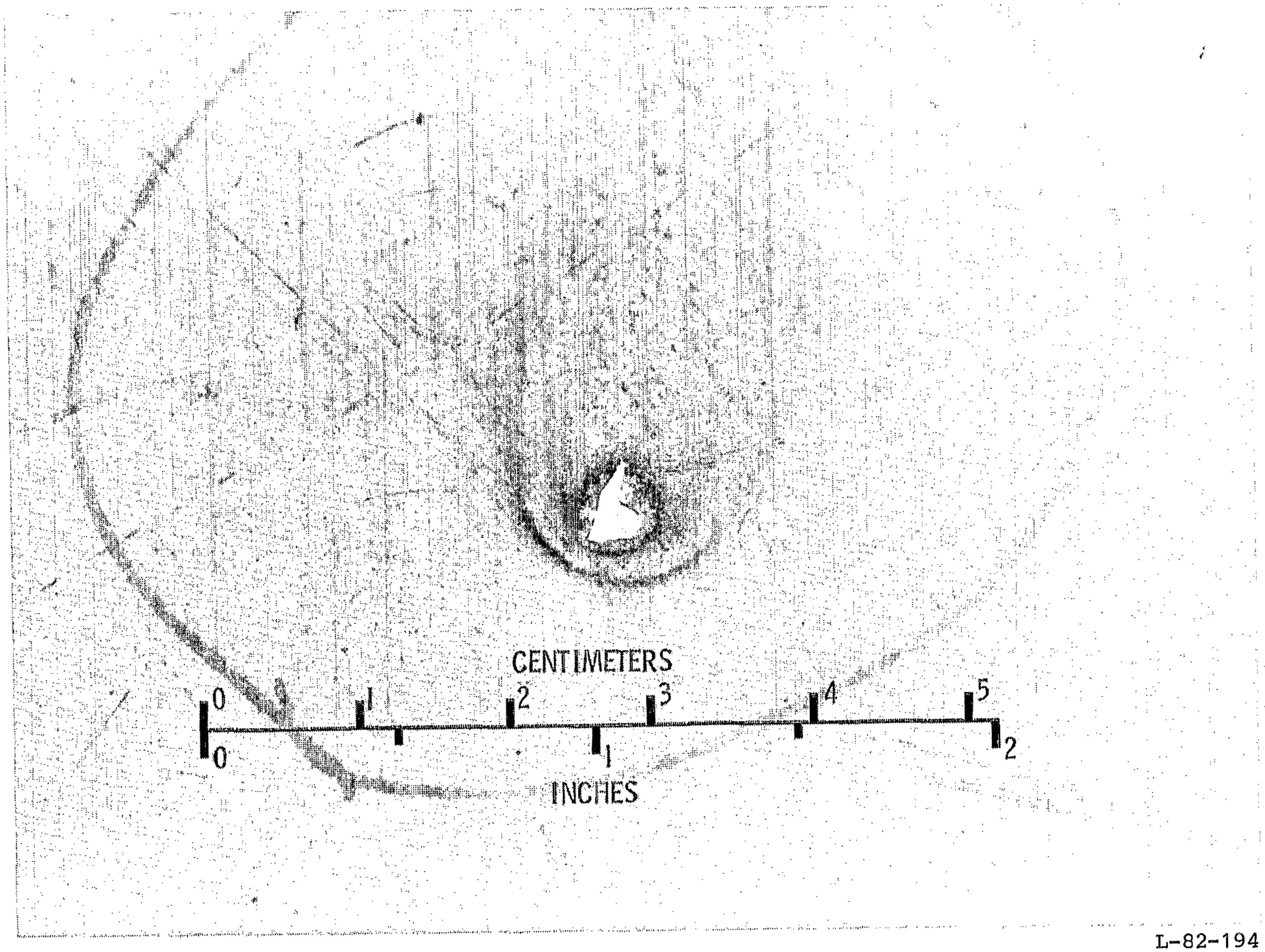
(a) Angle-of-attack vane.

Figure 4.- Lightning damage to F-106B research airplane from strike 1, flight 80-018, June 17, 1980.



(b) Rivet head on left side of radome.

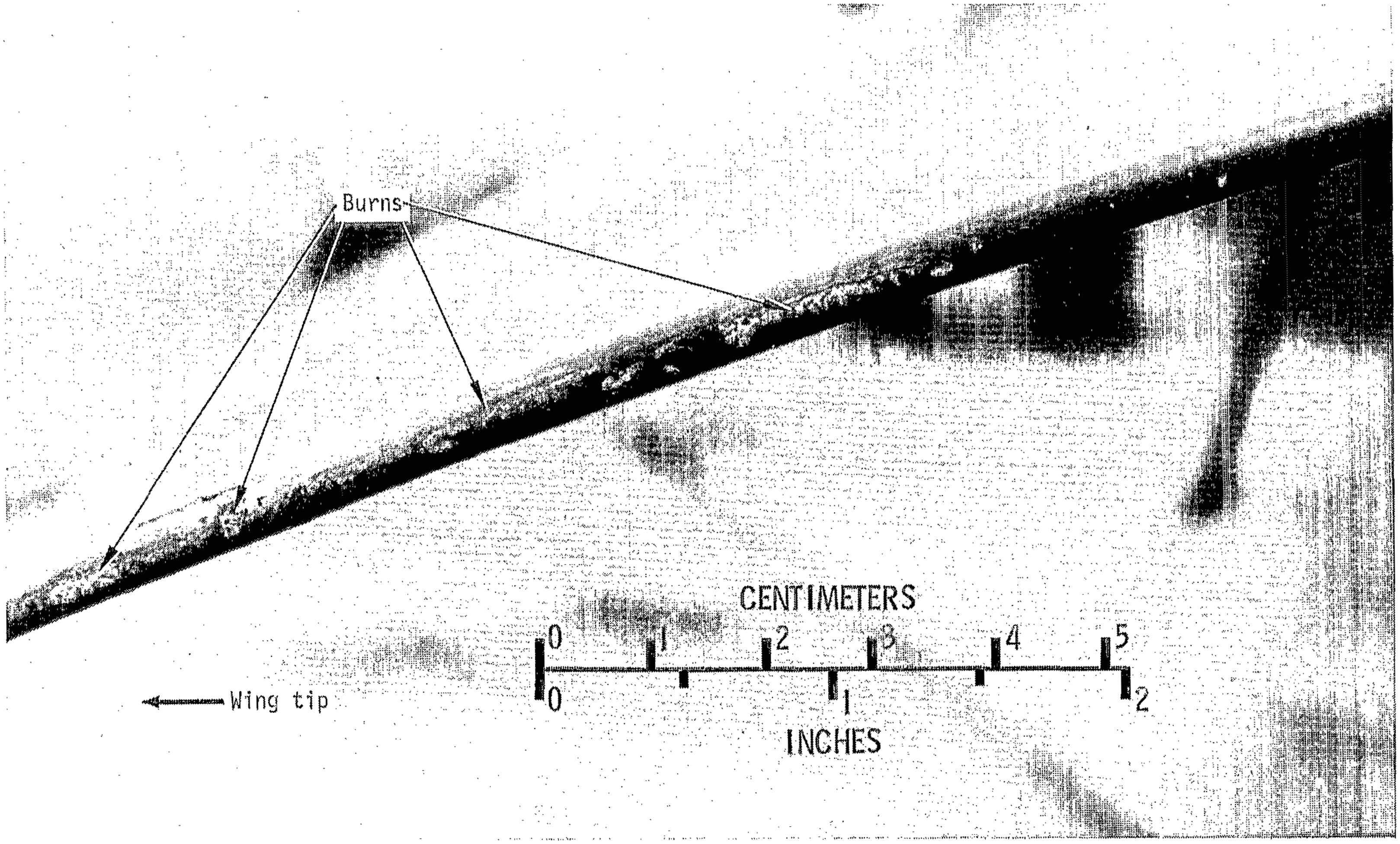
Figure 4.- Continued.



L-82-194

(c) Lightning attachment point on top of left wing.

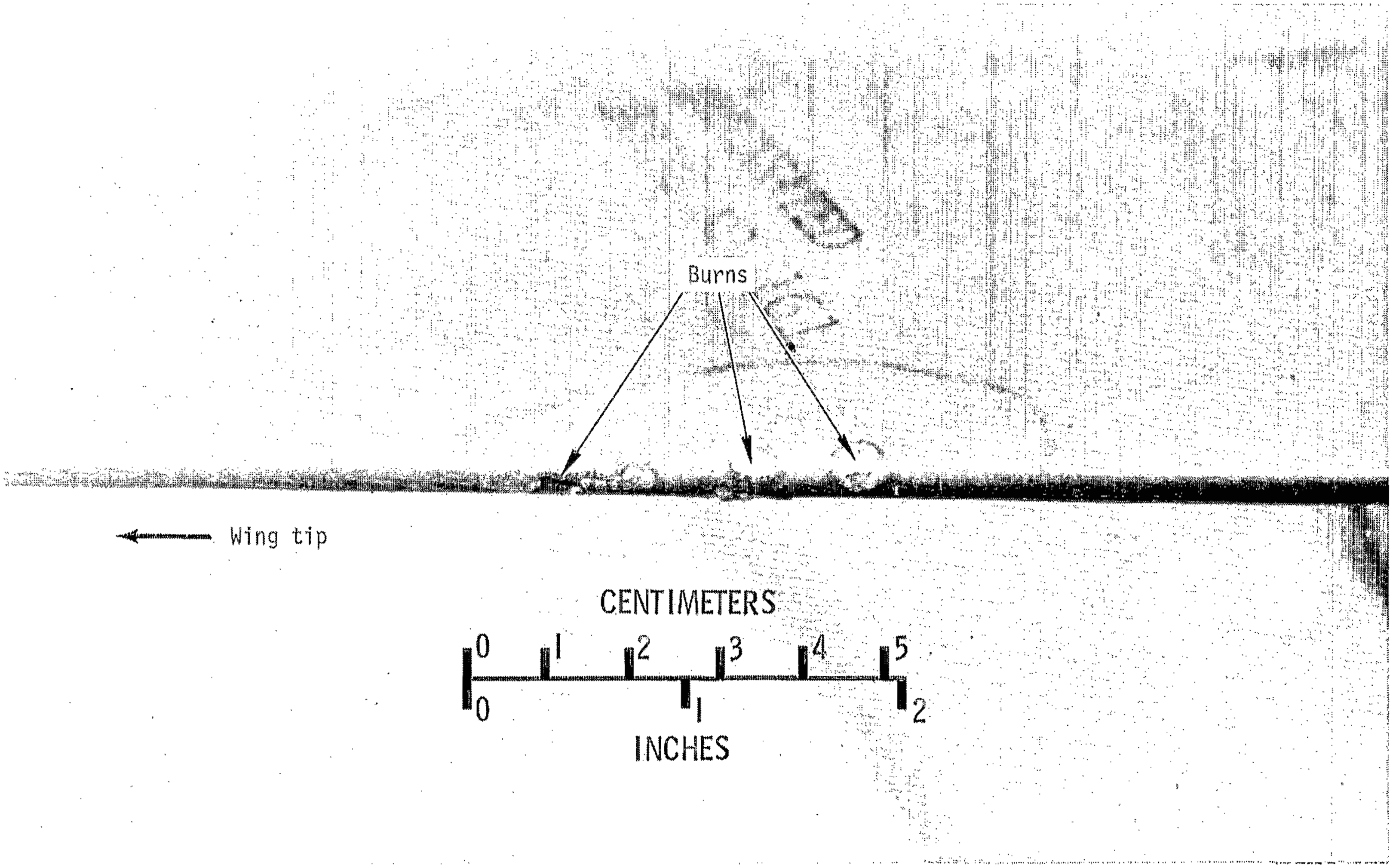
Figure 4.- Continued.



L-82-195

(d) Trailing edge of left wing, just inboard of tip.

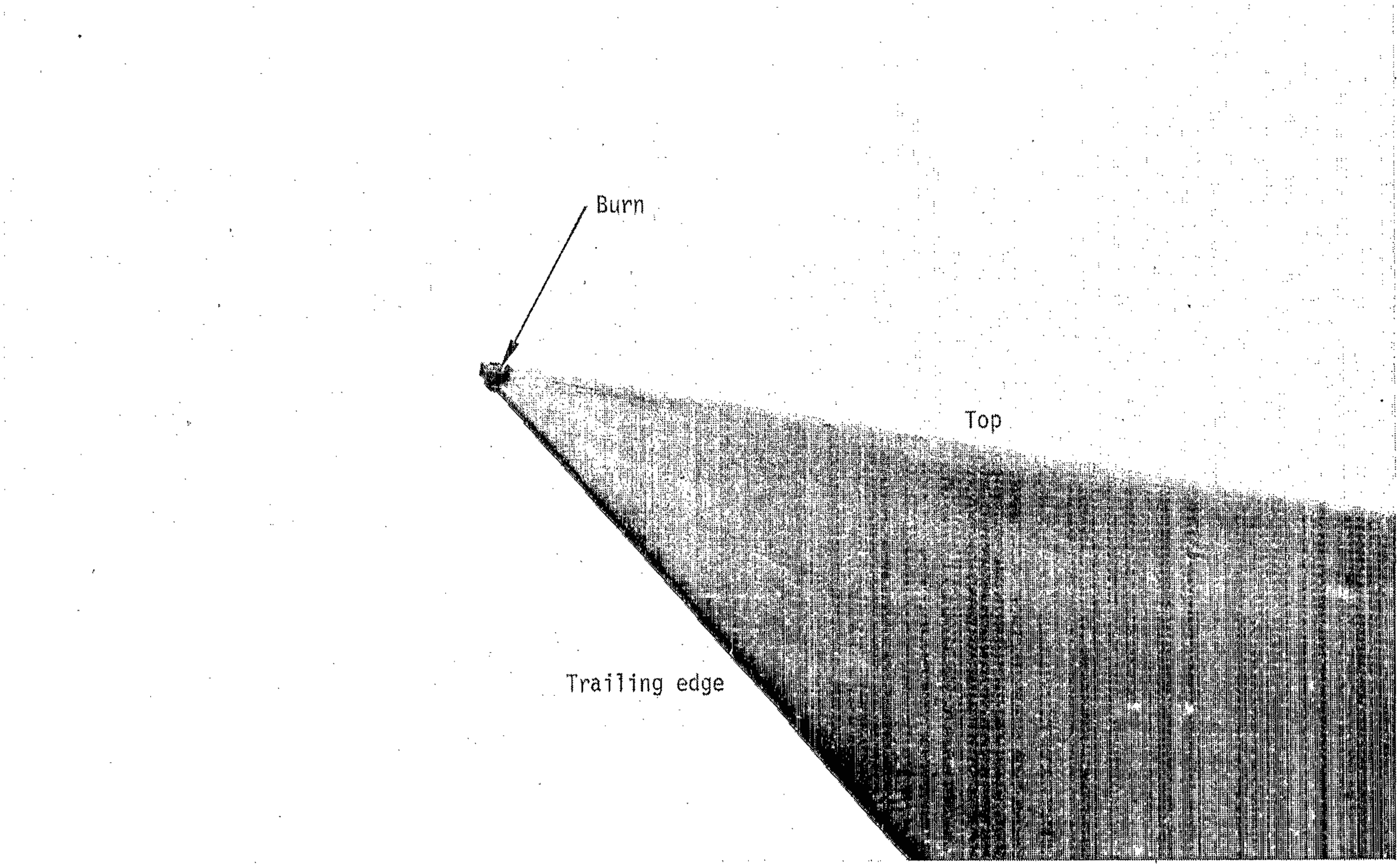
Figure 4.- Continued.



L-82-196

(e) Trailing edge of left wing, slightly inboard of view in figure 4(d).

Figure 4.- Continued.



L-82-197

(f) Tip of vertical-fin cap, looking towards left wing tip.

Figure 4.- Concluded.

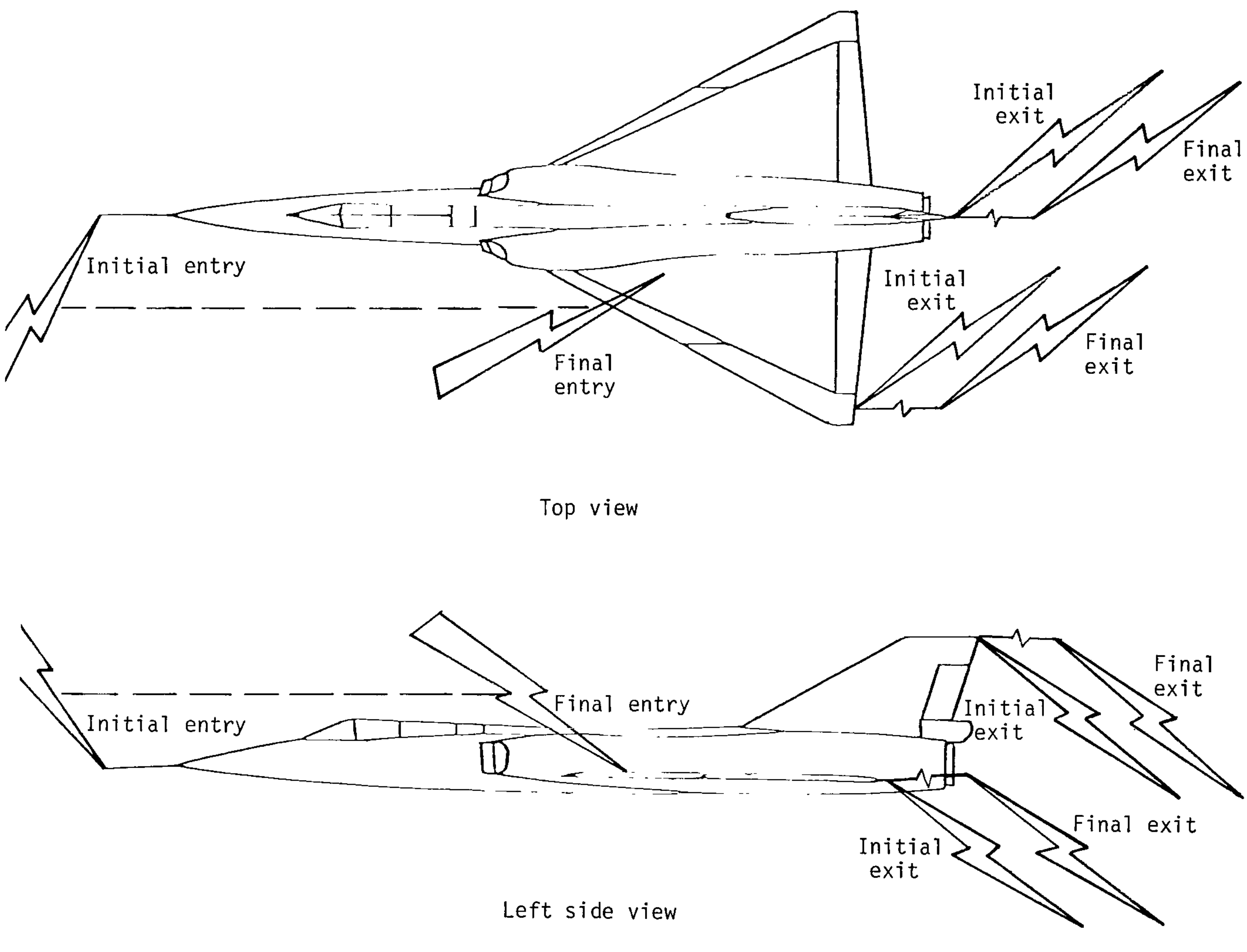


Figure 5.- Lightning strike scenario for strike 1, flight 80-018, June 17, 1980.

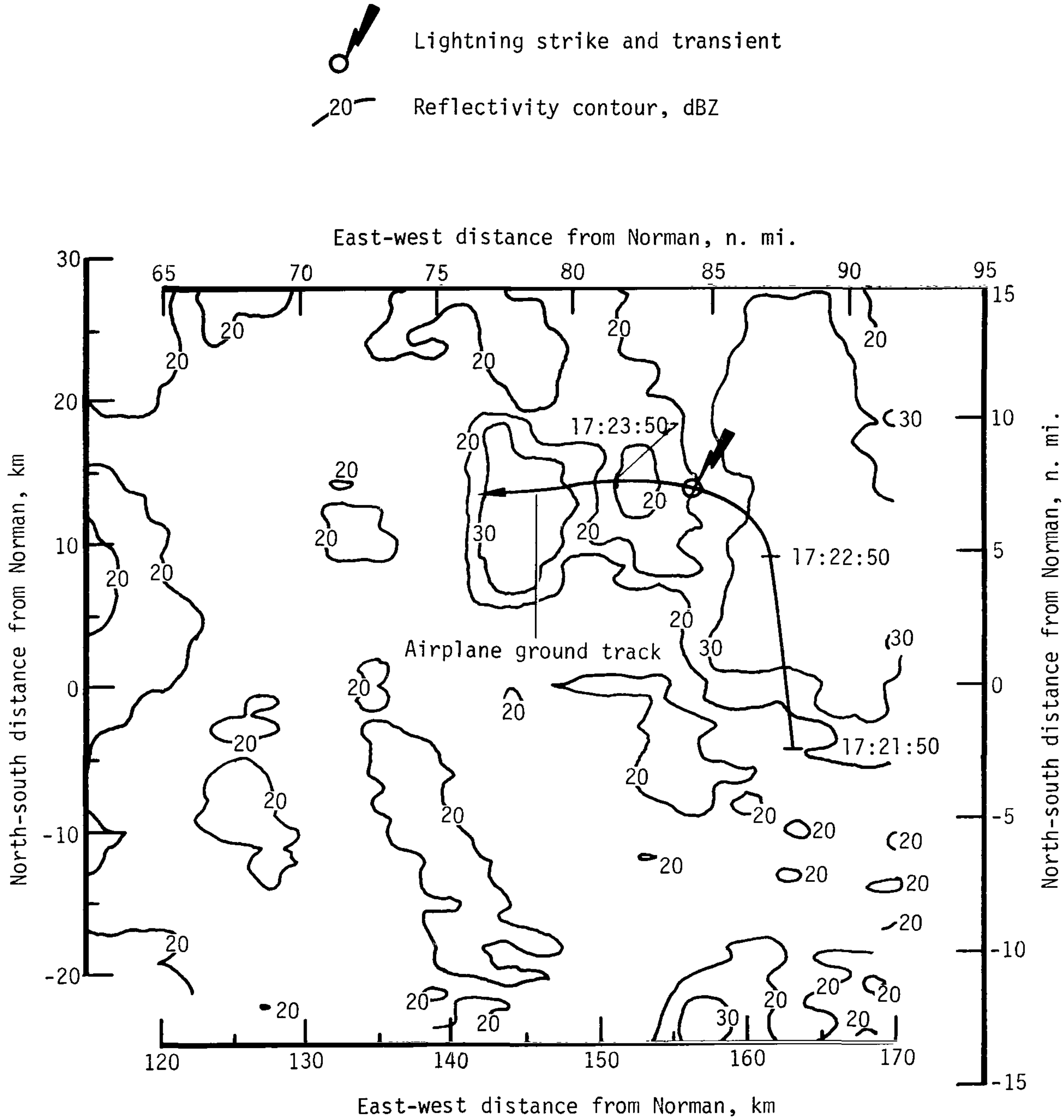


Figure 6.- Airplane ground track and precipitation reflectivity contours for lightning strike 1 at 17:23:24.0 GMT on June 17, 1980 (flight 80-018). Reflectivity data taken from NSSL Doppler radar at Norman, Okla., and interpolated to constant height of 4.5 km (14 800 ft).

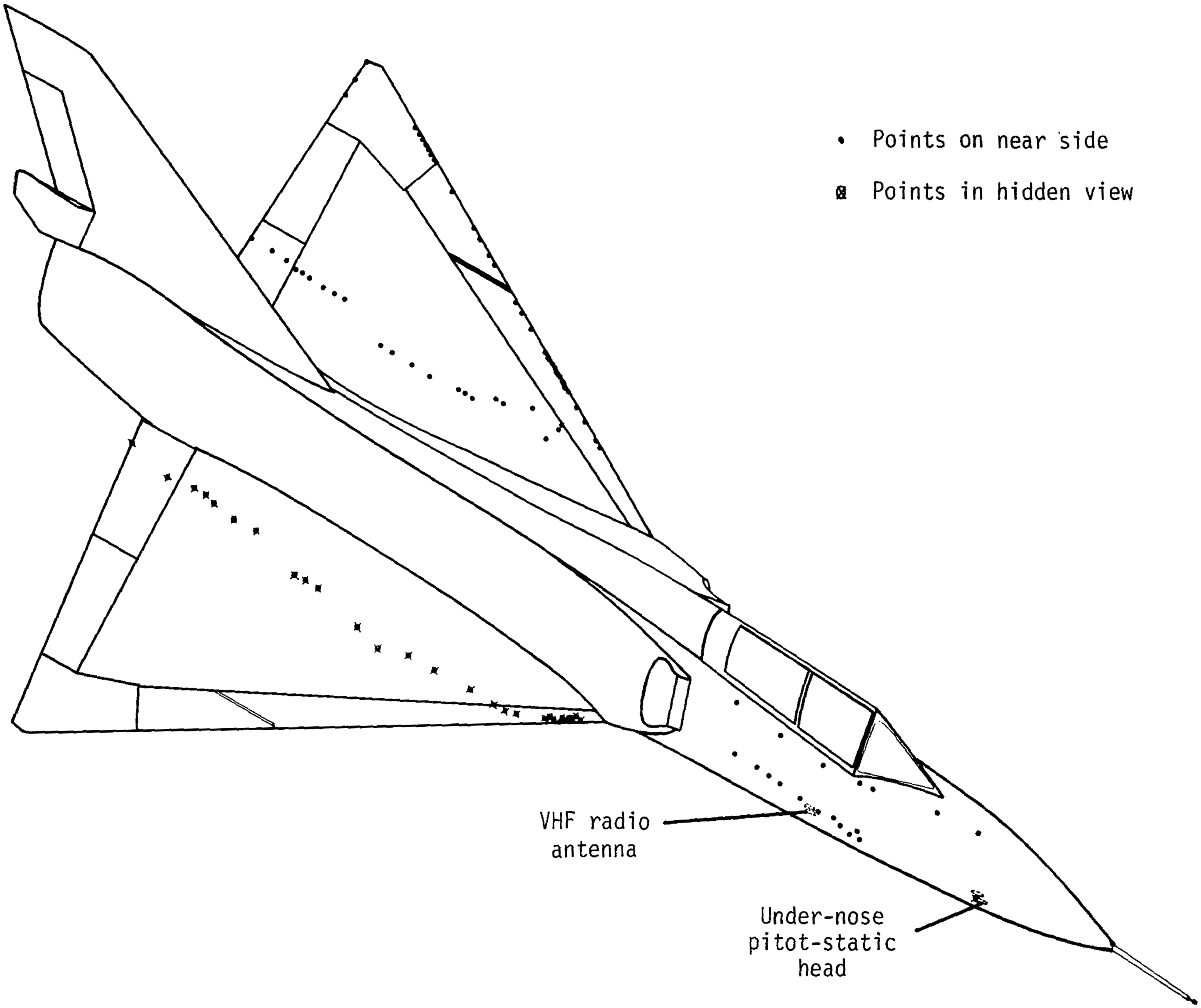


Figure 7.- Lightning attachment points for strikes 2 and 3, flight 80-019, June 17, 1980.

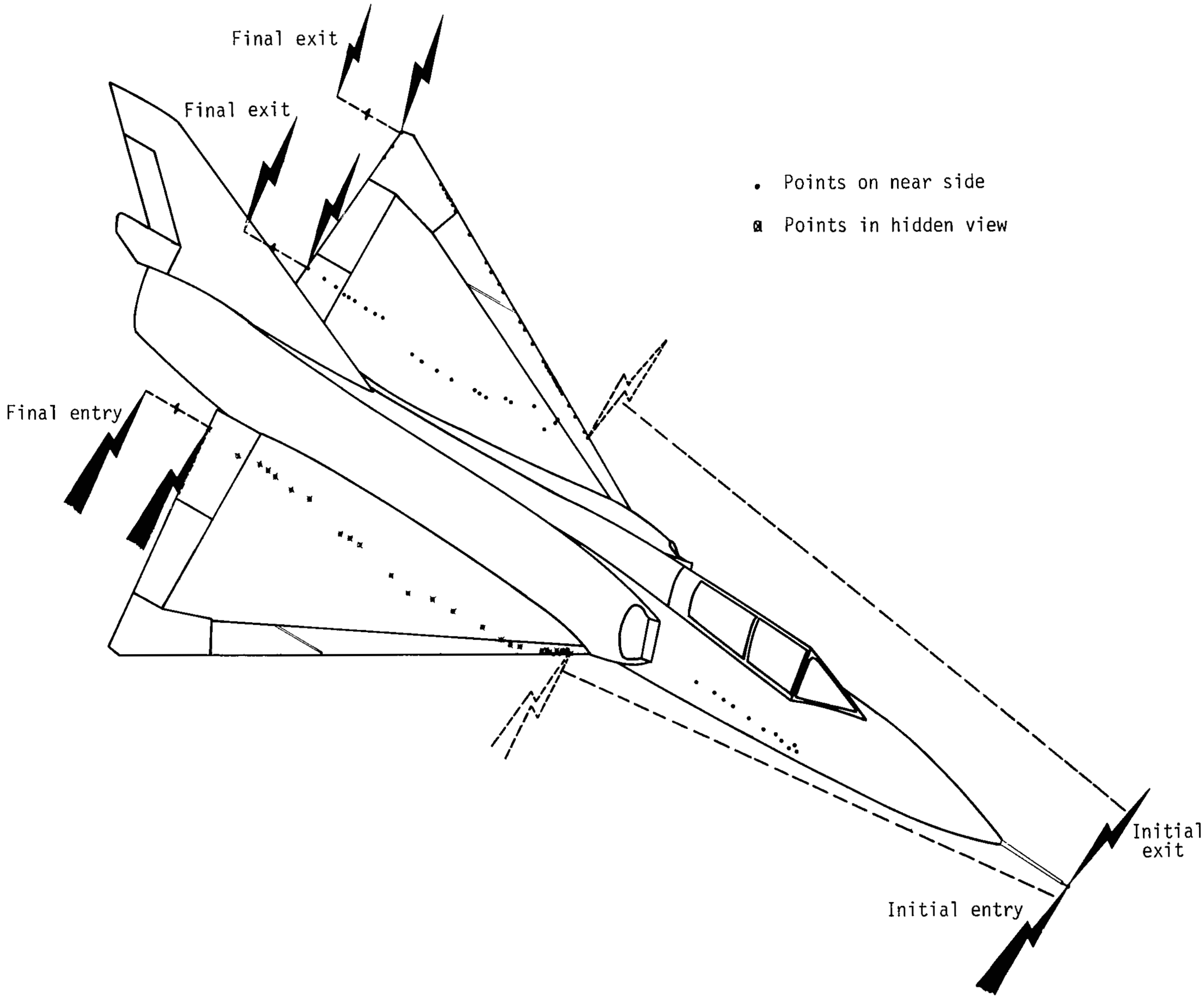
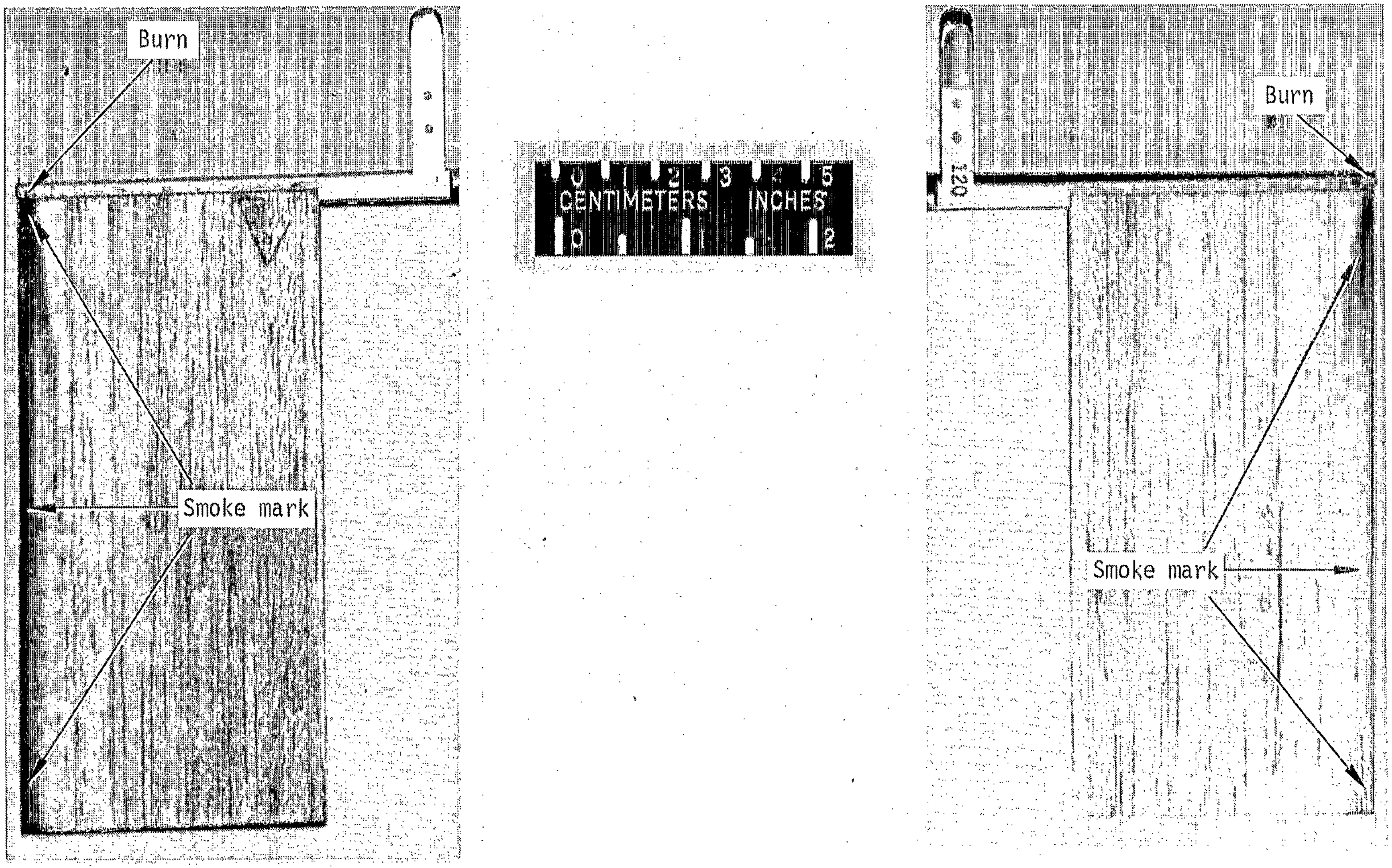


Figure 8.- Lightning attachment points for strike 2, flight 80-019, June 17, 1980.



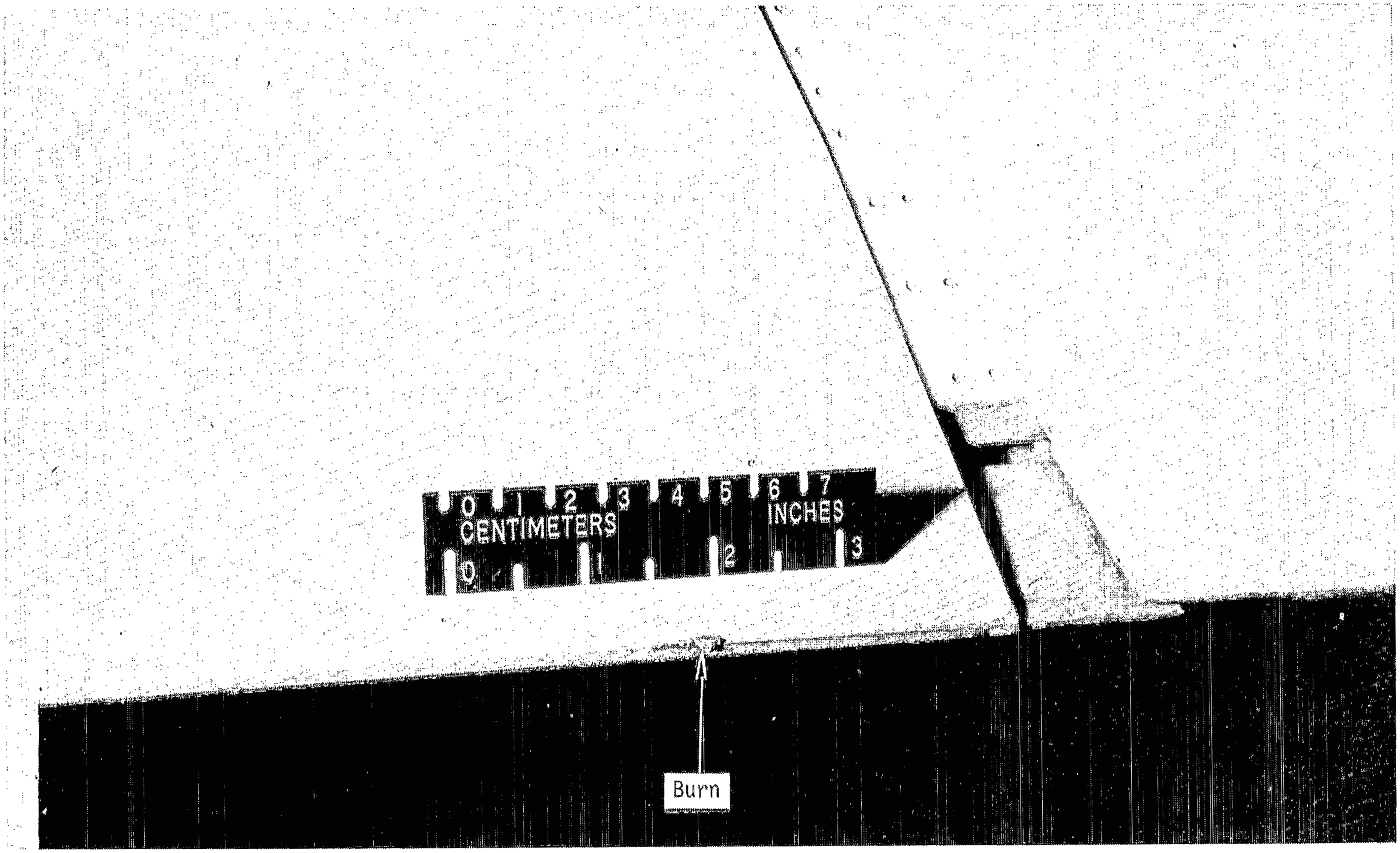
Left side

Right side

L-82-198

(a) Sideslip vane.

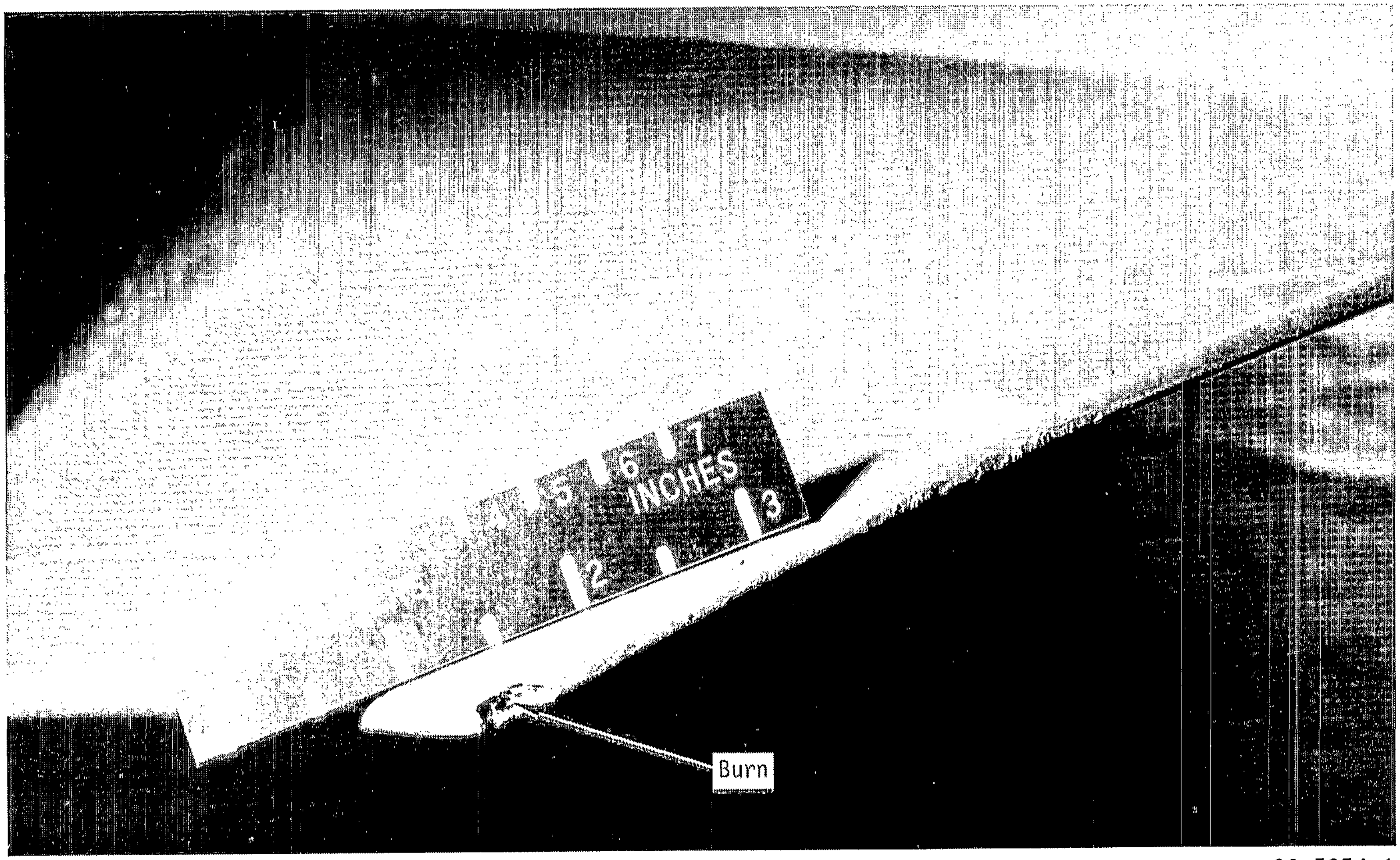
Figure 9.- Lightning damage to F-106B research airplane from strike 2, flight 80-019, June 17, 1980.



L-80-5356.1

(b) Trailing edge of left elevon.

Figure 9.- Continued.



L-80-5354.1

(c) Left wing tip.

Figure 9.- Concluded.

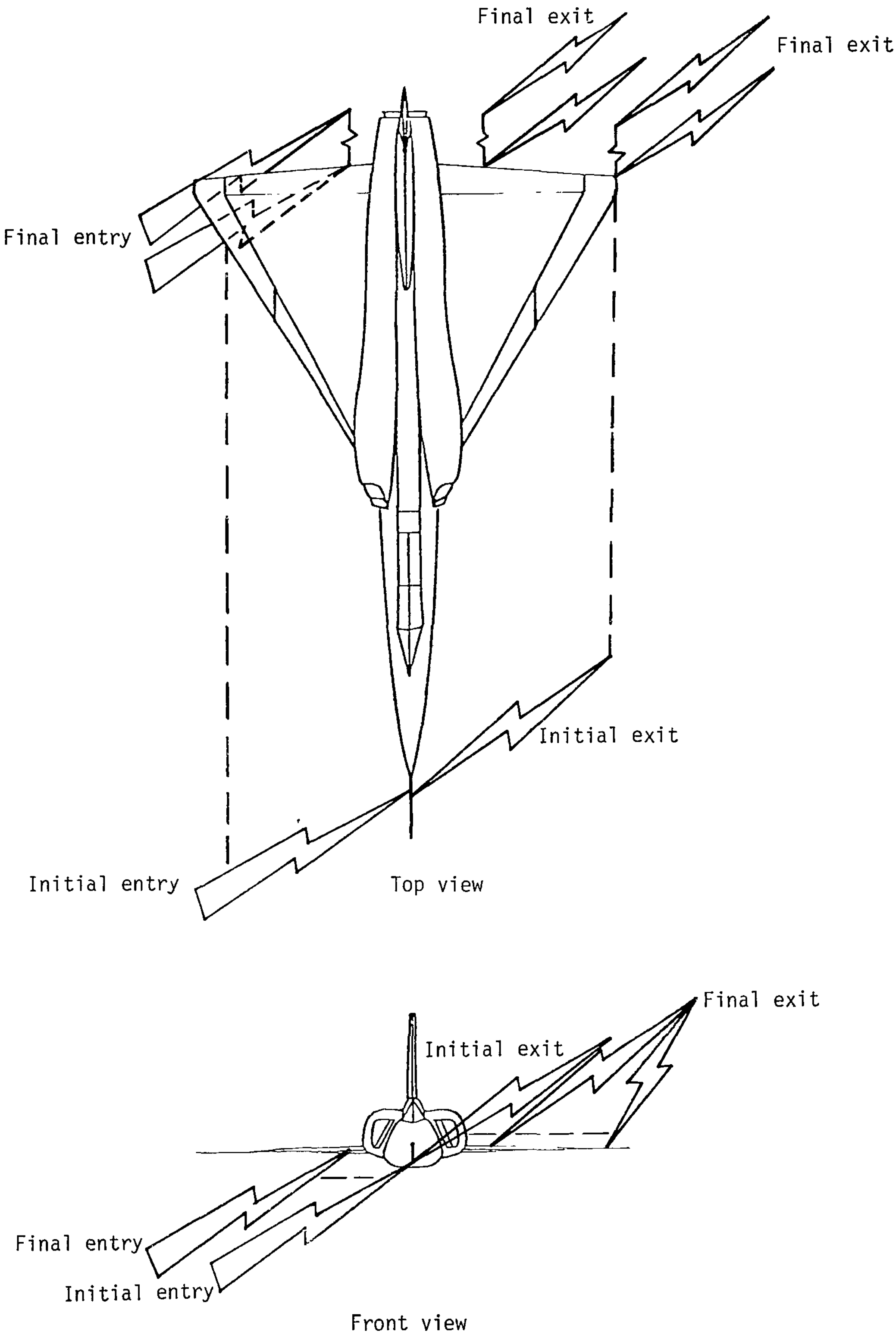


Figure 10.- Lightning strike scenario for strike 2, flight 80-019, June 17, 1980.

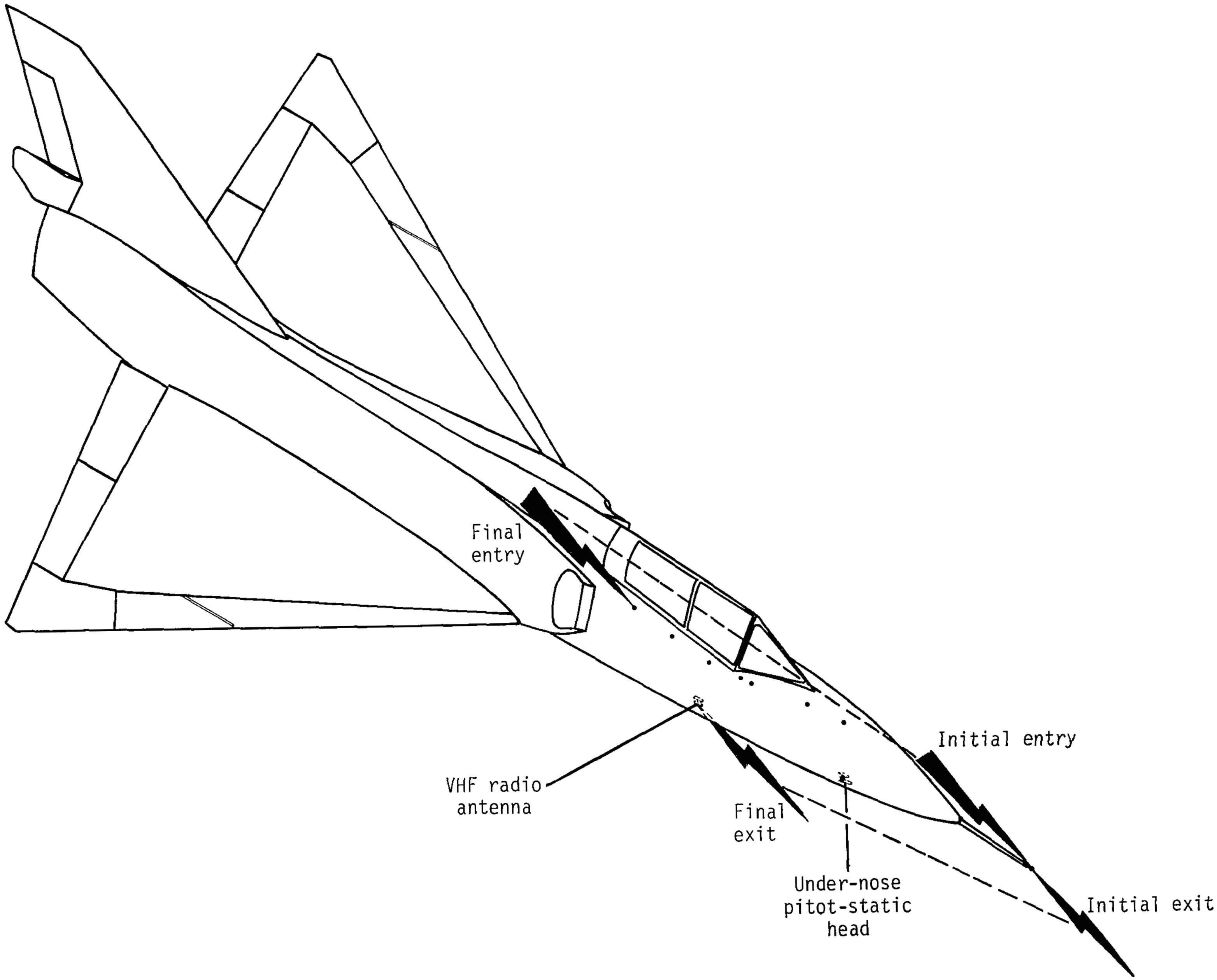
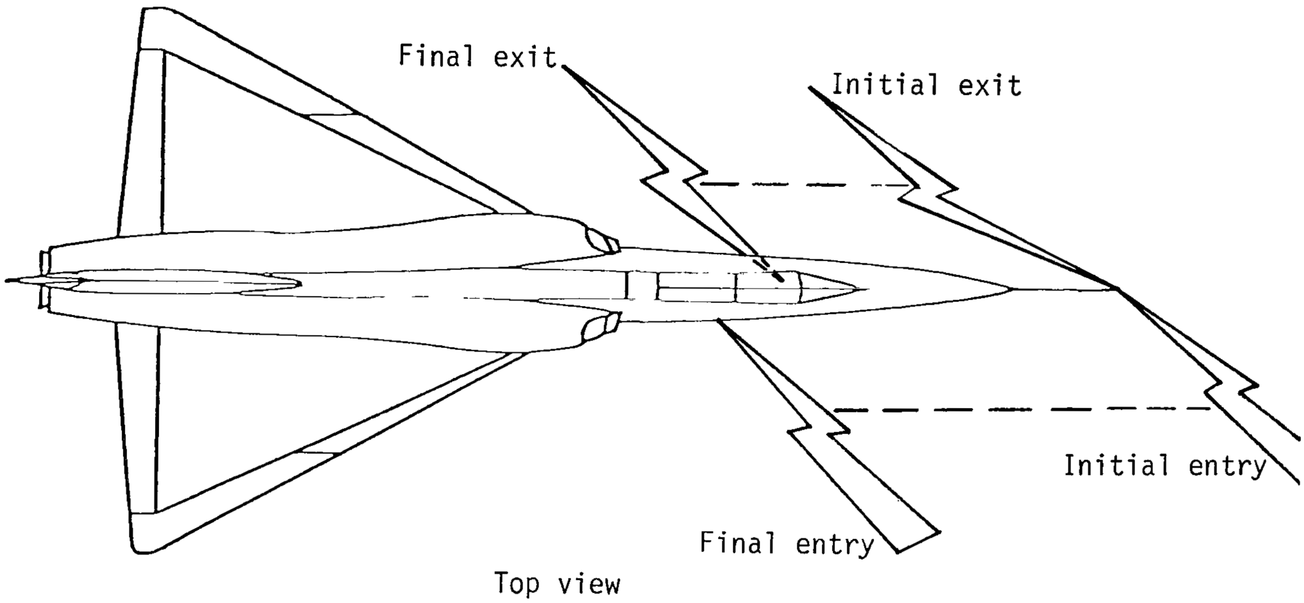


Figure 11.- Lightning attachment points for strike 3, flight 80-019, June 17, 1980.



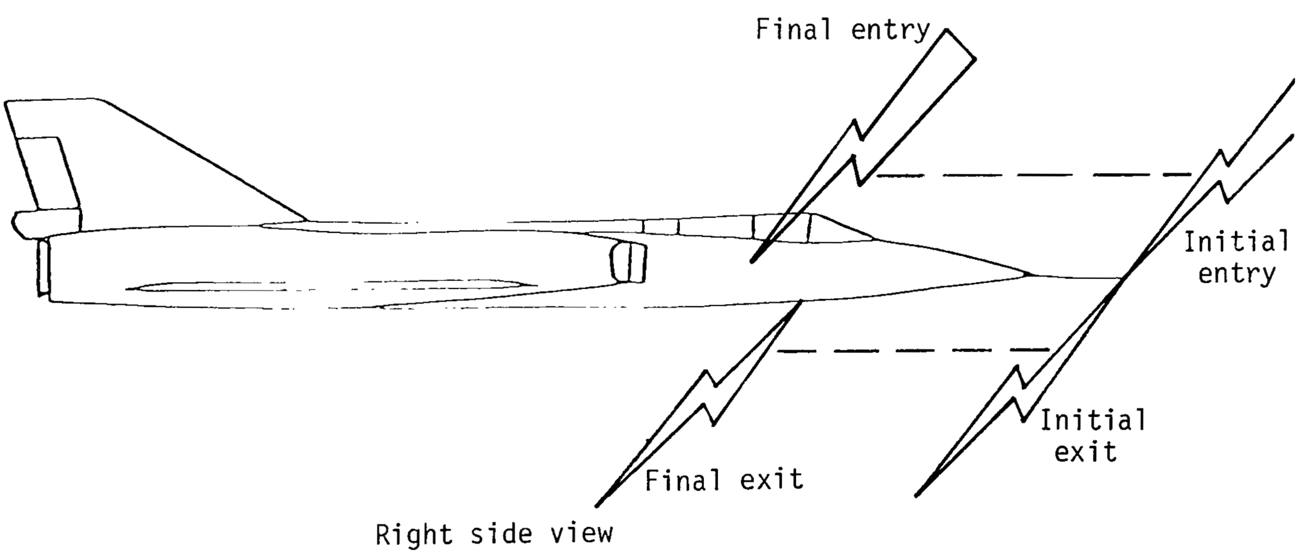
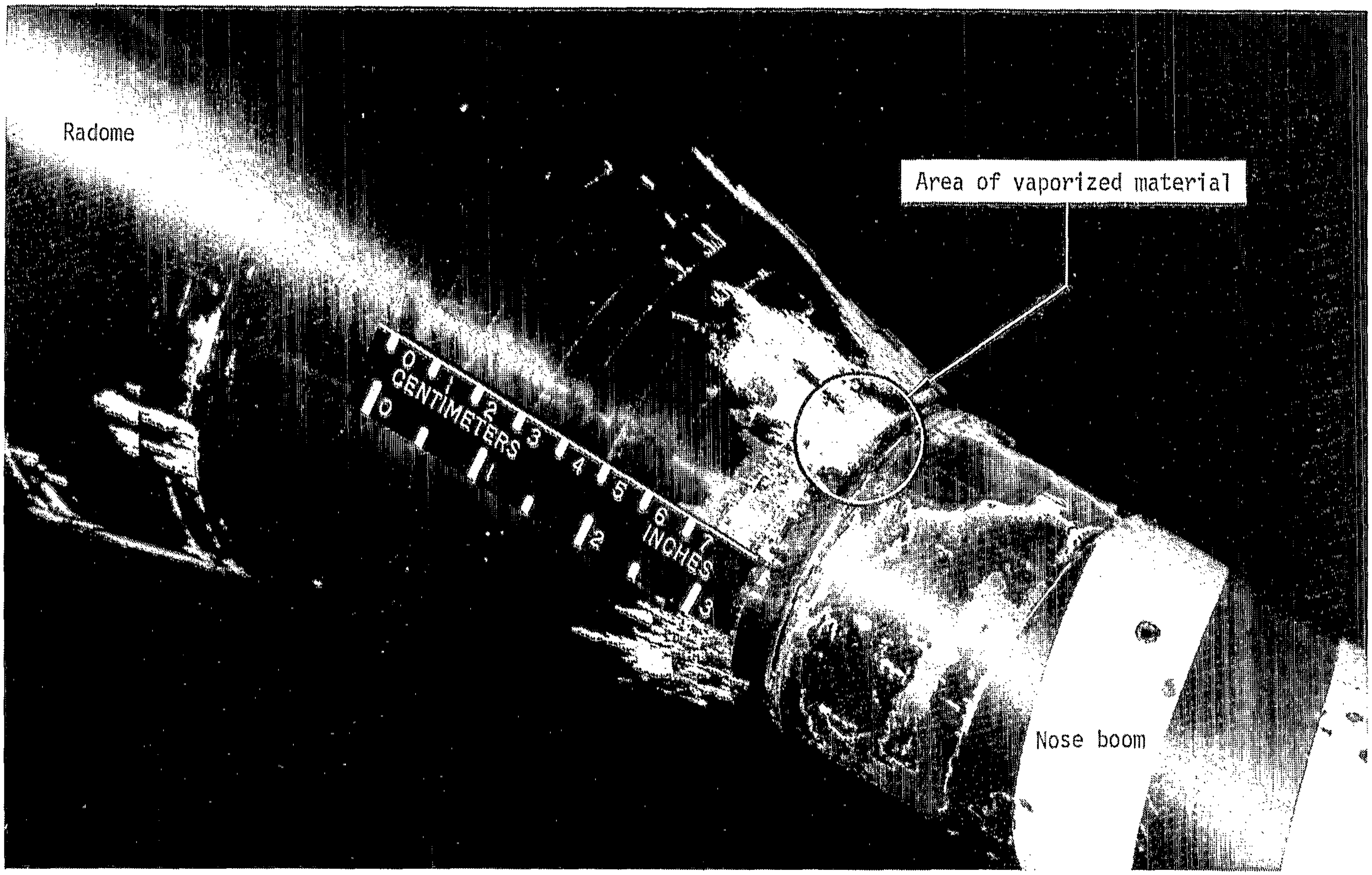


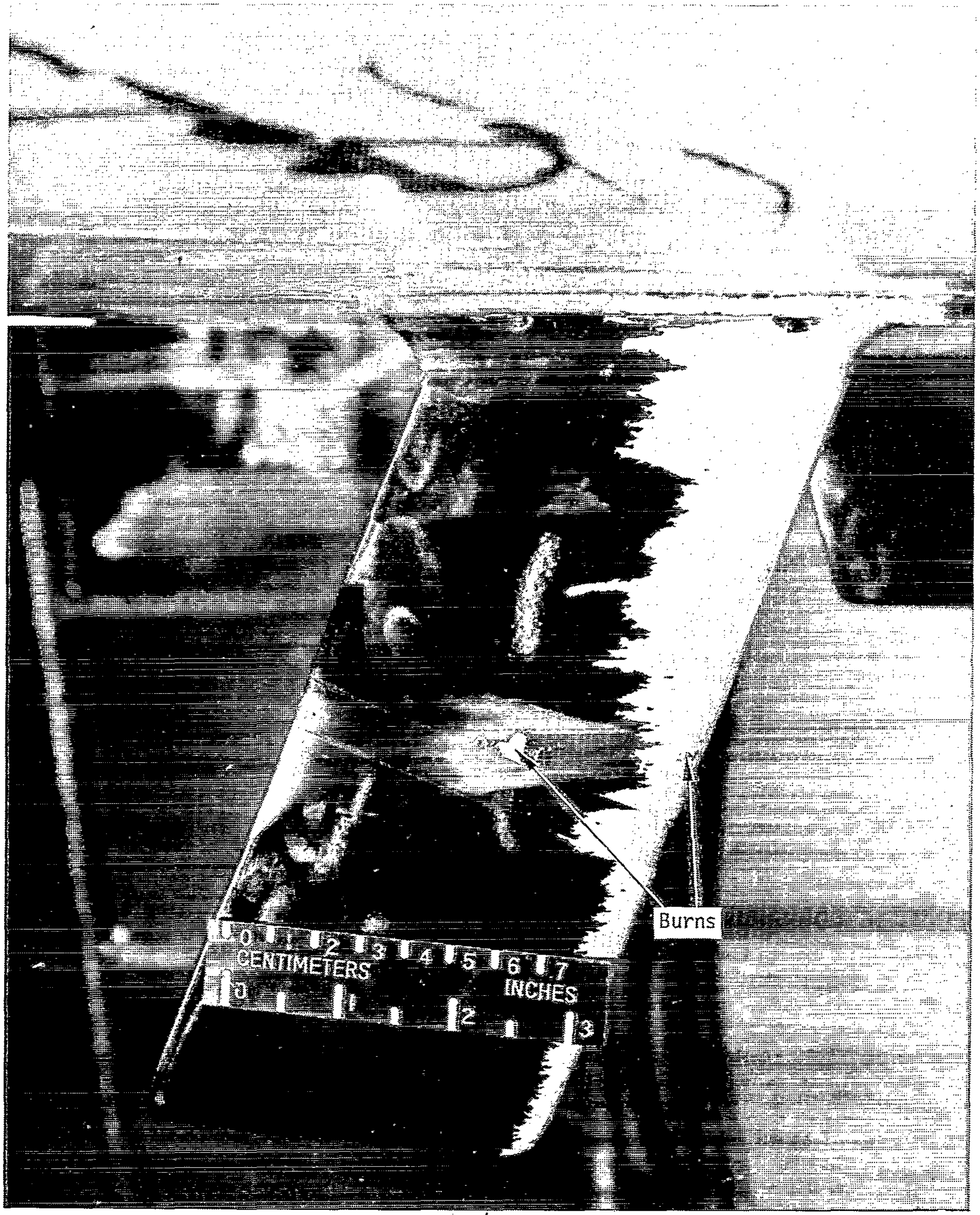
Figure 12.- Lightning strike scenario for strike 3, flight 80-019, June 17, 1980.



L-80-5357.1

(a) Nose-boom/radome junction.

Figure 13.- Lightning damage to F-106B research airplane from strike 3, flight 80-019, June 17, 1980.



L-80-5358.1

(b) VHF radio antenna.

Figure 13.- Concluded.

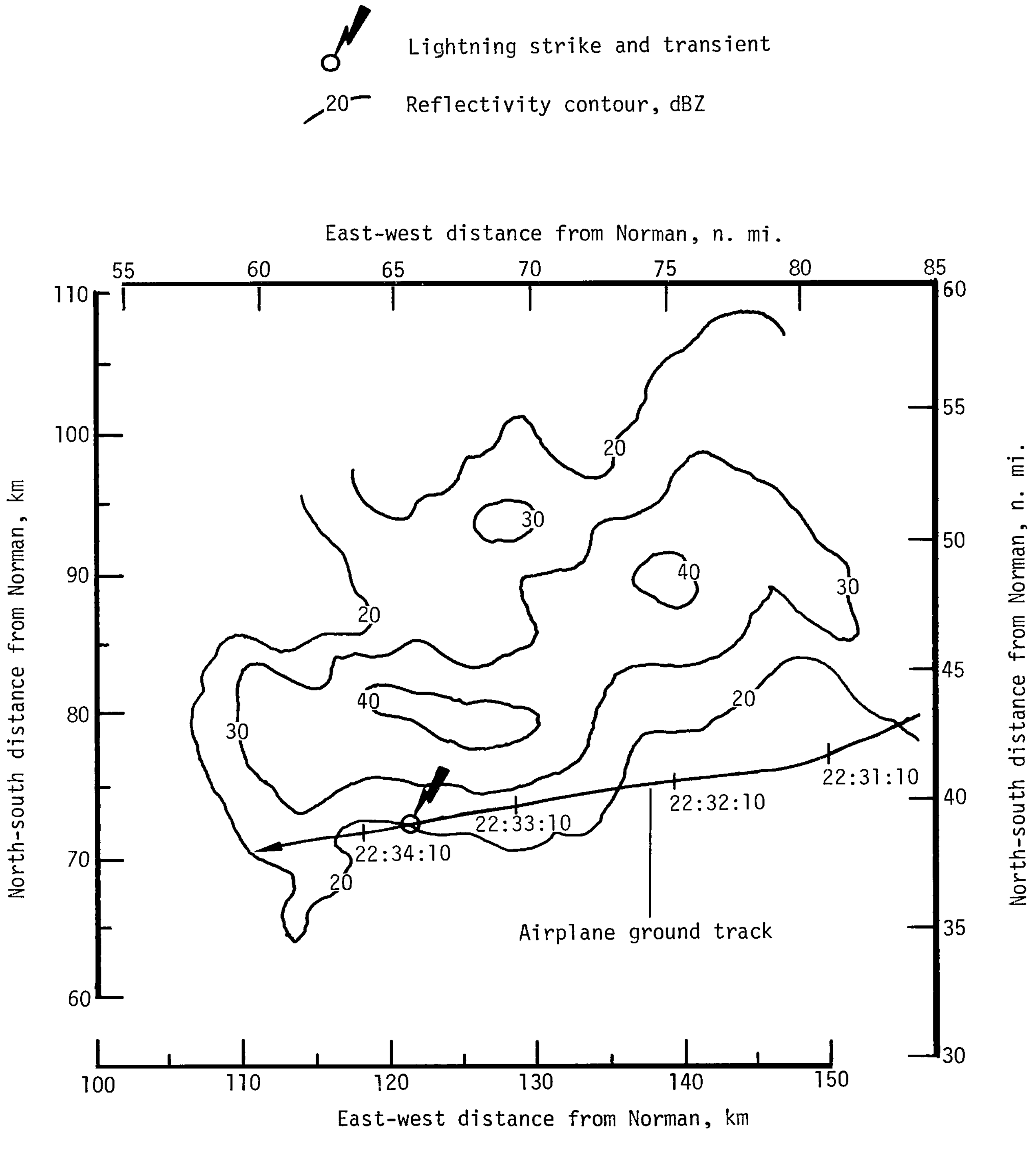


Figure 14.- Airplane ground track and precipitation reflectivity contours for strike 3 at 22:33:50.0 GMT on June 17, 1980 (flight 80-019). Reflectivity data taken from NSSL Doppler radar at Norman, Okla., and interpolated to constant height of 4.5 km (14 800 ft).

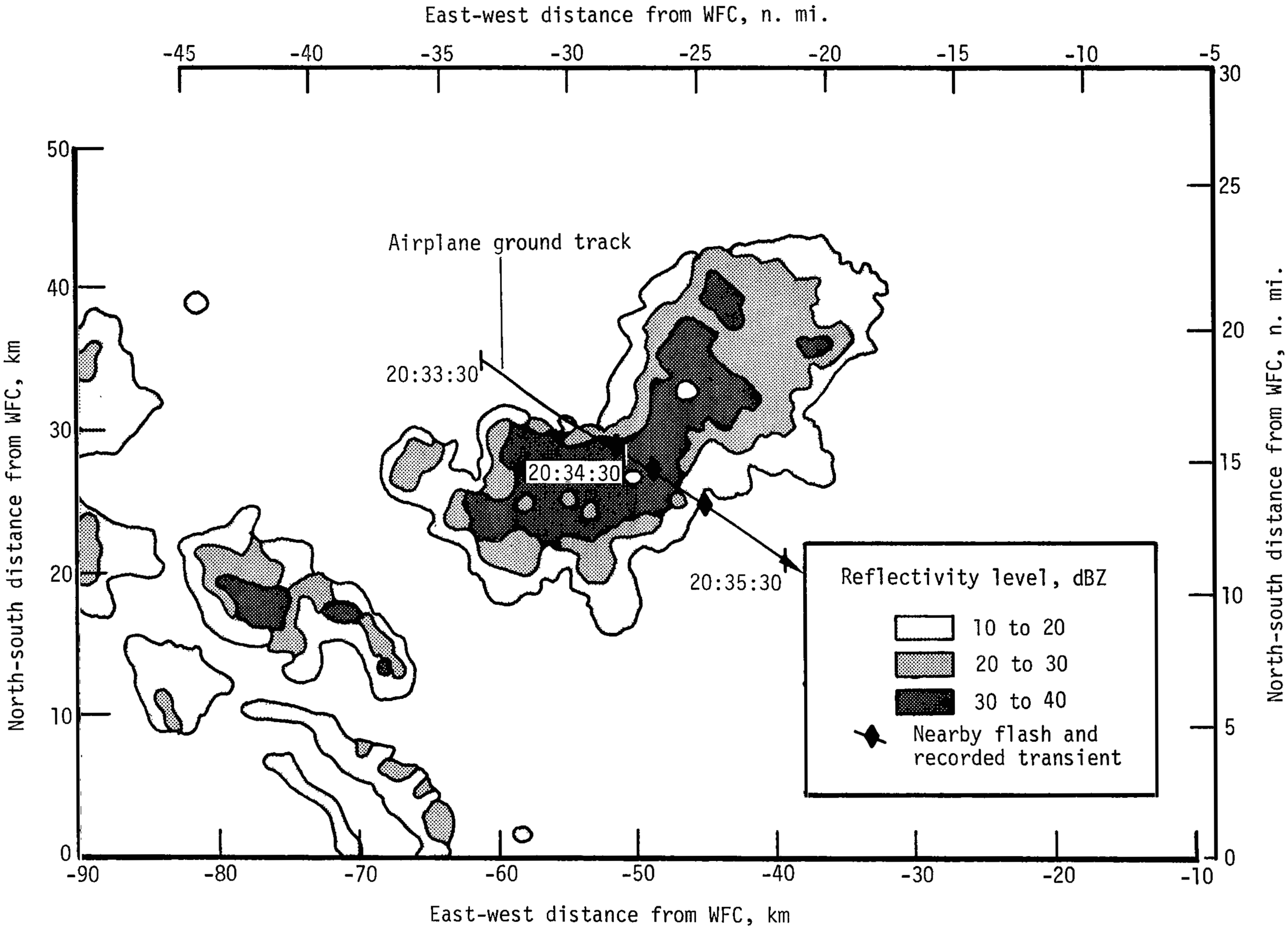


Figure 15.- Airplane ground track and precipitation reflectivity contours for nearby flashes 1-3 (20:34:28.5, 20:34:40.6, and 20:35:01 GMT), flight 80-023, July 22, 1980. Reflectivity data taken from NASA-Wallops SPANDAR radar at 20:31:57.3 GMT. Radar tilt angle = 0^{o}.

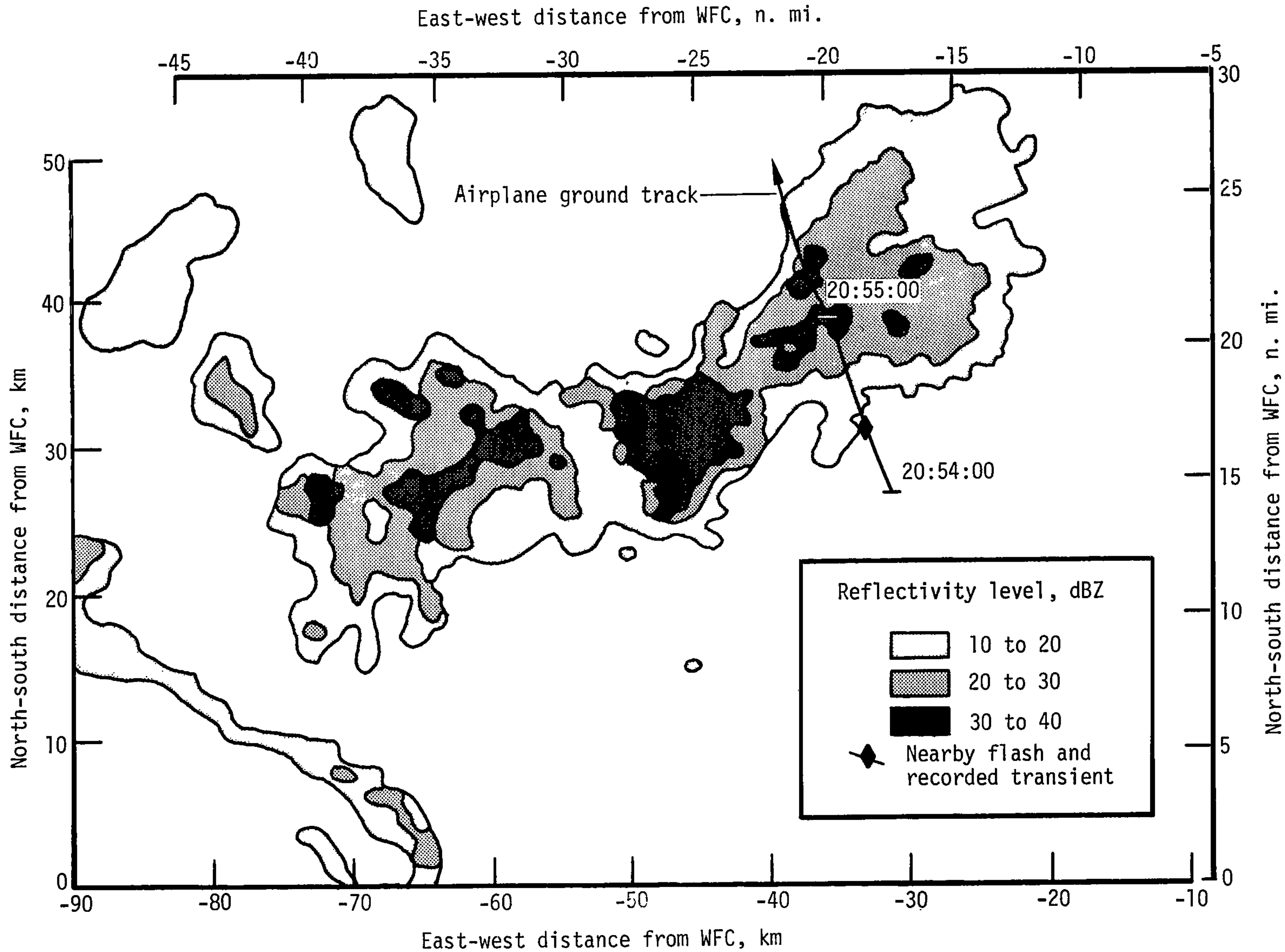


Figure 16.- Airplane ground track and precipitation reflectivity contours for nearby flash 4 (20:54:21.9 GMT), flight 80-023, July 22, 1980. Reflectivity data taken from NASA-Wallops SPANDAR radar at 20:56:51.5 GMT. Radar tilt angle = 0^o.

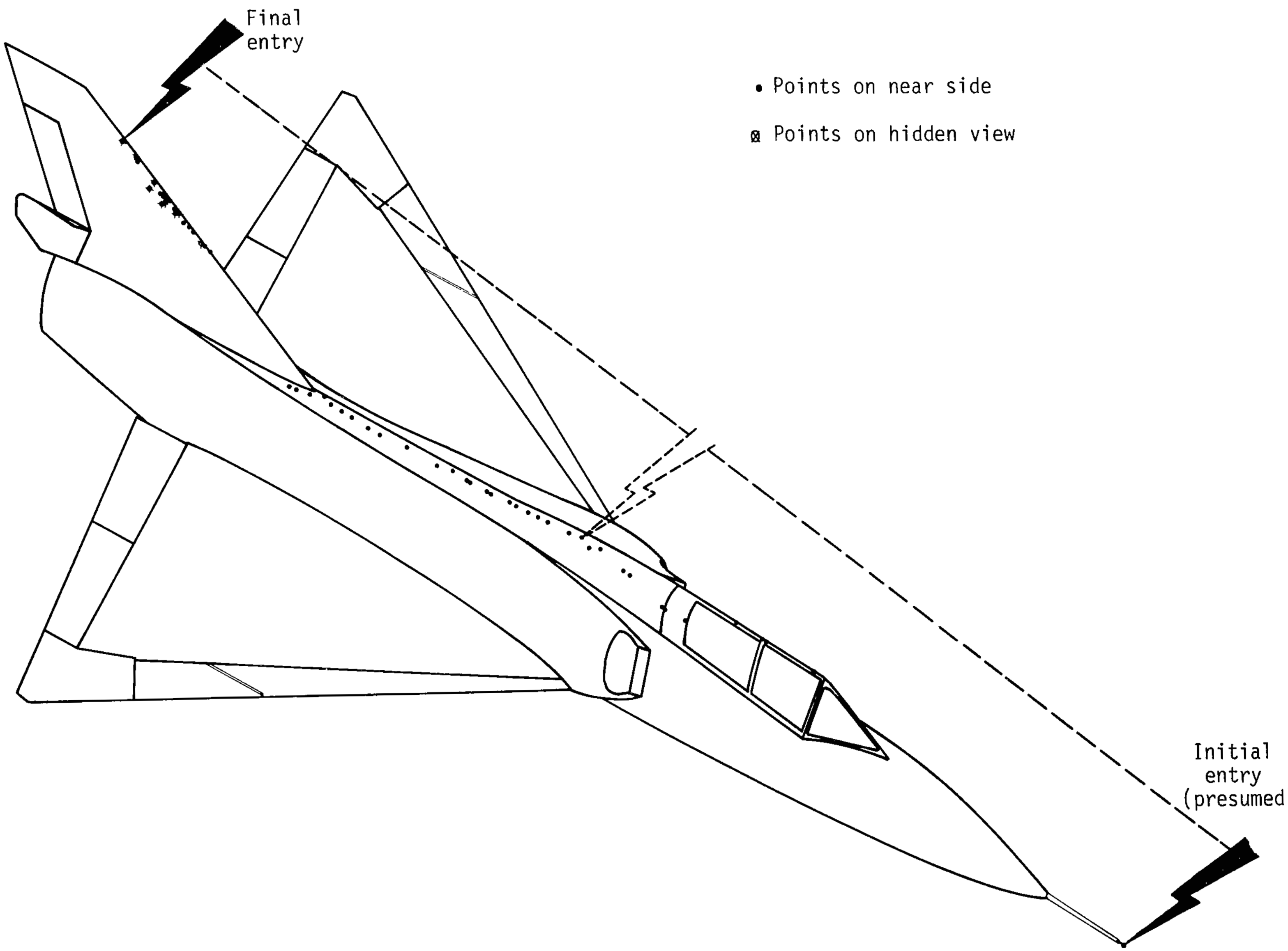


Figure 17.- Lightning attachment points for strike 4, flight 80-029, Aug. 12, 1980.
(No exit points found.)

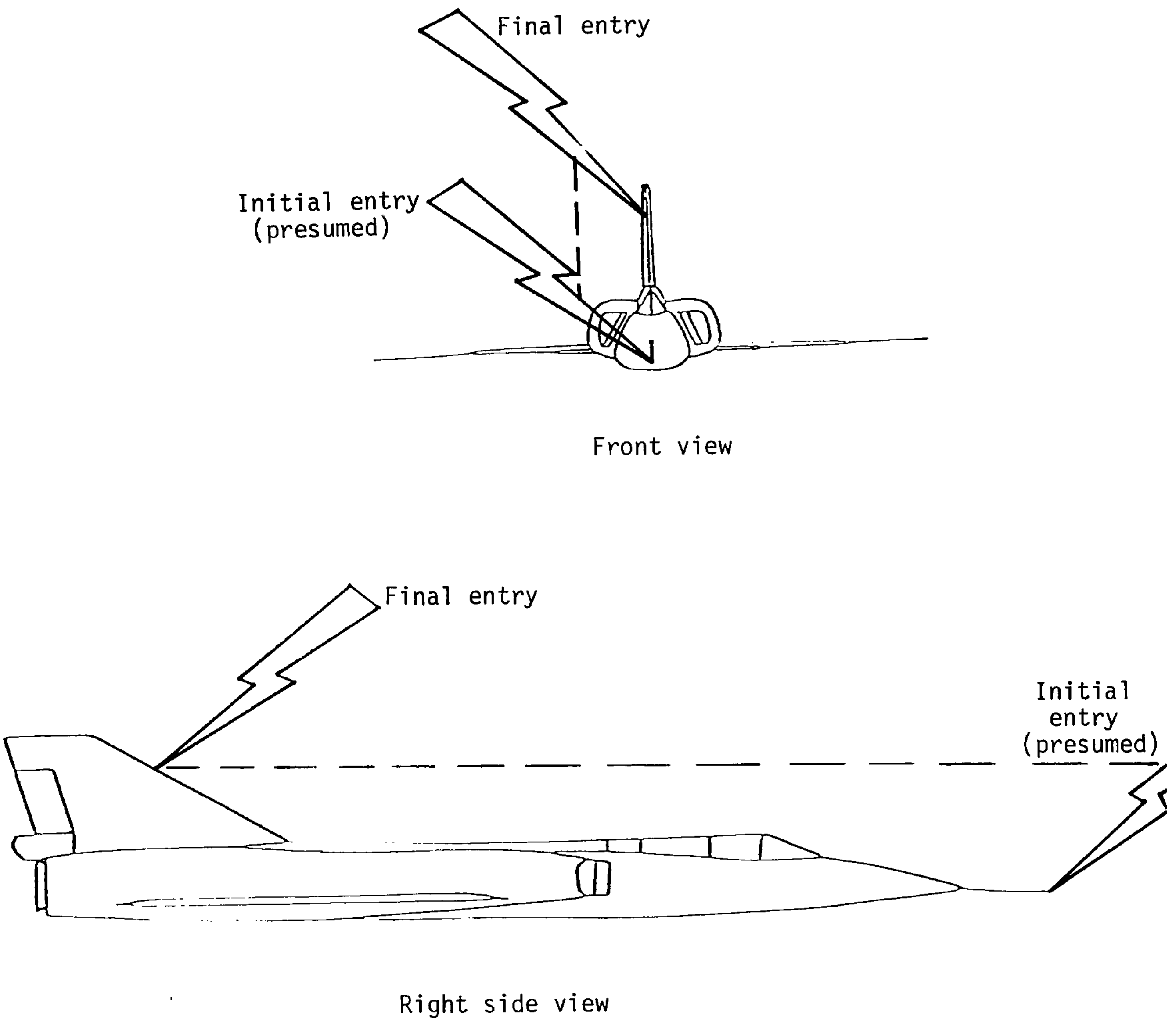


Figure 18.- Lightning strike scenario for strike 4, flight 80-029, Aug. 12, 1980.
(No exit points found.)

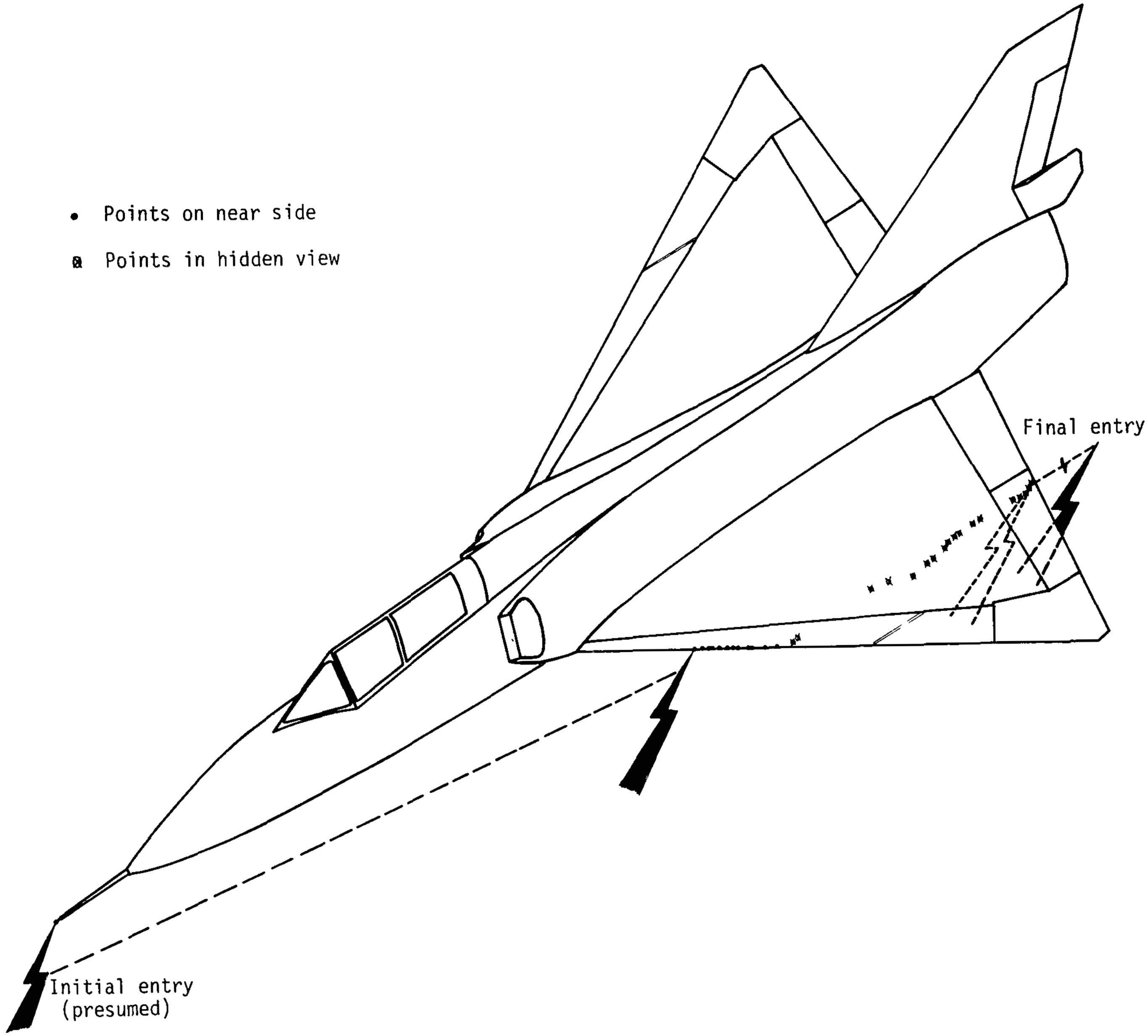
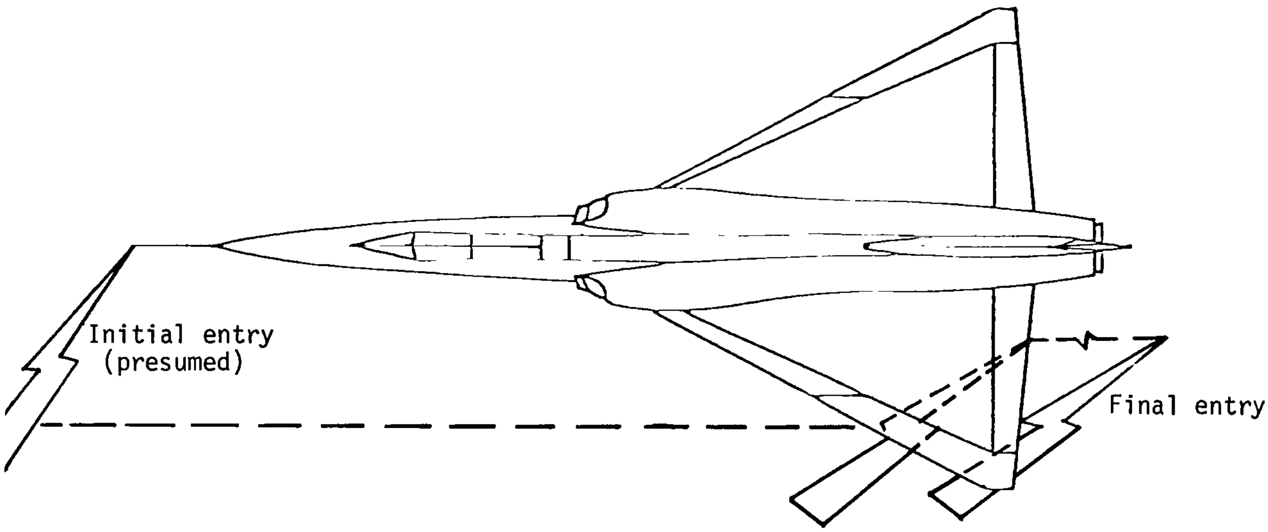
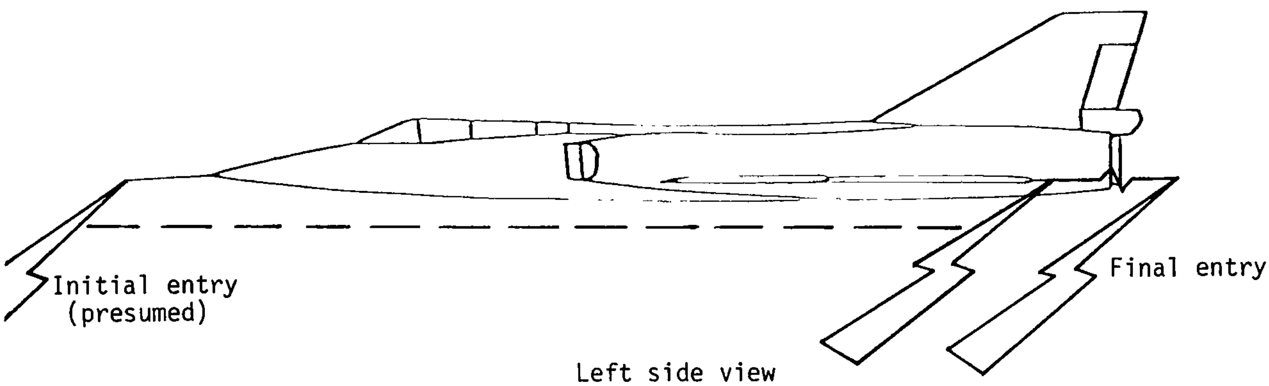


Figure 19.- Lightning attachment points for strike 5, flight 80-036, Sept. 1, 1980.
(No exit points found.)



Top view



Left side view

Figure 20.- Lightning strike scenario for strike 5, flight 80-036, Sept. 1, 1980.
(No exit points found.)

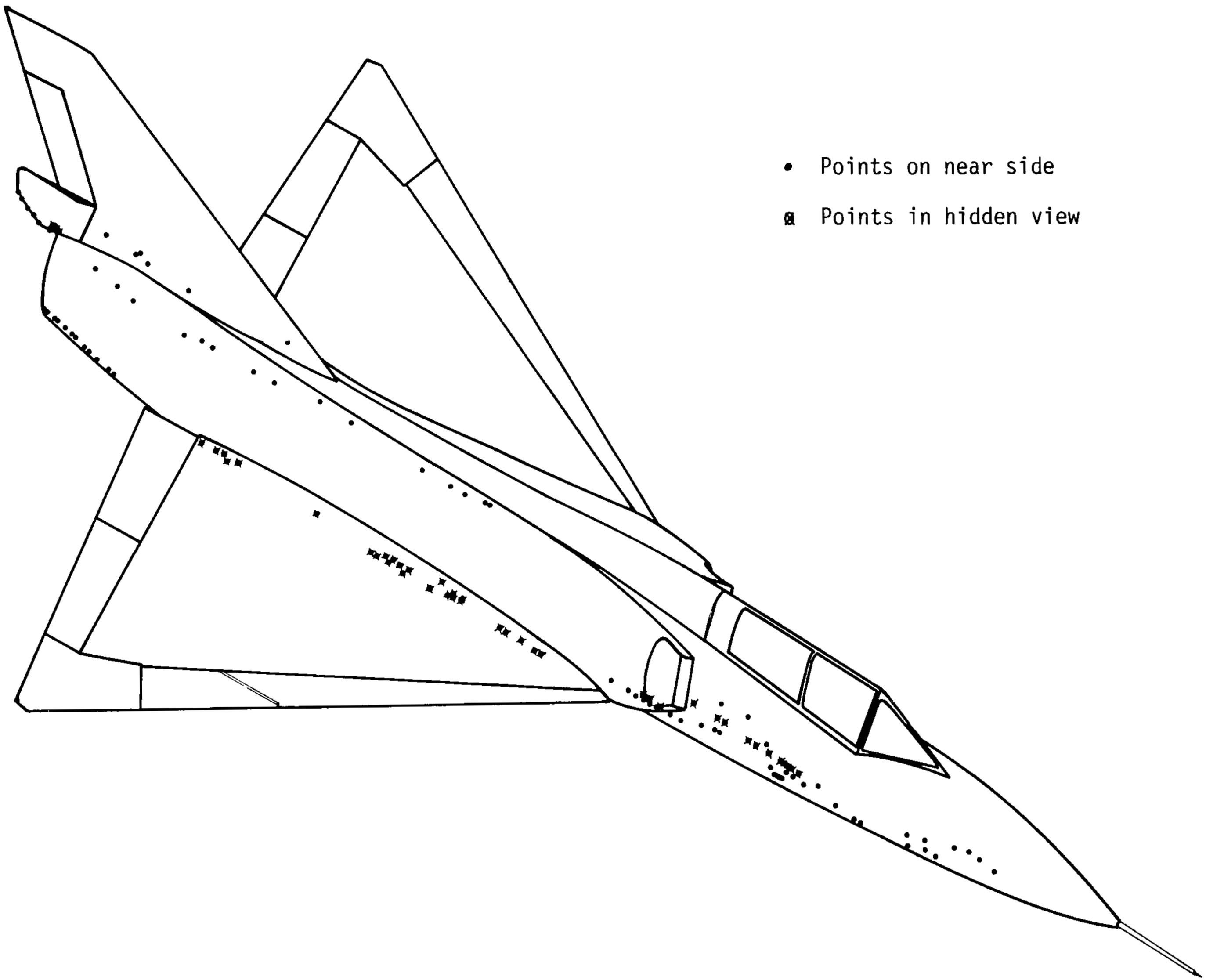


Figure 21.- Lightning attachment points for strikes 6 to 10, flight 80-038, Sept. 3, 1980.

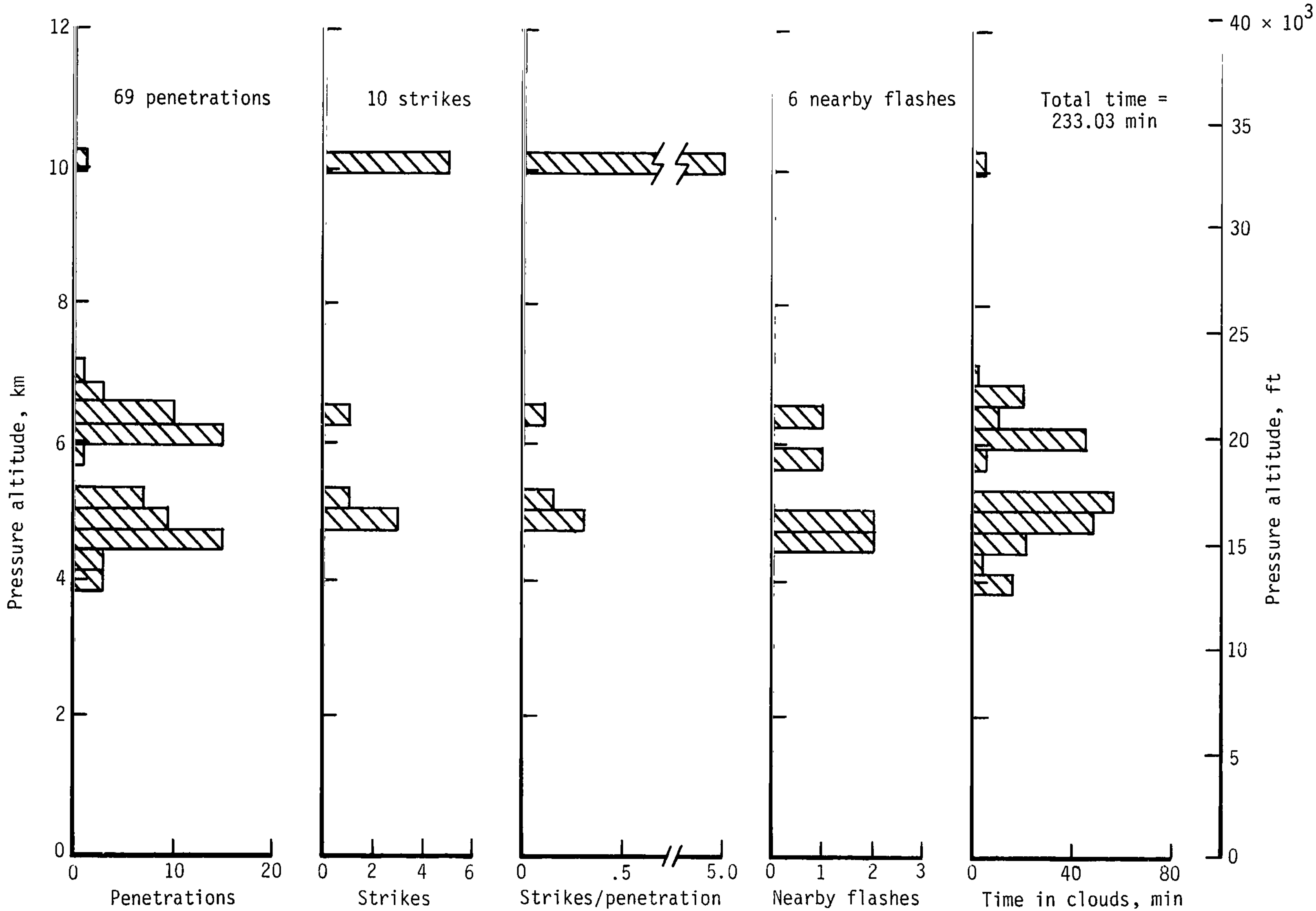


Figure 22.- Thunderstorm penetration and lightning statistics for Storm Hazards '80 Program.

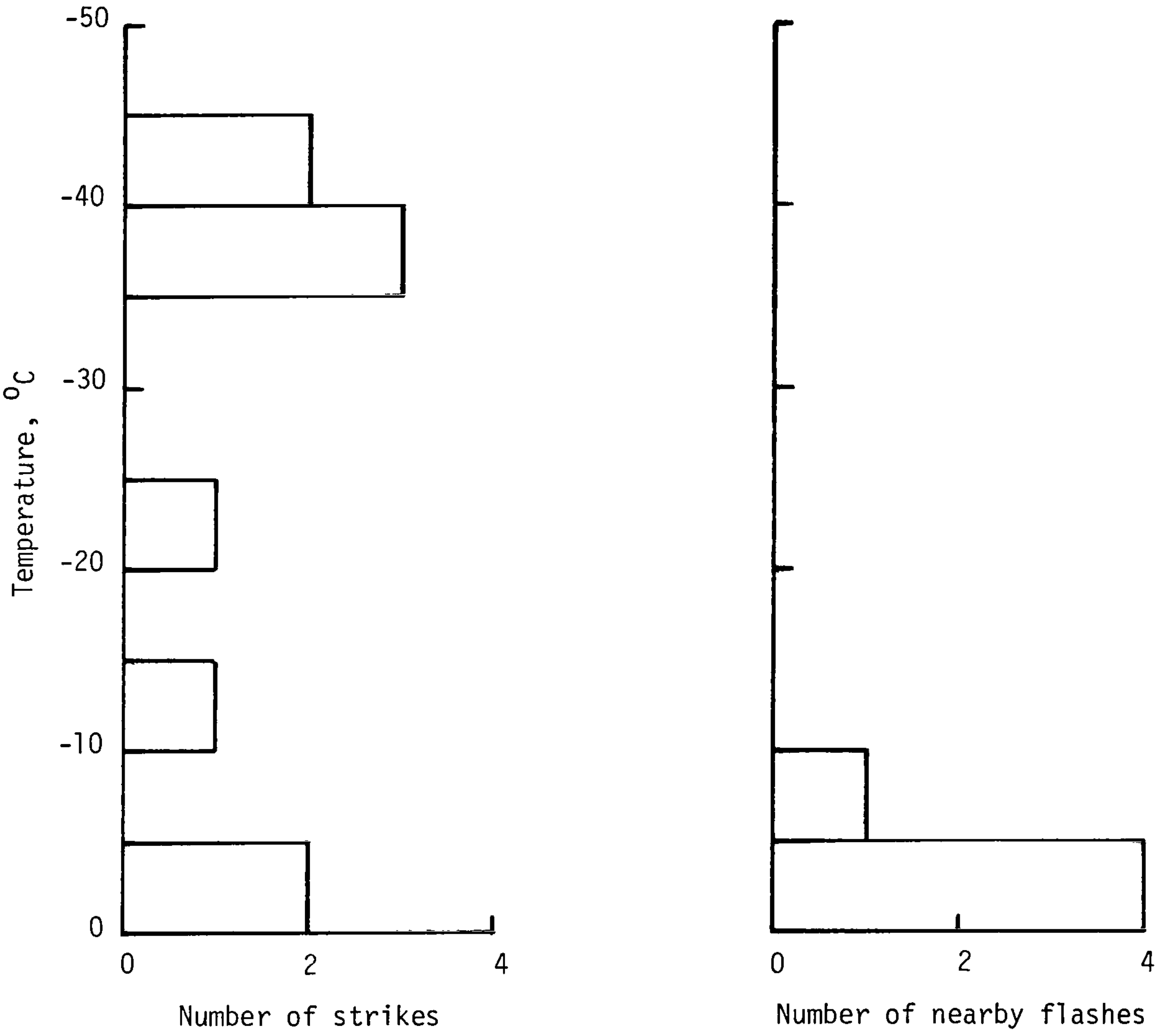


Figure 23.- Ambient temperature at which direct strikes and nearby flashes occurred during Storm Hazards '80 Program. (No temperature for one of each.)

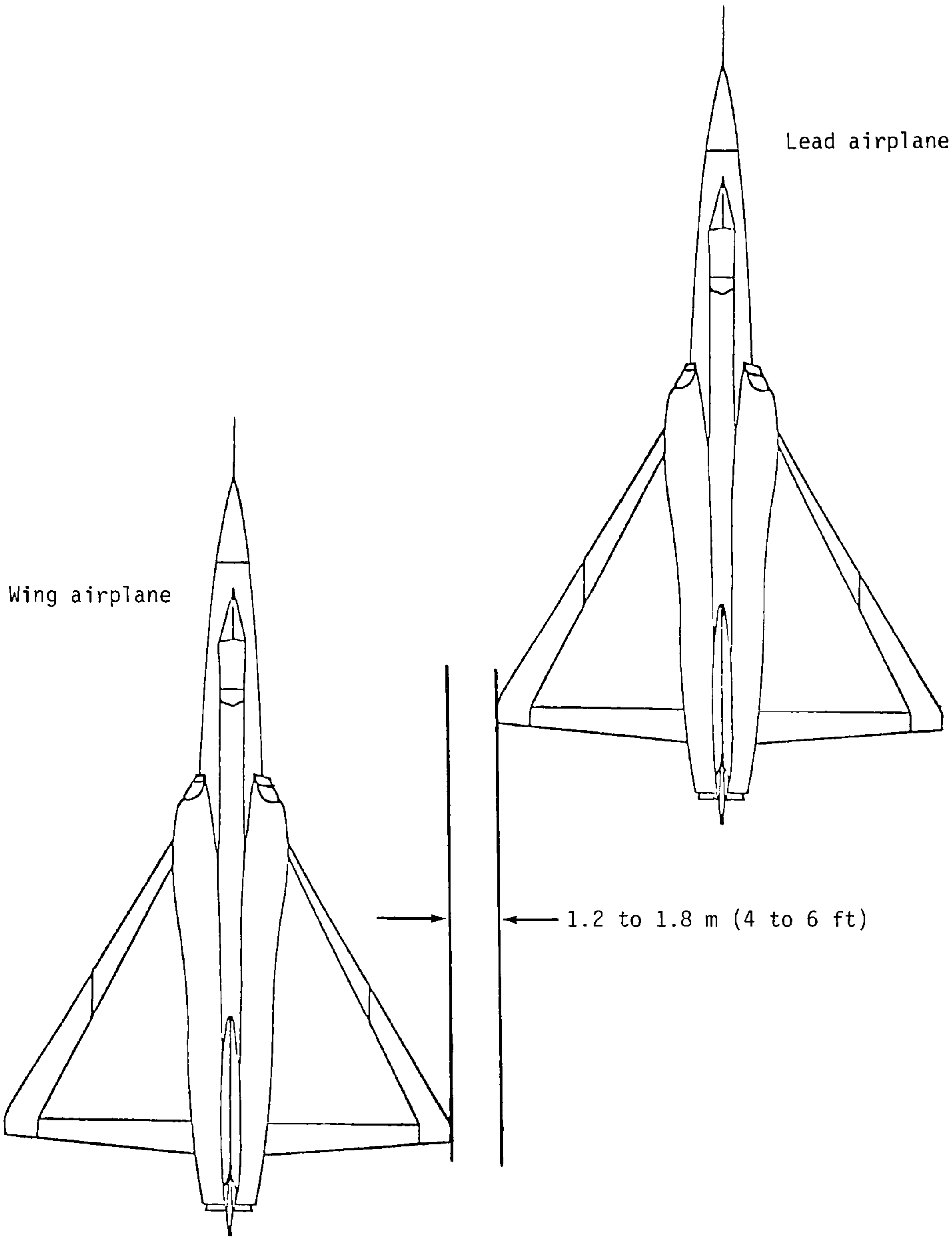


Figure 24.- Plan view showing relative location of two USAF F-106A airplanes at time of first lightning strike to formation.

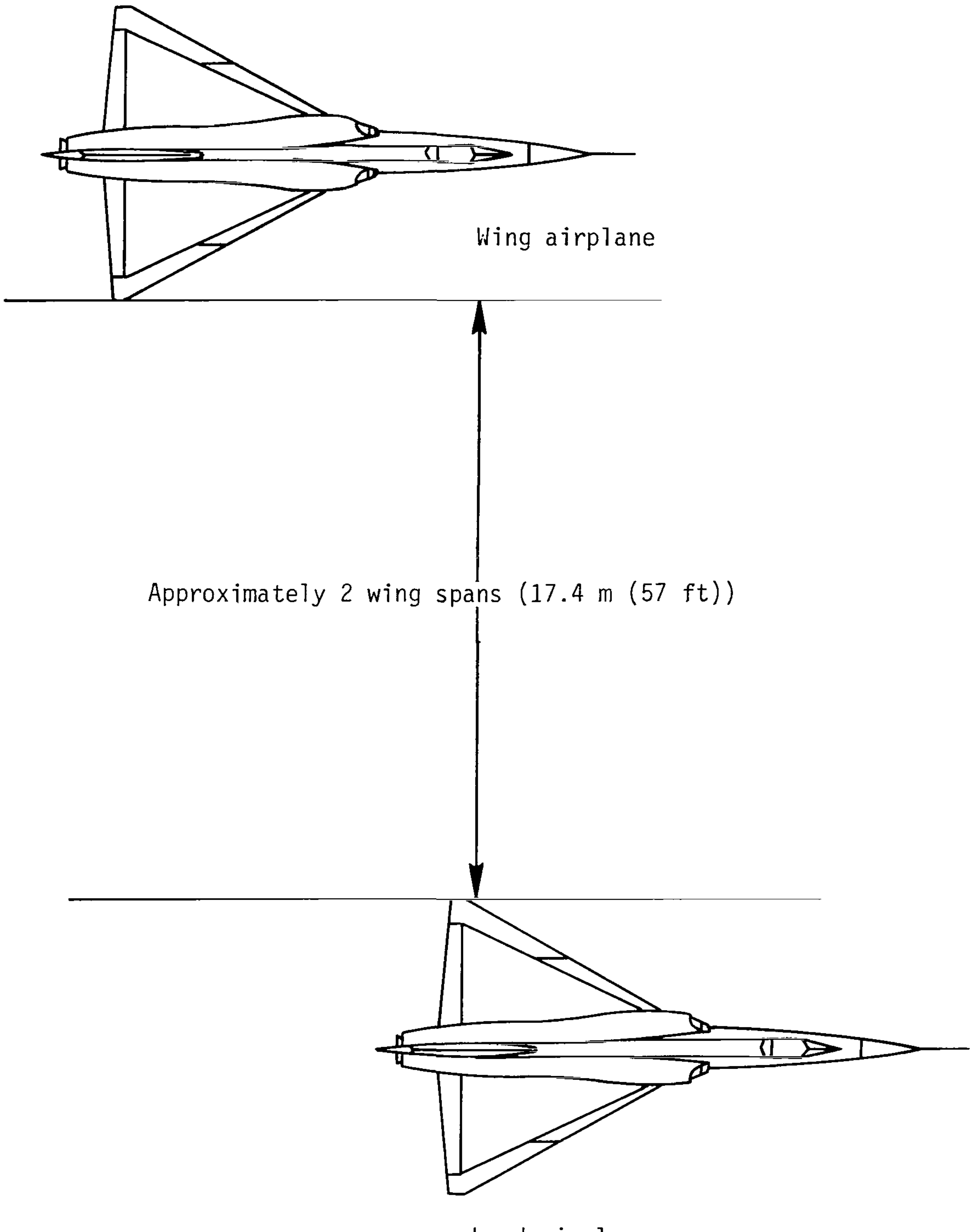


Figure 25.- Plan view showing relative location of two USAF F-106A airplanes at time of second lightning strike to formation.

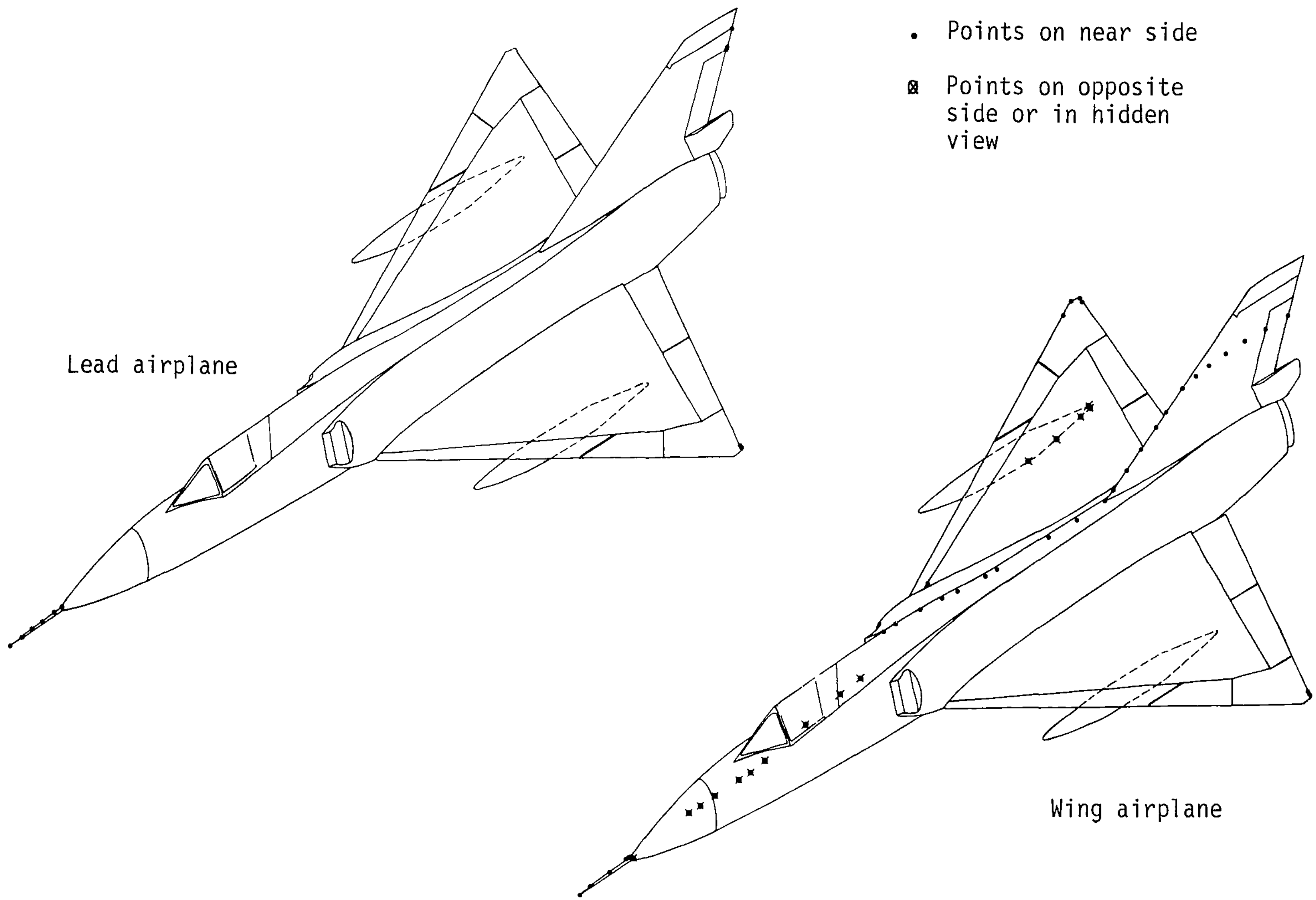


Figure 26.- Lightning attachment points found on two USAF F-106A airplanes following a pair of lightning strikes to the formation.

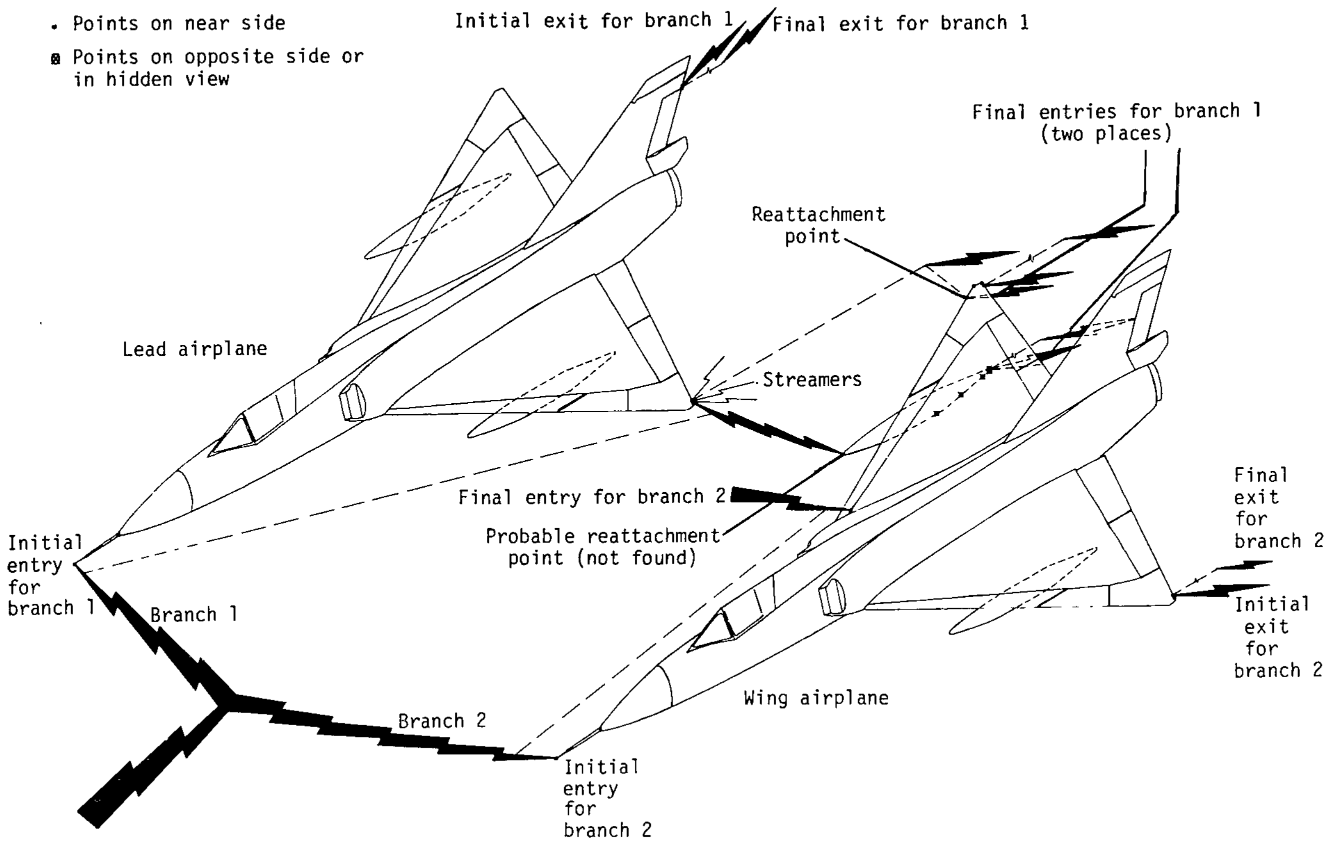


Figure 27.- Lightning strike scenario for first lightning strike to two USAF F-106A airplanes in close formation.

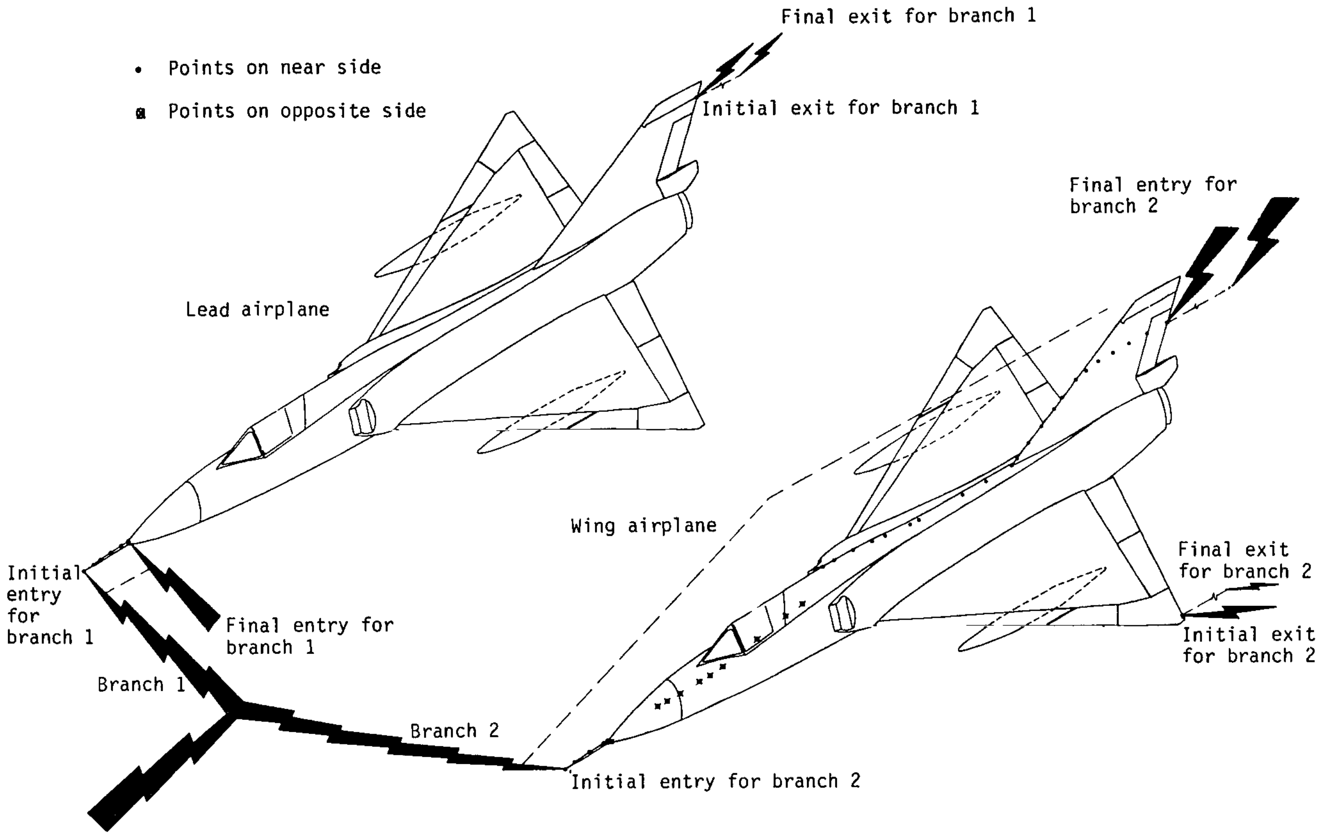


Figure 28.- Lightning strike scenario for second lightning strike to two USAF F-106A airplanes. A distance of two wing spans separate the airplanes.

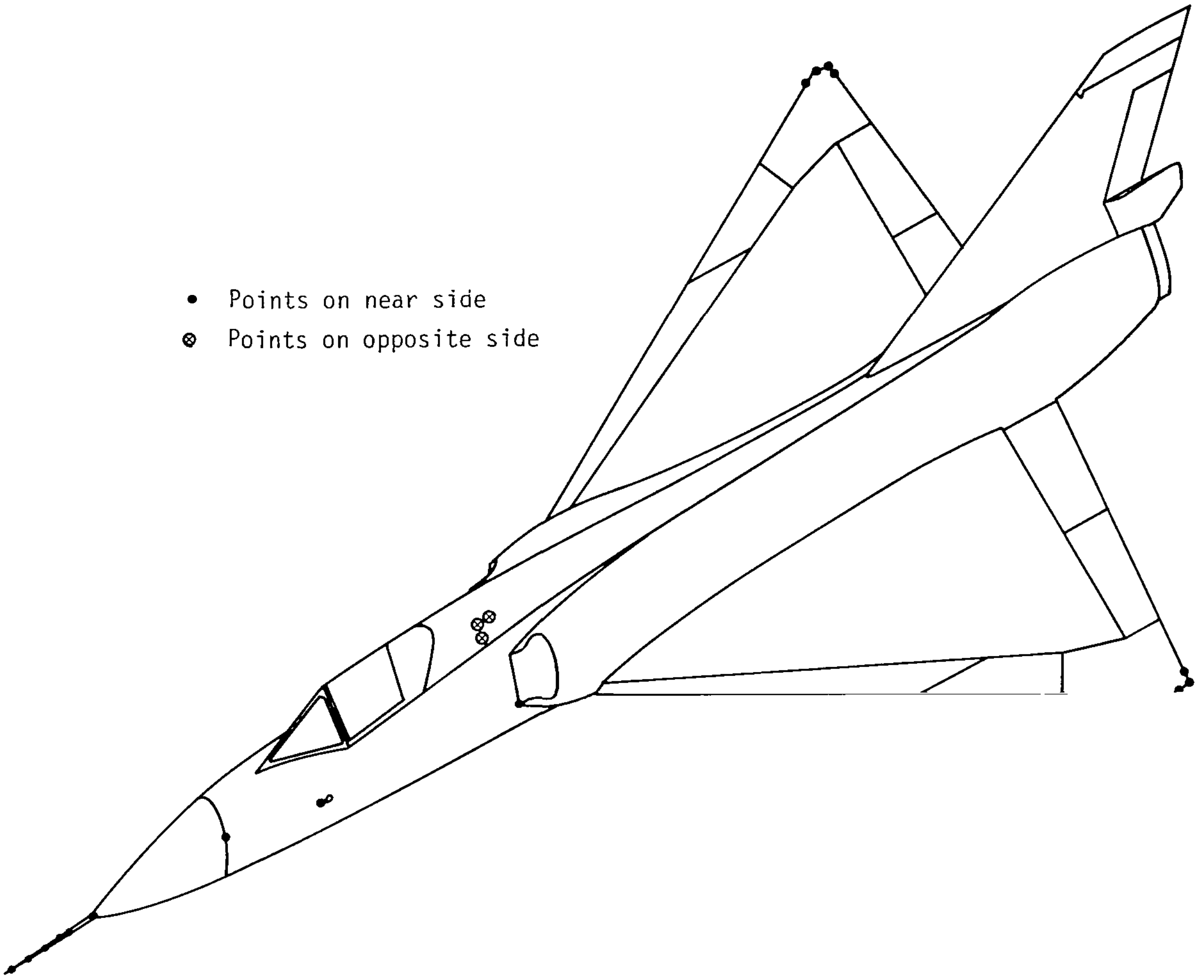


Figure 29.- Lightning attachment points found on USAF F-106A airplane following multiple strikes.

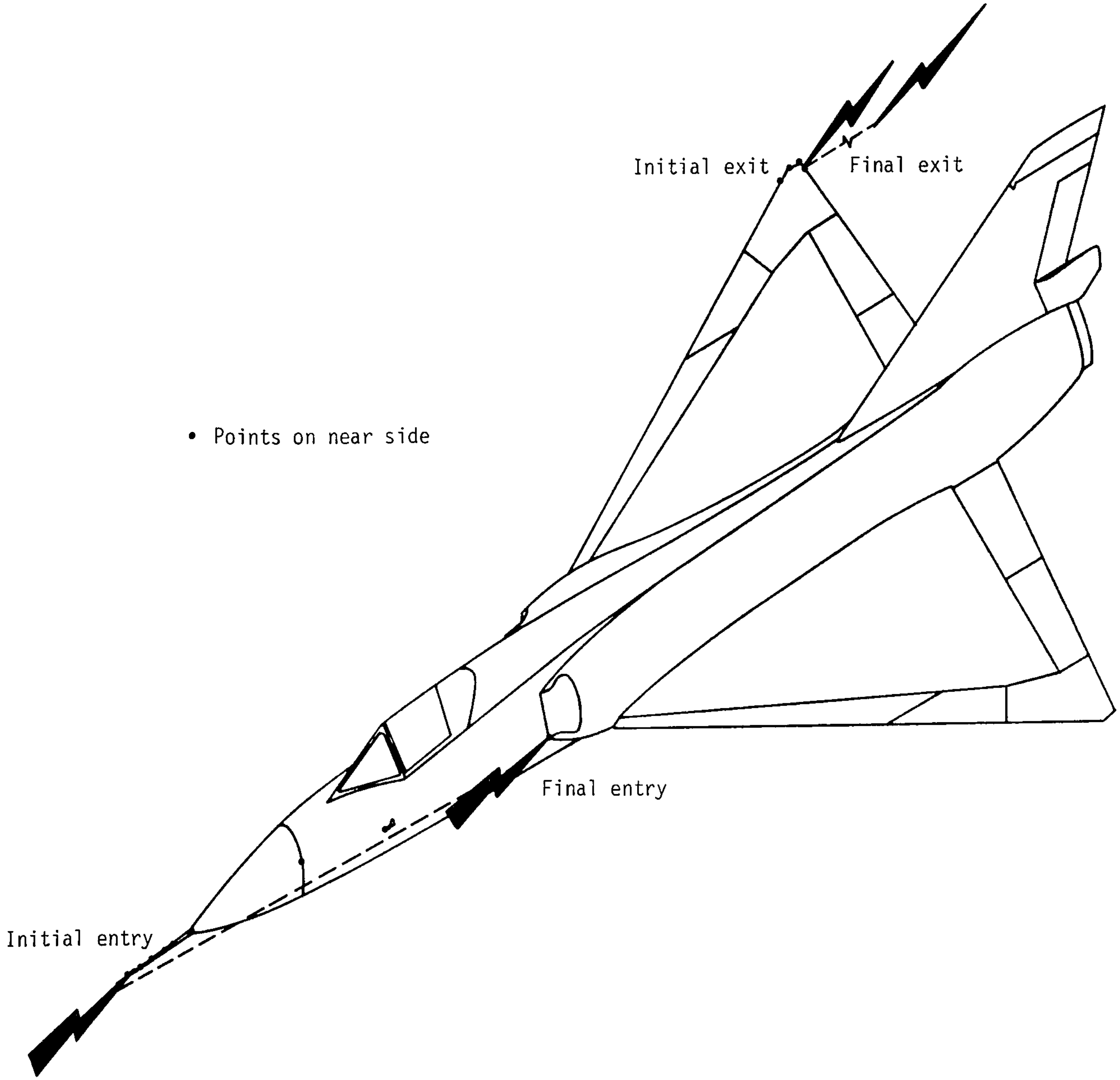


Figure 30.- Lightning attachment points ascribed to first strike of single USAF F-106A airplane.

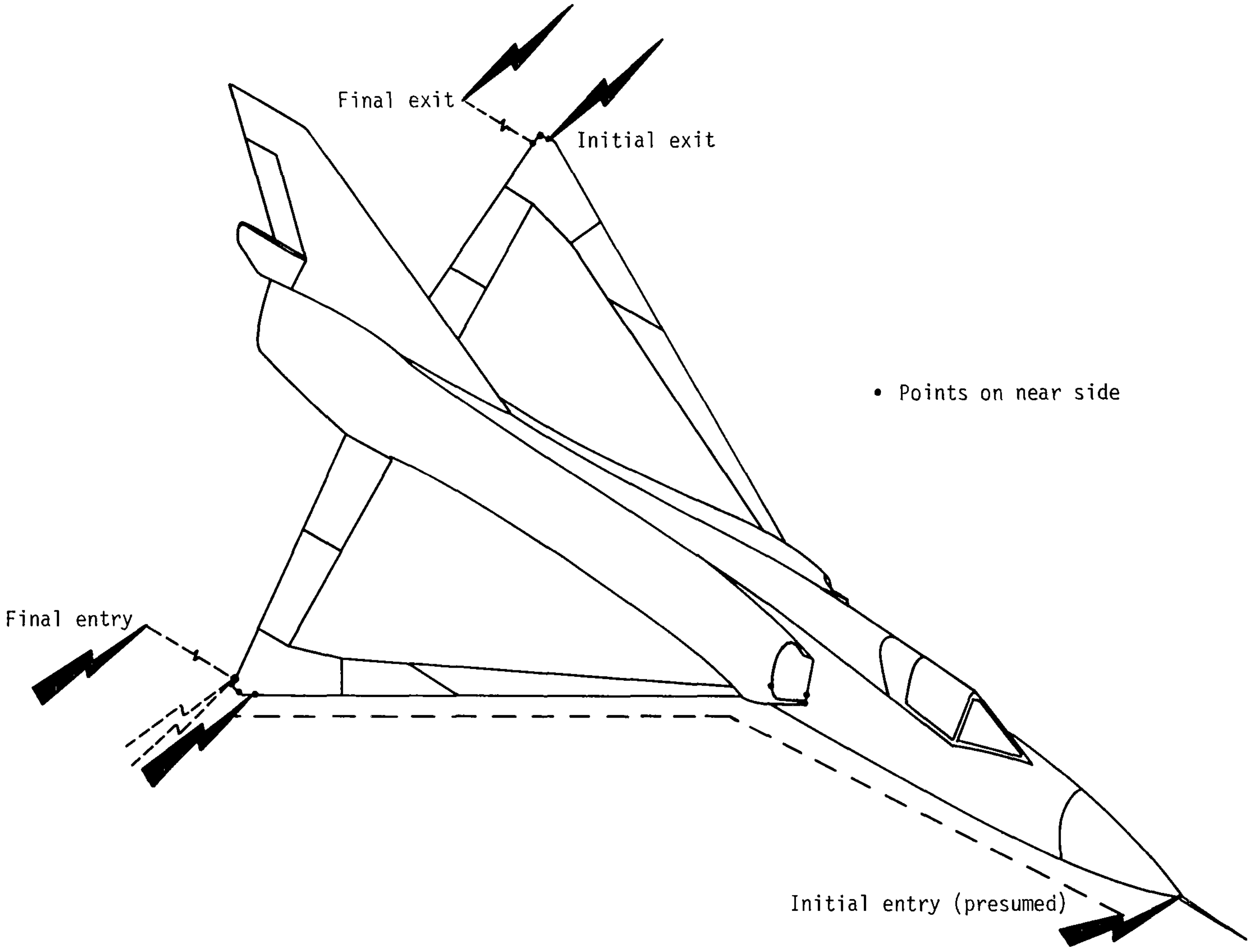


Figure 31.- Lightning attachment points ascribed to second strike of single USAF F-106A airplane.

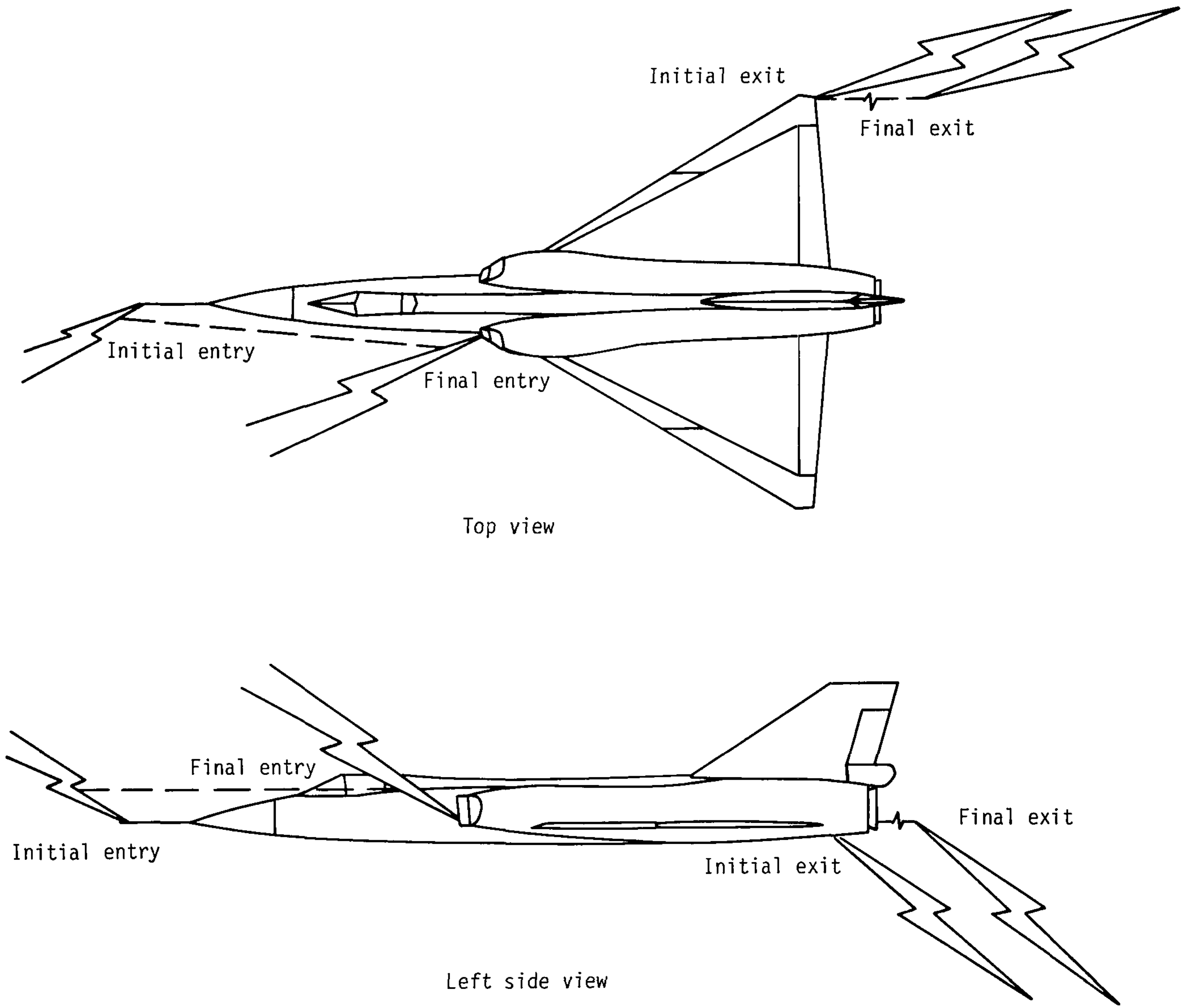


Figure 32.- Lightning strike scenario for first strike to single USAF F-106A airplane.

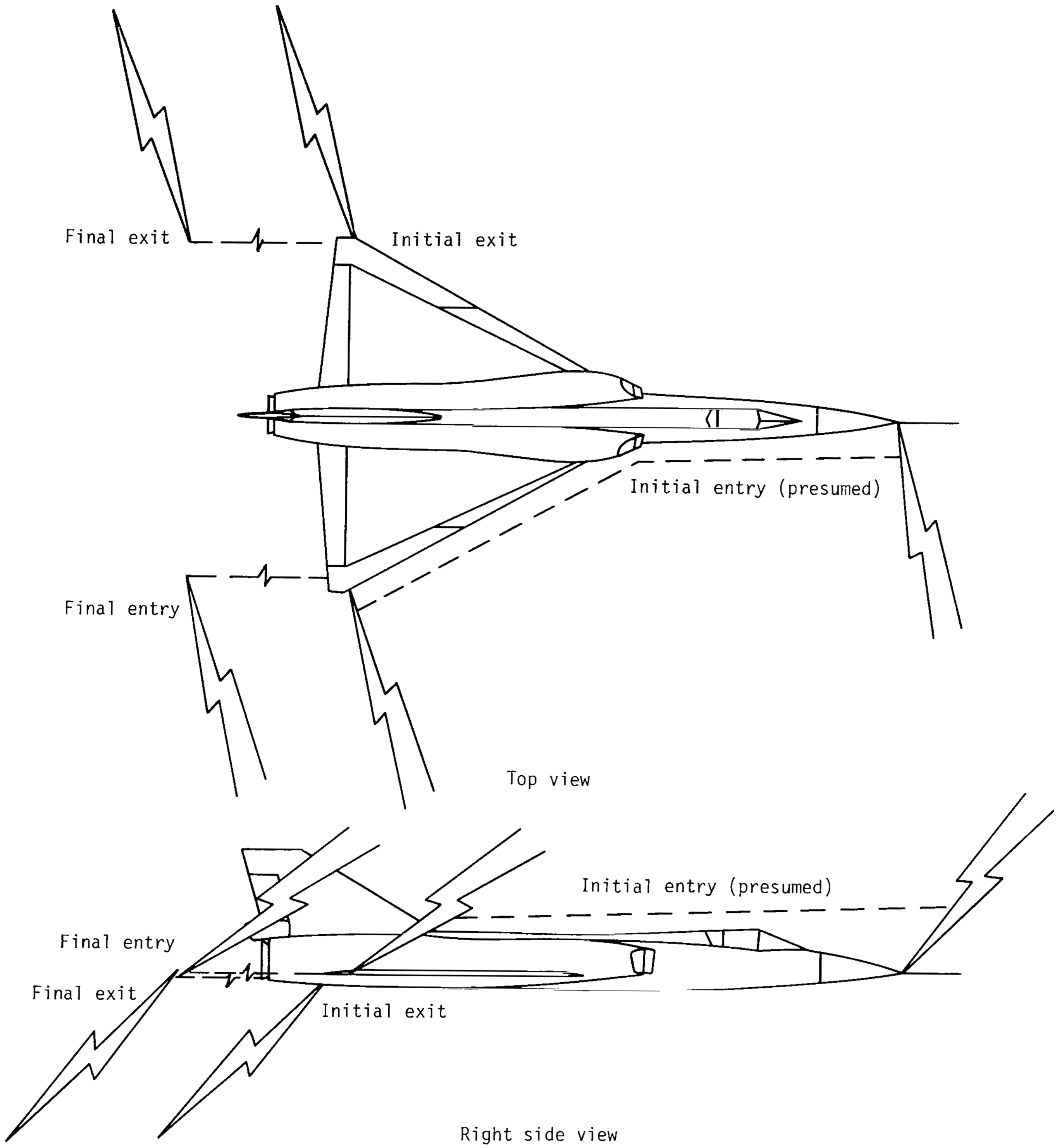


Figure 33.- Lightning strike scenario for second strike to single USAF F-106A airplane.

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15. Supplementary Notes

Bruce D. Fisher: Langley Research Center, Hampton, Virginia.
Gerald L. Keyser, Jr.: Air Force Systems Liaison Office, Langley Research Center, Hampton, Virginia.
Perry L. Deal: Langley Research Center, Hampton, Virginia.
Lightning scenarios developed with assistance of Lightning Technologies, Inc., under NASA Contract NAS1-15884.

16. Abstract

As part of the NASA Langley Research Center Storm Hazards Program, 69 thunderstorm penetrations were made in 1980 with an F-106B airplane in order to record direct-strike lightning data and the associated flight conditions. Ground-based weather radar measurements in conjunction with these penetrations were made by NOAA National Severe Storms Laboratory in Oklahoma and by NASA Wallops Flight Center in Virginia. In 1980, the airplane received 10 direct lightning strikes; in addition, lightning transient data were recorded from 6 nearby flashes. Following each flight, the airplane was thoroughly inspected for evidence of lightning attachment, and the individual lightning attachment points were plotted on isometric projections of the airplane to identify swept-flash patterns. This report presents pilot descriptions of the direct strikes to the airplane, shows the strike attachment patterns that were found, and discusses the implications of the patterns with respect to aircraft protection design. The flight conditions are also included. Finally, the lightning strike scenarios for three U.S. Air Force F-106A airplanes which were struck during routine operations are given in the appendix to this paper.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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