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MANAGING RISKS FROM LIGHTNING STRIKES TO AIRCRAFT

Bruce D. Fisher
NASA Langley Research Center
Hampton, VA 23665

and

J. Anderson Plumer
Lightning Technologies, Inc.
Pittsfield, MA 01201

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Bruce D. Fisher
NASA Langley Research Center
Mail Stop 247
Hampton, VA 23665-5225

and

J. Anderson Plumer
Lightning Technologies, Inc.
10 Downing Parkway
Pittsfield, MA 01201

ABSTRACT

The increasing use of composite materials and digital avionics promise aircraft of greater performance and efficiency than aircraft of the past. However, the use of these new technologies will compound lightning related problems on such aircraft. In addition, there is a common misconception that lightning location can be used to indicate the presence and location of other thunderstorm hazards to aircraft. This paper summarizes the findings of the NASA Langley Research Center Storm Hazards Program with respect to these issues. The Storm Hazards Program was conducted from 1978 to 1986 to improve the knowledge of the effects of some thunderstorm hazards on the design and operation of aircraft. During this program, nearly 1500 thunderstorm penetrations were made by a specially-instrumented and lightning-hardened F-106B "Delta Dart" airplane, during which the airplane experienced 714 direct lightning strikes. This paper reviews those thunderstorm environmental conditions found to be conducive to aircraft lightning strikes. In addition, the lightning-hardening procedures used on the NASA airplane are reviewed along with the lightning attachment patterns found on the exterior of the airplane. Finally, the NASA experience in using an airborne X-band weather radar and a lightning locator in and around thunderstorms is discussed.

INTRODUCTION

The risks from lightning strikes to aircraft can be managed by using the methods of in-flight avoidance and vehicle hardening. In the first method, the aircraft can be operated in such a way as to avoid thunderstorm and related conditions most conducive to aircraft lightning strikes. Unfortunately, lightning strikes occur to aircraft under some conditions which are not predictable or readily identifiable. These "non-thunderstorm" lightning strikes are not easily avoided. Therefore, avoidance, by itself, will not eliminate lightning-related hazards to flight safety. There also is a common misconception that lightning location can be used to indicate the presence and location of other thunderstorm hazards to aircraft.

In the second method, the aircraft is designed so as to minimize the adverse effects of the lightning strike on the vehicle and its systems. Although lightning is one of nature's most spectacular phenomena, it has not presented a significant threat to most aircraft flying today. Even though commercial aircraft experience approximately one direct strike every 3000 flight hours (ref. 1), the consequences are generally benign. The damage usually is confined to burn marks on the skin and at the trailing edges (refs. 1-3). The minimal amounts of damage experienced on many aircraft can be attributed to the widespread use of aluminum (an excellent electrical conductor) for the skins and primary structure, and the use of mechanical and hydraulic control systems, which are relatively immune to the adverse effects of lightning. However, complacency in the design of aircraft lightning protection is not warranted, as even in aircraft utilizing these traditional, proven design techniques, lightning catastrophes have occurred (refs. 3-5). In addition, many new aircraft designs will include the use of composite materials for primary aircraft structure and skins, and digital avionics for flight and engine controls and systems management. Although these new technologies promise improvements in aircraft performance and efficiency, their use will require that more specific lightning protection measures be incorporated in the design of new airframes and systems in order to maintain the excellent lightning safety record presently enjoyed by transport aircraft.

Significant insights into these lightning-related issues were made during the NASA Langley Research Center Storm Hazards Program, which was conducted to improve the state of the art of severe storm hazards detection and avoidance, as well as protection of aircraft against those hazards which cannot reasonably be avoided. In 1978, a commercially-available airborne lightning locator was flown on the periphery of thunderstorms in a NASA DHC-6 Twin Otter airplane (ref. 6). Following this preliminary phase, a specially-instrumented and lightning-hardened NASA F-106B airplane was flown through thunderstorms to elicit in-flight lightning strikes in order to quantify the electrical characteristics of in-flight lightning strikes, and to identify atmospheric conditions most conducive to such strikes. During the 1980-1986 thunderstorm seasons, the F-106B airplane made 1496 thunderstorm penetrations during which 714 direct lightning strikes were experienced. The flights of both aircraft were made in Oklahoma and Virginia in conjunction with ground-based guidance and measurements by the NOAA National Severe Storms Laboratory (NSSL) and the NASA Wallops Flight Facility, respectively. Starting in 1982, the UHF-band radar at NASA Wallops was used to direct the F-106B airplane to electrically-active

regions of the thunderstorms and to provide instrumental data used to determine if the lightning strikes were random encounters with naturally-occurring lightning channels or if the strikes were triggered by the airplane itself (refs. 7 and 8).

The purpose of this paper is to review those thunderstorm conditions found during the Storm Hazards Program to be conducive to aircraft lightning strikes. In addition, the lightning-hardening procedures used on the NASA F-106B airplane and the lightning attachment patterns found on the exterior of the airplane are reviewed with respect to their implications for aircraft lightning-safety design. Finally, the NASA experience in using an airborne X-band weather radar and a lightning locator in and around thunderstorms is discussed briefly in terms of hazards avoidance. The data in this paper update that previously presented to the Flight Safety Foundation (FSF) in reference 9, and expand on that presented to the FSF in references 10 and 11.

DESCRIPTION OF THE EXPERIMENT

DHC-6 Research Airplane

During the 1978 thunderstorm season, a commercially-available airborne lightning locator system was installed on a NASA DHC-6 "Twin Otter" airplane (figure 1) for flights on the periphery of thunderstorms. The airplane attitudes, airspeed, position and other flight conditions were measured by an onboard data system which included an Inertial Navigation System (INS). The onboard data system also recorded the lightning position data from the locator system. The airplane and its flight essential systems were inspected by a lightning safety specialist, and several lightning protection improvements were made to the airplane. Details on the DHC-6 airplane and its instrumentation may be found in reference 6.

F-106B Research Airplane

A thoroughly-instrumented and lightning-hardened NASA F-106B "Delta Dart" airplane (figure 2) was used to make thunderstorm penetrations starting in 1980 (ref. 12). The principal lightning hardening procedures, discussed in detail later in this paper and in reference 13, consisted of removing paint from most exterior surfaces of the airplane; installation of surge protective devices and electromagnetic shielding of electrical power and avionic systems; and, using JP-5 (or Jet A) fuel in lieu of the JP-4 (Jet B) fuel used in the U.S. Air Force F-106 fleet. Prior to each thunderstorm season, the lightning-hardening integrity was verified during ground tests 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 (ref. 13).

The airplane altitude, Mach number, attitudes, ambient temperature, position, and other flight conditions were measured by the Aircraft Instrumentation System (AIS) and the Inertial Navigation System (INS) (refs. 14 and 15). The direct-strike lightning instrumentation system (refs. 16-19) recorded electromagnetic waveforms from direct lightning strikes and nearby lightning flashes in flight using electromagnetic sensors located throughout the airplane and a shielded recording system located in the internal weapons bay.

The lightning attachments to the exterior of the airplane were filmed by combinations of eleven onboard cameras (refs. 9, 12, 20, and 21). In 1986, only eight cameras were used; the locations and fields of view of these eight cameras are shown in figure 3, and their characteristics are summarized in reference 12. These cameras were:

- one 16-mm movie camera mounted under a fairing on the left side of the fuselage, looking aft with a field of view including the left wing tip and vertical tail
- one black and white video camera installed in the cockpit between the pilot's ejection seat and the flight test engineer's forward instrument panel, facing aft with a field of view encompassing both wing tips
- one black and white video camera installed in the cockpit between the pilot's ejection seat and the flight test engineer's forward instrument panel facing forward with a field of view centered on the nose boom
- one black and white video camera installed in the air conditioner access compartment aft of the cockpit, facing upward with a 60° field of view (removed following installation of the wing tip video pod described below)
- two black and white video cameras installed in a pod mounted on the upper surface of the left wing tip with overlapping fields of view encompassing the airplane from just ahead of the nose boom to the trailing upper apex of the vertical fin cap
- three 70-mm still cameras installed on the same platform as the cockpit video cameras, with two cameras facing forward to provide a stereo pair, and one camera facing aft with the same field of view as the cockpit-mounted aft-facing video camera.

In addition, the airplane was equipped with a commercially-available X-band color digital weather radar. At NASA request, the receiver-transmitter unit was modified to contour the color green for precipitation reflectivity values of 30-40 dBZ; the color yellow for values of 40-50 dBZ; and the color red for values of 50 dBZ and above. These values are 10 dBZ higher than those used in the production models (e.g., the color green for values of 20-30 dBZ). From 1980-1984, the radar system consisted of a master display unit in the front cockpit for use by the research pilot with two slave units: one slave unit was located in the aft cockpit for use by the flight test engineer; and the second slave unit located in a video photopanel. In 1985 and 1986, the digital video stream from the master unit was recorded directly on a video cassette recorder, and the photopanel was eliminated.

Finally, the commercially-available airborne lightning locator system used earlier on the DHC-6

airplane was transferred to the F-106B airplane for use in real time by the crew. The digital recording technique used on the DHC-6 airplane was not used in the F-106B airplane.

Ground-Based Support

NOAA National Severe Storms Laboratory.- For the research flights in Oklahoma in 1979 with the DHC-6 airplane, and in 1980 and 1981 with the F-106B airplane, the NOAA-NSSL Doppler radar at Norman, OK was used to measure the precipitation reflectivity data (ref. 22) and wind velocity data (ref. 15). Additionally, an incoherent 10-cm wavelength surveillance radar (ref. 22) was used to provide air traffic control guidance to the airplane.

NASA Wallops Atmospheric Sciences Research Facility.- During storm penetrations in Virginia, the UHF band (70.5-cm wavelength) and S-band (10-cm wavelength) radars at the NASA Goddard Space Flight Center/ Wallops Flight Facility were used to locate lightning flashes, and to determine precipitation reflectivity, respectively. The specifications for these radars are given in reference 7. Each of these radars had the capability of airplane tracking ("slaving") via inputs from a third radar which tracked a C-band transponder mounted on the airplane. Descriptions of all of the systems used at NASA Wallops in support of the Storm Hazards missions are given in reference 23.

NASA Langley Flight Service Station.- For those missions which occurred in Virginia, the primary responsibility to launch and recall the airplane, select the storms and altitudes of interest, and provide real-time flight support and guidance to the aircrew was assigned to the Storm Hazards project personnel located in a dedicated area of the NASA Langley Flight Service Station. The NASA Langley personnel worked in concert with their counterparts at NASA Wallops, with real-time discussions of radar data and flight strategy taking place over a dedicated telephone line between the two sites. Personnel at both sites could communicate with the flight crew via radio. Generally, the airplanes were flown within 150 n.mi. of NASA Langley to maintain line of sight communications with NASA Langley and NASA Wallops.

The equipment installed at NASA Langley to support the mission evolved until it included communications systems, lightning detection systems, time displays, and an integrated video display which tied much of these data together. These systems and the integrated video display are described in references 9 and 24.

By using the integrated video display system, it was possible for the NASA Langley personnel to better utilize the NASA Wallops data in recommending safe headings to thunderstorm targets of interest. In fact, the display allowed the NASA Langley staff to independently support flights when NASA Wallops support was not available.

Thunderstorm Penetration Procedures

Guidance to the F-106B airplane in Virginia was based on observations of storm structures and of lightning flash distribution with the NASA-Wallops S-band and UHF-band radars, respectively (refs. 7 and 8). During a thunderstorm penetration, the F-106B airplane was tracked by a C-band radar to which the UHF-band radar was "slaved," so that lightning echoes from nearby flashes and direct strikes to the airplane were obtained with the UHF-band radar. Immediately after the penetration, while the airplane was turning for a new penetration, several horizontal and vertical scans of the storm were conducted with the S-band radar. Because of the lack of time for an extensive series of scans between penetrations, the radial penetrations to and from the S-band radar were preferred for study of the storm structure.

In addition to the ground-based guidance from NASA Langley and NASA Wallops, the pilots also used data from an onboard X-band digital weather radar to adjust the airplane heading so that the airplane flight path would not cross any precipitation reflectivity contour of 50 dBZ or higher, nor pass within 10 miles of the downwind edge of the 50 dBZ contour in order to avoid hail. Prior to each penetration, the pilot and the personnel on the ground selected an escape heading to be used in the event that the airplane had to terminate a penetration and rapidly depart the storm. The research pilot always had the final decision on penetration and continuation of the flight. The thunderstorm penetration techniques used in Virginia were developed using the NOAA-NSSL guidelines used successfully in the U.S. Air Force Rough Rider Program and with the NASA F-106B airplane in 1980 and 1981. During the 1984 thunderstorm season, joint thunderstorm operations were made with the FAA/USAF Convair 580 thunderstorm research airplane. The techniques used for the joint operations are described in reference 24.

RISK MANAGEMENT

Avoidance

Flight conditions conducive to aircraft lightning strikes.- The number of missions, thunderstorm penetrations, direct strikes to the aircraft and nearby flashes (lightning channels close enough to the airplane to trigger the onboard lightning instrumentation without actually attaching to the airplane) for the Storm Hazards 1980-1986 seasons are summarized by year in table 1. The data show that the 184 thunderstorm research missions resulted in 714 direct lightning strikes and 188 nearby flashes during 1496 penetrations.

Histograms showing the number and durations of penetrations, and the number of strikes and nearby flashes experienced from 1980-1986 are shown for altitude intervals of 2000 ft in figure 6, and for ambient temperature intervals of 5°C in figure 5. Penetrations were made by the F-106B airplane at pressure altitudes ranging from 2400 ft to 40 000 ft with a mean penetration altitude of 22 900 ft (figure 4). Temperature data (mean value during the penetration) were available for 1368 penetrations, with values ranging from 20°C

to −60°C, with an overall mean value of −19°C (figure 5). The distributions of penetration duration time with altitude and ambient temperature are very similar to the corresponding penetration distributions.

A plot of lightning strike incidents as a function of altitude for commercial aircraft in routine operations is shown in figure 6 (from ref. 2 with updated data from ref. 1). Based on data such as that shown in figure 6, most penetrations in the 1980 and 1981 seasons were made at altitudes corresponding to ambient temperatures between ±10°C in expectation of receiving a large number of strikes. However, very few strikes were experienced (see table 1 and refs. 25 and 26). Starting in 1982, the NASA Wallops UHF-band radar was used to guide the F-106B airplane through the upper electrically-active regions of thunderstorms (see refs. 7 and 27), resulting in hundreds of high altitude direct lightning strikes (table 1 and refs. 7, 14, and 20). Starting in the 1984 season, the UHF-band radar was used to provide guidance to electrically-active regions in thunderstorms at altitudes below 20 000 ft (ref. 8), the same range of altitudes studied previously in 1980 and 1981. The low altitude research efforts of 1980-81 and 1984-86 are shown in the low altitude/warm temperature peaks in the penetration and duration data in figures 4 and 5.

The Storm Hazards Program strike statistics shown in figures 4 and 5 differ significantly from the published strike data for commercial aircraft (refs. 1 and 2 - see figure 6) and for U.S. Air Force aircraft (ref. 3), in which most lightning strikes were found to occur between ambient temperatures of ±10°C. In the Storm Hazards Program, direct strikes were experienced at pressure altitudes ranging from 14 000 ft to 40 000 ft with a mean value of 29 600 ft (figure 4). The corresponding ambient temperature values ranged from 5°C to −65°C, with a mean value of −30°C (figure 5). The nearby flash data are very similar to the direct strike data.

Despite spending approximately 1559 mins of penetration duration time at altitudes below 20 000 ft (37 percent), only 98 direct strikes were experienced (14 percent) (see table 1). In fact, the peak strike rates in figure 4 of 7 strikes/penetration and 1.4 strikes/min occurred at pressure altitudes between 38 000 ft and 40 000 ft corresponding to ambient temperatures colder than −40°C. (During one research flight through a thunderstorm anvil at 38 000 ft altitude in 1984, the F-106B airplane experienced 72 direct strikes in 45 mins of penetration time, with the instantaneous strike rate twice reaching a value of 9 strikes/min.) On the other hand, the peak strike rate near the freezing level (0°C) was only 0.1 strike/min (in the altitude interval between 18 000 ft and 20 000 ft, corresponding to ambient temperatures of −5°C to −10°C).

The NASA Storm Hazards pressure and temperature lightning strike statistics differ from the commercial and U.S. Air Force data for two reasons. First, the NASA data came solely from intentional thunderstorm penetrations, while the commercial and military data were derived from a variety of meteorological conditions, mostly in "nonstormy" clouds. For example, some of the commercial airline strikes were reported in snow storms or in winter time nimbostratus clouds (ref. 1). U.S. Air Force aircraft have reported lightning strikes in cirrus clouds downwind of previous thunderstorm activity, in cumulus clouds around the periphery of thunderstorms, and even in stratiform clouds and light rain showers not associated with thunderstorms (ref. 28). (The NASA Storm Hazards Program did not study the non-thunderstorm lightning strike phenomenon.) Second, commercial and military aircraft will normally deviate from course to avoid thunderstorms which reach cruise altitudes, and only penetrate when required to do so in the terminal area, where typical assigned altitudes are near the freezing level. Therefore, the NASA distributions of lightning strikes with respect to pressure altitude and ambient temperature differ from the commercial/military data because of the higher percentage of time spent by the NASA F-106B research airplane in the upper flash density center of thunderstorms, compared with the low percentage of time spent in thunderstorms at those altitudes by aircraft in routine operations. However, lightning strikes have been encountered at nearly all temperatures and altitudes in the Storm Hazards Program, indicating that there is no altitude at which aircraft are immune from the possibility of a lightning strike in a thunderstorm.

Although these Storm Hazards data differ from the commercial/military data, there is strong agreement with the results of two other thunderstorm flight test programs. The high altitude strike data are in good agreement with the results of the U.S. Air Force Rough Rider Program (ref. 29), in which the peak lightning activity was found to occur at an ambient temperature of −40°C. In addition, the low altitude strike data are nearly identical to the data from the USAF/FAA Convair 580 low altitude lightning measurement program (ref. 30), in which 63 percent of the 21 strikes experienced by that airplane occurred at an altitude of 18 000 ft, although only 16 percent of the flying time was spent at that altitude.

The most successful piloting technique used in searching for lightning was to fly through the thunderstorm cells which were the best defined visually and on the airborne weather radar. Frequently, heavy turbulence and precipitation were encountered during these penetrations. However, the lightning strikes rarely occurred in the heaviest turbulence and precipitation, and occasionally, there was no lightning activity whatsoever. These findings are shown in figure 7, in which the percentage of direct strikes to the F-106B airplane is plotted as a function of the flight crew's opinion of relative turbulence and precipitation intensity at the time of the strikes. The data are plotted for those strikes which occurred above and below 20 000 ft altitude. In both altitude regimes, most lightning strikes (approximately 80 percent) occurred in thunderstorm regions in which the crews characterized the turbulence and precipitation as negligible to light. In addition, although a strong correlation between lightning strikes and vertical drafts (predominantly downdrafts) was found for a small data set in 1981 and 1982, most strong turbulence episodes encountered by the

airplane were not associated with lightning (refs. 31 and 32).

Unlike the temperature and altitude data discussed above, there is no discrepancy between the precipitation and turbulence data gathered in this program and that data gathered during commercial (refs. 1 and 2) and military operations (ref. 3). As before, the data are in agreement with those from the USAF/FAA Convair 580 program (ref. 30). Commercial aircraft reported that 77 percent of all strikes occurred in light to moderate turbulence, with 22 percent of all strikes occurring with no turbulence. Eighty-one percent of all commercial strikes occurred in rain; only 2 percent of the strikes were associated with rain and hail. For military aircraft, only 20 percent of the strikes were associated with turbulence, 67 percent of the strikes occurred in rain, 5 percent occurred in hail or snow, and 10 percent occurred in "clear air." Finally, for the Convair 580 research program, 90 percent of the strikes occurred in light to negligible turbulence; all the strikes were associated with rain. In summary, the thunderstorm research data gathered by the NASA F-106B airplane and the USAF/FAA Convair 580 airplane, as well as the commercial/military data, have shown that the number of direct strikes to aircraft do not show a positive correlation to turbulence and precipitation intensities.

Although the Doppler radar data recorded in 1981 and 1982 using the NASA Wallops S-band radar (ref. 31) showed heavy turbulence within the high precipitation reflectivity cores of thunderstorms, heavy turbulence also was found between cells, near storm boundaries, and in innocuous-appearing low reflectivity factor regions. Similar results were found during the multi-year Rough Rider Program turbulence studies (ref. 33). Therefore, it was concluded that turbulence and precipitation are not necessarily correlated.

Triggered lightning, St. Elmo's fire, and static discharges.- There has long been interest in the lightning research community over the manner in which lightning strikes occur to aircraft. One theory states that aircraft lightning strikes are the result of the aircraft simply being in the "wrong place at the right time," and being approached by a naturally-occurring lightning leader (ref. 2). If such a leader approaches within approximately 50 m of the aircraft, it is likely that the electric field presented to the aircraft will be of sufficient intensity to ionize air about the aircraft's extremities and induce a junction leader to propagate from the aircraft and join with the approaching lightning leader. This process is illustrated in figure 8. The second theory states that the aircraft itself triggers the lightning flash (ref. 34), as illustrated in figure 9.

When an aircraft flies through an electric field, the aircraft diverts and compresses adjacent equipotential lines as the aircraft flies between two charge centers. The highest electric fields about the aircraft will occur around extremities, where the equipotential lines are compressed closest together. Typically, these are the nose, wing, and empennage tips, some engine nacelles, and also smaller protrusions, such as antennas or pitot probes. If an aircraft intercepts a naturally-occurring strike, the oncoming lightning leader will intensify the electric field and induce streamers from the aircraft extremities. One of these streamers will meet the nearest branch of the advancing lightning leader and form a continuous spark from the cloud charge center to the aircraft. Aircraft have very low capacitance, which means that comparatively little charge can accumulate on an aircraft. Therefore, the aircraft merely becomes an extension of the path being taken by the leader on its way to an ultimate destination at a reservoir of opposite polarity charge, which may be elsewhere in the cloud (an intracloud strike) or on the ground (a cloud-to-ground strike). Streamers may propagate onward from one or more extremities of the aircraft at the same time, with the branches continuing from the aircraft independently of each other until one or more of them reach their destination. Thus, the aircraft has become part of the conducting path between charge centers. Heretofore, it generally had been believed that large aircraft could cause a sufficient perturbation in the ambient electric field to initiate a lightning leader, but that such a leader would nevertheless originate from a nearby charge center and not from the aircraft. Such strikes were evident during natural icing tests of such wide-body aircraft as the Boeing 747 and the McDonnell-Douglas DC-10.

The research conducted in the NASA Storm Hazards Program has provided the first instrumental proof, using onboard camera systems and the ground-based UHF-band radar, of aircraft-triggered lightning flashes originating at the aircraft (refs. 7 and 8). Approximately 90 percent of the airplane strikes observed by the UHF-band radar at altitudes above 20 000 ft were triggered by the F-106B airplane (ref. 7). The UHF-band radar data also indicate that intercepted lightning strikes can occur, with most intercepted strikes in thunderstorms occurring at altitudes below 20 000 ft (ref. 8). Analyses of onboard and ground-based lightning electromagnetic waveforms have shown that a high percentage of the strikes experienced by the USAF/FAA Convair 580 airplane also were triggered by that airplane (ref. 30).

The current NASA theory on aircraft-triggered lightning strikes (ref. 35) states that a sharp-edged metal object on an aircraft will concentrate the local electric field sufficiently to trigger a local breakdown in the presence of an ambient electric field of proper magnitude and orientation, with the streamers propagating from the aircraft outward to charge centers. The magnitude of the electric field in some triggering cases can be much less than that experienced in thunderstorms. Thunderstorm models (ref. 35) indicate that triggering should be far more prevalent at higher altitudes and colder temperatures (where field strengths are higher), as has been seen during the F-106B airplane flights. A comparison of the NASA data with that from commercial/military aircraft operations indicates that some lightning strikes to these aircraft in "nonstormy" conditions near the freezing level also may be triggered lightning strikes. A common misconception is that bright flashes which are preceded or accompanied by St. Elmo's fire are "static discharges." As explained

below, a "static discharge" that produces a bright flash and/or an audible report is actually a lightning strike.

When an aircraft flies through dry precipitation in the form of sleet, hail, or snow, the impact of these particles on the aircraft will cause a charge to separate from the particle and join the aircraft, leaving the aircraft with a preponderance of positive or negative charge (depending on the form of precipitation), thereby changing the potential of the aircraft with respect to its surroundings. This phenomenon is known as triboelectric charging. It is commonly referred to as precipitation static, or P-static.

The P-static charging process is easily capable of raising the aircraft to a potential of 50 kV, or more, with respect to its surroundings, a charge sufficient to cause ionization at sharp extremities. This ionization radiates broadband electromagnetic radiation throughout the low- and high-frequency spectrum. This radiation is often received as interference, or static, by aircraft radios.

The electromagnetic radiation from P-static results from a continuous series of minute streamer-like discharges of ionized air in the immediate vicinity of sharp extremities, or from small electrical discharges across and inside dielectric surfaces, such as windshields. These discharges also produce a continuous ultraviolet glow visible at night which is called St. Elmo's Fire, or corona. The St. Elmo's Fire will occur initially from the sharpest extremities, where the surrounding field first reaches the ionization potential for air (as is the case for lightning leaders). The P-static is a continuous phenomenon which lasts as long as the aircraft is being charged by impact with dry precipitation. Because of its low capacitance, an aircraft cannot retain enough P-static charge to produce a startling flash of several meters in length, or a loud report. (On the other hand, many lightning strikes occur out of the field of view of the crew and passengers or may be of short duration and small amperage, resulting in dimly lit channels and muffled reports.)

The P-static discharging process may be intensified when the aircraft is in a region where the ambient electric field is relatively intense, as is the case when a lightning flash is imminent. When the lightning flash occurs (whether a nearby flash or a direct strike), the main charge centers are neutralized, and the electric field collapses, thereby reducing the intensity of P-static discharging. For this reason many pilots report that P-static interference gradually intensifies until a bright flash occurs, and then diminishes instantaneously. This experience has lead to the incorrect belief that the flash was a sudden static discharge from the aircraft. In fact, P-static interference is reported in about 50 percent of all commercial lightning-strike incidents (refs. 1 and 2). However, none of the 714 strikes to the F-106B airplane were accompanied by precipitation static. In summary, precipitation static and lightning are different phenomena which frequently, but not necessarily, occur at the same time. The streamers caused by the electric field or the approaching lightning leader frequently occur at the same aircraft locations as the St. Elmo's Fire created by precipitation static, further confusing the real-time perceptions of the phenomena. The capacitance of an aircraft is too small for an aircraft to store up sufficient charge from precipitation static for an appreciable electrical discharge to occur. Therefore, the static discharges which are reported are actually lightning strikes, and are not caused by precipitation static/St. Elmo's Fire.

Airborne lightning location.- The primary function of any airborne lightning location device is to provide a reliable indication of the existence of lightning and an accurate display of the location of the lightning activity. The output of such devices also are being used to warn aircrews of the potential for lightning strikes to their aircraft and of the location and intensity of other atmospheric hazards (ref. 36). During the NASA Storm Hazards Program, the UHF-band radar data were used to determine a Probability of Direct Strike (PDS), defined in references 7 and 8 as the ratio of the number of direct strikes to the F-106B airplane to the total number of flashes occurring in the radar resolution volume containing the airplane. For both high and low altitude research flights in thunderstorms, it was found that there was an inverse relationship between PDS and flash rate, with the higher PDS values occurring in regions of the storms with a flash rate of 0 to 10 flashes/min rather than in storm regions with flash rates greater than 10 flashes/min. This result implies that the greatest threat of triggered lightning may be located in storm regions with low natural lightning flash rates. Therefore, flight into an area with few indicated lightning discharges does not insure that the aircraft is in a region with low risk of triggered lightning.

In addition, the absence of lightning activity ahead does not necessarily mean the absence of convective activity or the hazards associated with heavy precipitation, turbulence and hail. NASA experience during F-106B flights in the Chesapeake Bay region indicated that 10-15 percent of the convective build-ups with cloud tops which exceeded 30 000-35 000 ft showed no electrical activity throughout their lifetime. In these cases, precipitation reflectivities of up to 35-40 dBZ would be indicated, with no indications of lightning. Such build-ups did contain significant updrafts and turbulence, however. During the ground-based Doppler radar research conducted in 1980 and 1981, it was concluded that the use of lightning location methods to map hazardous turbulence within thunderstorms was unreliable, since most strong turbulence episodes encountered by the F-106B airplane were not associated with lightning (ref. 32). Finally, the lack of correlation between aircraft lightning strikes, turbulence, and precipitation can be seen in the Storm Hazards data discussed previously in figure 7.

The Storm Hazards results from dedicated research flights are in agreement with the commercial and military strike incident data taken during regular operations. Only 40 percent of the commercial pilots observed lightning around the

time of the strike (ref. 1), and only a very small percentage of the military reports mentioned the build-up of electrical activity prior to the strike (ref. 3). Therefore, it can be concluded that generic airborne lightning location devices do not necessarily indicate the location or intensity of other atmospheric hazards, nor do they provide a reliable warning of the potential for triggered lightning.

The commercially-available airborne lightning locater system described in reference 36 was flight tested in the NASA DHC-6 airplane in 1978 in Oklahoma and Virginia (ref. 6). Thirteen storms were studied in Oklahoma in conjunction with ground-based Doppler weather radar measurements by the NOAA-NSSL. One storm was studied over the Chesapeake Bay in conjunction with ground-based precipitation reflectivity measurements by the NASA-Wallops S-band radar. During the flights on the periphery of the thunderstorms in Oklahoma, the data from the airborne lightning locator system were found to be in general agreement with the locations of the most severe weather as indicated by the NOAA-NSSL Doppler radar. However, when comparing lightning locations from the airborne lightning locator system with the ground-based Doppler radar measurements of reflectivity and spectrum width (a measure of turbulence), the lightning locations tended to be further from the aircraft position than the Doppler radar contours, but at the same relative bearing from the aircraft as the Doppler radar contours. Of the 14 storms studied, two storms (one in Oklahoma and one in Virginia) had little lightning activity but heavy precipitation and moderate turbulence.

During the sole research flight over the Chesapeake Bay in 1978, the DHC-6 airplane made a single storm penetration. The results of this penetration are typical of the NASA experience with airborne lightning location. The storm appeared to be benign visually. The airplane ground track from the onboard INS is shown superimposed on the precipitation reflectivity contours from the NASA Wallops S-band radar in figure 10 (from ref. 6). The peak reflectivity detected was 60-65 dBZ, with maximum cloud tops of 29 000 ft and 30 000 ft. During the 6-minute data period, only one lightning event was detected by the airborne system in the vicinity of the storm contours, and the event is plotted in its true relative position with respect to the NASA Wallops radar in figure 10 (see ref. 6). Two other lightning points were recorded during the data period, but the airborne system placed both points outside the plotted region in figure 10 in areas of clear air.

As the DHC-6 aircraft flew deeper into the storm cell, the turbulence began to increase and the rain intensity became heavy. The pilot executed a 90° turn to depart the storm because of the worsening conditions. During the turn, the airplane experienced moderate turbulence, with a peak vertical acceleration of 0.7 g incremental. No hail was encountered, although the turn apparently was begun when the airplane was in an area of reflectivity between 55 and 60 dBZ. (In all probability, the airplane was in an area of lower peak reflectivity since the radar was sampling a volume of the storm beneath the altitude at which the airplane was flying.) In summary, this storm penetration was made through a storm which appeared to be benign visually and electrically, yet contained moderate turbulence and moderate to heavy rain.

<u>Use of an airborne X-band weather radar.</u>- Although the NASA Storm Hazards Program emphasized lightning research, some airborne data on the performance of a commercially-available airborne X-band weather radar were collected. Attenuation of X-band radar signals by heavy rain rates is well documented in the literature (ref. 37), and at least one fatal air carrier accident has been attributed to this phenomenon (ref. 38). Examples of attenuation in the X-band radar data taken aboard the F-106B airplane also have been noted (refs. 11 and 24). Photographs of the radar display from the ground-based NASA Wallops S-band radar and the airborne X-band radar for the same storm are shown in figures 11 and 12, respectively (from ref. 24). The ground tracks of the NASA F-106B airplane and the FAA/USAF Convair 580 airplane (ref. 30) (the two airplanes were making simultaneous penetrations of the same storm) have been graphically superimposed on the S-band radar photograph in figure 11, which was taken at 21:16:24 GMT. The tilt angle of the S-band radar was set so that the radar would sample the storm at the nominal 14 000 ft altitude used by the Convair 580 airplane.

The photograph of the airborne weather radar display in the F-106B cockpit, figure 12, was taken at 21:15:47 GMT while the F-106B airplane was approximately 5 n.mi. away from the leading edge of the 30 dBZ contour at an altitude of 18 000 ft. The position and heading of the F-106B airplane at the time of this photograph are indicated in figure 11. A small area with a precipitation reflectivity value of 50 dBZ or greater is visible in the center of the storm cell; as the airplane penetrated further, this area became larger, and the airplane flew through an area of small hail. No storm areas with precipitation reflectivity values of 50 dBZ or greater are visible in the vicinity of the F-106B airplane in figure 11. The differences in storm appearance on the two radar displays are caused by the following: differences in radar sampling altitude; actual differences in storm characteristics between the sampling altitudes of the ground-based radar and the F-106B penetration altitude; loss of detail in the ground-based radar display because of the large size of the radar sample volume of this radar (sample volume, in turn, is a function of radar beam width, pulse width and range to the target); and, the attenuation of the X-band weather radar in the F-106B airplane. (The ground-based S-band radar is not subject to attenuation.) The true extent of the 50 dBZ core in the storm cell shown in figure 12 was masked by the intervening rainfall between the core and the airborne radar, with the true extent and intensity of the core only becoming apparent as the airplane penetrated further into the storm and approached the core.

In summary, the NASA experience has been that the judicious and intelligent use of airborne radars (for detecting precipitation) can provide adequate information for safe avoidance of many hazardous areas. The use of an airborne lightning

locator can provide significant additional data. It is important to emphasize, however, that these devices should be used for avoidance of hazardous areas, not navigation through such areas.

Managing lightning risks by avoidance.- In order to minimize the chances of encountering hail, the F-106B airplane was not flown into thunderstorm regions where the precipitation reflectivity values exceeded 50 dBZ, although the UHF-band radar studies found that the lower altitude lightning flash density center was closely associated with high reflectivity cores (ref. 27). Therefore, no comments can be made from the Storm Hazards data concerning the probability of encountering naturally-occurring lightning strikes in such areas of thunderstorms. However, the data are still applicable to most commercial and military aircraft operations, since few of these aircraft will have occasion to fly into regions of such high reflectivity. The data in this paper provide the following guidelines:

1. The probability of lightning strikes to aircraft operating within or near thunderstorm clouds increases as a function of altitude (decreasing temperature) up to about 38 000 ft (-40°C). This trend includes the anvil or "blow-off" region downwind of the thunderstorm core. However, there is no safe altitude (temperature) at which the aircraft is immune from lightning strikes. (It should be noted that the intensities of the electric currents and charges associated with lower altitude strikes generally are greater than those associated with higher altitude strikes, most of which do not reach the earth. The recorded incidents in which unusually severe damage has occurred (refs. 2 and 39), and the catastrophic accidents which have been attributed to lightning (refs. 3-5) have nearly all occurred at altitudes at or below the freezing level (i.e., from 5000 to 15 000 ft).
2. Comparison of research data with operational strike incident data has shown that aircraft lightning strikes can occur in cloud formations other than those associated with thunderstorms, especially during flight near the freezing level (0°C).
3. Most strikes occurred in regions where the turbulence and precipitation levels were characterized as negligible to light. It also was found that turbulence and precipitation intensities are not correlated.
4. Many aircraft strikes are triggered by the presence of the airplane, although strikes in which the airplane is randomly intercepted by a naturally-occurring lightning channel do occur, especially at lower altitudes. These lower-altitude strikes tend to be the most severe, as noted in (1) above.
5. "Static discharges" accompanied by a bright flash and/or a loud report are actually lightning strikes. P-static/St. Elmo's Fire is a different phenomenon than that associated with aircraft lightning strikes. However, the conditions that produce P-static are often found in lightning-producing clouds. Therefore, P-static can provide some forewarning. In fact, nearly 50 percent of all commercial strike incidents have reported P-static prior to the strike.
6. Airborne lightning location devices can provide significant additional information on stormy areas that lie ahead that would not otherwise be available in the cockpit. However, these devices do not provide positive indications as to the location or intensity of other storm hazards, and they may not even provide a reliable indication of the potential for aircraft-triggered lightning.
7. An airborne X-band weather radar provided the most significant cockpit information used for thunderstorm penetration. However, the radar data did not provide reliable indications of the location or intensity of turbulence and lightning. In addition, X-band weather radars are susceptible to attenuation effects from heavy rain rates.
8. Airborne devices should be used to avoid areas of potential risk, not to aid in penetration through such areas.

Vehicle Hardening

Lightning-hardening techniques used on the F-106B airplane.- The second, and equally important, major approach to management of lightning-related risks is to protect the airframe and flight-essential systems from adverse lightning effects. The NASA Storm Hazards Program also afforded an opportunity to evaluate several basic approaches to protection design, since the airplane had to be sufficiently protected to minimize, to the maximum extent possible within the state of the art, hazards to the flight crew due to the large number of anticipated strikes. This part of the paper describes the lightning protection features of the NASA F-106B airplane and some lessons learned which are applicable to other aircraft.

Since the primary mission of the Storm Hazards Program was to collect direct lightning strike data, care was taken to select an aircraft that had shown few adverse lightning effects in service. Although the F-106 airplane was designed and manufactured prior to the creation of lightning protection specifications, the USAF F-106 fleet had experienced very few serious incidents, despite having been involved with substantial lightning strikes (ref. 39). The inherent lightning protection features in the F-106 airplane included the following: use of aluminum and magnesium skins and structural materials, providing good electromagnetic shielding for the avionics and data instrumentation; use of hydraulic control systems, which are nearly immune to lightning effects; use of gold foil heater strips in the canopy defog system and the presence of a metal overhead canopy rail, minimizing the aperture size for electromagnetic coupling into the cockpit; use of twin engine intakes, minimizing the possibility of

the lightning shock wave disturbing the airflow into the engine, which could result in engine roll-back or flame-out; and, the use of a pressurized fuel system, minimizing the probability of a detonation of the fuel from a spark or arc in the fuel system or from a hot spot or burnthrough of the skin of an integral fuel tank.

Because of the nature of the mission, additional lightning protection was installed in the NASA airplane. The lightning protection modifications made prior to the first research flight included the following: installation of transient suppressors on each of the airplane's 115 VAC power distribution busses which supplied power to any externally-mounted electrical apparatus, including the pitot heaters, air data probe heaters, and canopy defog circuits; exclusive use of JP-5 (Jet A) jet fuel in lieu of the more volatile JP-4 (Jet B) jet fuel used in the USAF F-106 fleet; application of additional sealant over the dome nuts and fasteners in the fuel tanks to minimize the chances of an arc or spark contacting fuel vapors in the tanks; and, improvement of the electrical bonding of fuel tank components and externally-mounted electrical apparatus such as probes and antennas.

The production vertical fin cap on the F-106 airplane is unprotected fiberglass. Prior to the first mission, this component was flame-sprayed with aluminum to provide a conductive layer over the piece. During the program, the fiberglass fin cap was replaced with experimental composite caps (ref. 40): a Kevlar unit in which an outerply of interwoven Thorstrand fibers was included for lightning protection; and a graphite epoxy cap which relied on the conductivity of the graphite fibers for protection.

Prior to each thunderstorm season, there was an internal inspection of the fuel tanks to check for electrical continuity in the fuel and vent lines and to assure that all pieces of plumbing and other interior parts were electrically bonded to the airplane. Unacceptably high resistance readings occasionally would be found across a fuel line coupling, or the thickness of sealants covering exposed fasteners would be found to be too thin. In these cases, the couplings would be tightened to provide better metal-to-metal contact and additional sealant would be applied. Following each of these annual inspections and the normal quality assurance inspections, the lightning-hardening integrity was verified during ground tests in which simulated lightning currents and voltages of greater than average intensity were conducted through the airplane with the airplane manned and all airplane and data systems operating (ref. 13).

During the course of the program, additional lightning protection modifications were found to be necessary. Heavy-gauge aluminum foil was wrapped around the exposed radar control cables in the radome to provide additional electromagnetic shielding after the pilots noticed that the radar display in the front cockpit would frequently vanish for several sweeps following a lightning strike to the nose boom. A replacement radome, to which commercially-available segmented lightning diverter strips were bonded, was installed following the discovery of several small circuitous lightning punctures in the unprotected production radome. The five diverter strips were symmetrically located on the fiberglass radome, with each strip providing an exterior attachment path from the base of the metal nose boom to the metal structure of the airplane at the radome bulkhead. Based on the attachment patterns found on the exterior of the airplane (see discussion later in this paper), paint and primer were removed from most exterior surfaces of the airplane to reduce swept-stroke lightning dwell times, hence minimizing the chance of a lightning melt-through anywhere on the airplane.

Finally, as reported in reference 40, each of the vertical fin caps required periodic refurbishment due to the effects of the lightning strikes. The flame-sprayed aluminum on the fiberglass fin cap and the Thorstrand on the Kevlar tail were sacrificial, evaporating from the conduction of the lightning currents. Periodically, the fiberglass tail was resprayed, and a new Thorstrand ply was bonded over the Kevlar tail. A graphite/epoxy lightning discharge protection rod (ref. 41) was added to the trailing upper apex of the graphite/epoxy tail to alleviate the severe erosion which was occurring at that location. From visual inspection, no structural damage from the lightning strikes was detected in any of the tails (ref. 40). Lightning protection guidelines for adhesively-bonded composite aircraft structures, developed during a corollary effort to the Storm Hazards Program, may be found in reference 42.

Maintenance and quality assurance played significant roles in the safe and successful completion of this program. Without the efforts of the aircraft maintenance crew, the thunderstorm environment likely would have degraded several of the lightning protection modifications which were made. The efforts of these personnel also provided the inputs for the additional modifications which were made during the program. The importance of maintenance to aircraft lightning protection is discussed in detail in reference 43.

The digital peak counters used in the airborne lightning data system recorded a peak current amplitude of 54 kA. Wing-tip erosion damage and the depth and size of several burn marks on the aluminum skin are physically similar to the damage created by simulated lightning discharges in the laboratory with peak current amplitudes of 100 kA. Even with lightning strikes of this magnitude, the adverse physical effects of the lightning on the NASA F-106B airplane have been relatively minor, both structurally and electrically (ref. 9).

<u>Lightning-hardening specifications</u>.- The lightning-hardening techniques discussed above for the NASA F-106B research airplane are not unique to that specific aircraft. Rather, these techniques are applied to many production aircraft, and are documented in the government airworthiness requirements, specifications and standards given in table 2. The documents given in table 2 are continually under review, using data taken from operational civilian and military lightning incidents, as well as from dedicated

research programs, such as the NASA Storm Hazards Program and the USAF/FAA Convair 580 program (ref. 30).

The greatest impact of the results of the Storm Hazards Program on the documents given in table 2 has been defining the characteristics of the lightning engineering waveform used in lightning simulation (refs. 18 and 19) and in clarifying some of the more questionable aspects of establishing lightning strike zones on aircraft. The NASA effort in the clarification of lightning strike zones will be discussed in the remainder of this paper.

Airborne photography and lightning attachment patterns.- Removal of most paint from the exterior metal surfaces of the airplane in order to minimize the lightning dwell times made it very difficult to track the swept-stroke attachment paths because of the small size of the melted spots. Therefore, the onboard camera systems provided the primary means of documenting these patterns. One example of the photographic coverage possible with the system used in 1986 is provided by the photographs from strike 13 of 1986. Coverage was provided by the four video cameras in use (fore- and aft-viewing cameras in the cockpit and the two cameras on the left wing tip). The photoelectric diodes in the cockpit did not sense the strike; therefore, the movie camera and the three cockpit-mounted still cameras did not actuate.

The lightning strike scenario for the strike is shown in figure 13. At the instant of strike initiation, the lightning channel orientation was inferred to be as shown in figure 13(a), with the entry portion of the channel descending downward from the right of the airplane centerline to the nose boom, and the exit channel continuing to the left and downward from one of the probes or antennas beneath the fuselage. (The terms "entry" and "exit" as used here are defined in reference 20.) The initial attachment of the entry channel to the nose boom can be seen in the photographs taken from the forward-facing, cockpit mounted video camera at 19:37:43.208 GMT (figure 14(a)), and from the wing-tip mounted, cockpit-facing video camera at 19:37:43.207 GMT (figure 15(a)). As the airplane flew forward through the stationary lightning channel, the entry portion of the channel, which initially attached to the nose boom, swept back over the radome along a segmented diverter strip and along the right side of the fuselage, as shown schematically in figure 13(b), and photographically in figures 14(b) and 15(b) (both taken at 19:37:43.242 GMT). The entry channel then continued to sweep aft along the top of the aircraft (figure 13(c)), with the channel sweeping up the leading edge of the vertical tail (figure 13(d)) until it reached its final attachment point on the graphite lightning diversion rod located at the trailing upper apex of the vertical fin cap (figure 13(e)). During this time period, the exit channel swept aft along the bottom of the airplane until it reached its final attachment point on the jet engine exhaust nozzle (figures 13(b-e)). The swept entry channel can be seen sweeping aft along the top of the fuselage aft of the cockpit in figure 15(c) (19:37:43.276 GMT). The swept entry channel can be seen sweeping up the leading edge of the vertical tail in figure 16 (corresponding to figure 13(d)), a photograph taken from the wing-tip mounted empennage-facing video camera at 19:37:43.309 GMT. The view of the swept entry channel from the aft-facing, cockpit-mounted video camera (not shown) was almost completely blocked throughout the duration of the flash by the overhead canopy rail and the aft cockpit bulkhead, with the entry channel appearing as a glow in the rear of the airplane behind the flight test engineer's right shoulder.

The swept-exit channel was blocked from the fields of view of the four video cameras by the fuselage and wings until the channel swept aft of the trailing edge of the left wing and appeared in the field of view of the wing-tip mounted, empennage-facing video camera at 19:37:48.275 GMT. The swept exit channel can be seen attached to its final attachment point on the engine exhaust nozzle in figure 16.

The estimated duration of the lightning flash was 325 ms, as measured from the time at which the channel first appeared in the field of view of the two video cameras viewing the nose boom (19:37:43.208 GMT) until the time of the last video frame in which the channel was visible (the aft-facing, cockpit-mounted video camera at 19:37:43.532 GMT). In summary, the onboard photographic systems were able to document that strike 13 of 1986 was a nose-to-tail swept strike with a duration of approximately 325 ms, and to show the surface areas along the airplane which were exposed to lightning re-attachment as the airplane flew through the lightning channel.

Data such as these have shown that there were four general strike scenarios in the swept flash attachment patterns on the exterior of this airplane (refs. 9 and 14):

1. Flashes which initially attach to the nose of the aircraft and subsequently "sweep" alongside it, reattaching at a succession of spots along the fuselage. In these cases, the initial and final exit point is usually the trailing edge of an extremity such as a wing or vertical fin tip. The final entry point is a trailing edge of the fuselage, because the flash is usually still alive by the time the aircraft has flown completely through it.
2. Similar to (1) except that the entry channel sweeps aft across the top or bottom wing surface instead of the fuselage.
3. Strikes in which the initial entry and exit points occur at the nose. In this case, the lightning flash appears to "touch" the aircraft nose but continues on from this point to another destination. The aircraft then flies through the flash, resulting in successive entry points along one side of the fuselage or wing and exit points along the other. Again, because the flash usually exists for a longer time than it takes the aircraft to fly its length, the final entry and exit points are located along trailing edges.

4. Strikes in which the initial and final entry and exit points are confined to the aft extremities.

With most of these general scenarios, swept-flash channels frequently have been found which rejoin behind the airplane after the airplane has flown through the channel. These same four attachment patterns also have been identified on the FAA/USAF Convair 580 airplane (ref. 30).

Lightning strike zones on aircraft have been defined as follows (see ref. 44):

- o Zone 1A - **Initial attachment point with low possibility of lightning arc channel hang-on.** Surfaces within this zone include the aircraft nose, engine nacelles, and the forward surfaces of wing tips. Zone 1A includes those areas in which the first return stroke of a cloud-to-earth lightning flash will attach.
- o Zone 1B - **Initial attachment point with high possibility of lightning arc channel hang-on,** such as the trailing edges of extremities. All lightning flash currents are expected to enter/exit in this zone.
- o Zone 2A - **A swept-stroke zone with low possibility of lightning arc channel hang-on,** such as fuselage surfaces aft of Zone 1A. Only a subsequent stroke (re-strike) and some continuing currents of low amplitude are expected to occur in this zone.
- o Zone 2B - **A swept-stroke zone with high possibility of lightning arc channel hang-on.** This zone includes surfaces aft of Zone 2A, such as the trailing edges of some flight control surfaces.
- o Zone 3: **All of the vehicle areas other than those covered by Zone 1 and 2 regions.** In Zone 3, there is a low possibility of any attachment of the lightning channel; however, structures in this zone usually must conduct Zone 1A or 1B currents since they usually lie between some pair of attachment points. These currents may affect systems or components located within the aircraft.

The intensities of lightning currents expected in each of the zones described above have been defined for design and certification purposes in references 44-46, also found in table 2. In general, surfaces and structures located in Zones 1A and 1B receive more intense currents, and therefore, may have to be provided with greater degrees of protection than surfaces in other zones.

Although references 44 and 45 contain guidelines for determining the location of each zone on specific airplanes, such was not done for the F-106 airplane since it was designed prior to the creation of the specifications. Application of the zones to an existing aircraft can be controversial, due to differing interpretations of the guidelines. However, in the case of the Storm Hazards Program's F-106B airplane, it was possible to locate the zones on the airplane's exterior from direct observation of the lightning attachment patterns left from the 714 direct lightning strikes which were experienced.

Applying the zone definitions to the four attachment patterns discussed earlier resulted in the F-106 lightning attachment zones shown in figure 17. The nose boom, wing and vertical fin tips, speed brake, afterburner and fuselage trailing edges are known to have received initial lightning leader attachments, and thus are located in Zone 1. Though not specifically stated in the definitions, Zone 1A locations are intended to include surfaces which may be reached by the first return stroke, which may occur a finite time period after initial leader attachment. For the F-106B airplane, the calculation in ref. 12 has shown that surfaces up 180 in. aft of the forward tip of the nose boom may fall within Zone 1A. The outboard edges of wing tips are also within Zone 1A for the same reason (see figure 17). Finally, the upper portion of the canopy also is considered in Zone 1A because it represents a significant projection above the fuselage. It is thought that some leaders have initially struck or originated from the canopy of the NASA F-106B airplane.

Since the airplane is moving forward when leader attachment occurs, the leaders do not remain attached to forward extremities but "sweep" aft and reattach successively to additional spots along surfaces aft of the initial strike locations. When the airplane has travelled completely through the flash channel, the channels hang onto the aircraft trailing edges, usually (but not always) for the remaining lifetime of the flash. In accordance with the zone definitions, initial attachment spots where the flash does remain attached are within Zone 1B. For the F-106B airplane then, Zone 1B included the trailing edges of the wing tips, vertical fin tip, speed brake and fuselage. The Zone 1B region also included the afterburner, including the area up to 14 in. inside the afterburner (figure 17).

In accordance with the definitions, surfaces which lie directly aft of Zone 1A are in Zone 2A, with trailing edges aft of Zone 2A falling in Zone 2B. Surfaces within Zone 2B include the elevon and rudder trailing edges. The entire top and bottom surfaces of the wings are in Zone 2A, as lightning channels were observed to sweep across each of these after attaching initially to the nose boom. However, no leaders are known to have initially struck the leading edges of the wings or

vertical fin; therefore, these surfaces are located in Zone 2A instead of Zone 1A. Swept flashes which reach the wing leading edge usually originate at the nose boom, sweep aft along either side of the fuselage, and then sweep outboard along the wing leading edge a random distance before continuing directly aft across the top or bottom surface of the wing. The tendency for swept flashes to sweep aft across the wing surfaces may be influenced by the wing leading edge sweep angle, since lightning flashes are not known to sweep outboard along straight (unswept) wings. Operational data have suggested that the critical wing sweep angle for this phenomenon may be 45° The wing leading edge is swept 60° on the F-106B airplane.

Finally, the NASA data illustrate that much, if not all, of an aircraft surface may be exposed to "direct" or "swept" lightning strike attachments. In fact, there was no Zone 3 on the F-106B airplane (figure 17).

The NASA Storm Hazards Program constituted the first systematic study of lightning attachment patterns on a full-scale aircraft in flight. The lightning attachment zones shown in figure 17 imply that new aircraft designs using delta wings or highly swept wing leading edges probably will require surface protection from lightning attachment over the complete exterior, an especially significant design feature for vehicles incorporating surfaces of composite materials. In addition, the lightning attachment within the tail pipe of the airplane have shown that engines and associated control and instrumentation systems may require lightning protection (see ref. 47), especially if "fly-by-wire" controls are employed without mechanical backup.

Managing lightning risks by vehicle hardening.- The data in this paper provide the following broad guidelines:

1. Aircraft incorporating conventional materials and design technologies such as metal skins and mechanical/hydraulic primary or backup flight and engine control systems are relatively immune from major lightning damage. However, even in these aircraft, lightning-related catastrophies occasionally occur. Most of these accidents have resulted from ignition of flammable vapors in fuel tanks, and nearly all of the aircraft involved have been fueled with highly volatile fuels, such as Jet-B or JP-4. There have been no confirmed in-flight fuel-vapor-ignition accidents involving aircraft fueled solely with Jet-A or Jet-A1 fuel. Nevertheless, if an aircraft is going to be operated in conditions conducive to lightning strikes, a review of its lightning protection design in comparison to present-day lightning protection guidelines (as was done for the NASA F-106B airplane) may be warranted.
2. The technologies presently exist to provide adequate lightning protection for aircraft designs using composite structure and full or high-authority electronic control systems. Specific protection designs usually must be incorporated in the airframe as well as its flight-critical or flight-essential systems. Systems of particular concern include:
   - o electronic flight control systems, especially full-authority systems
   - o electronic engine controls (EEC)
   - o integrated cockpit displays and flight management systems
   - o composite-material flight control surfaces
   - o composite-material pressure hull skins and structures
   - o fuel tanks and other fuel system components
   - o other structures or systems employing new-technology materials or designs
3. Aircraft lightning protection guidelines are constantly being updated with new information from aircraft operators, protection design specialists, and research projects such as the NASA Storm Hazards Program and the FAA/USAF Convair 580 program.
4. A thorough and timely maintenance and inspection program is essential to ensure that the integrity of the lightning protection features is maintained throughout the life of the aircraft, and that modifications contain adequate protection themselves, and when installed, do not degrade or deviate existing protection features of the aircraft.

CONCLUDING REMARKS

The experience and technical data produced by the NASA Langley Research Center Storm Hazards Program has resulted in a substantial increase in knowledge regarding lightning interactions with aircraft, and has demonstrated several ways by which the risks from lightning strikes to aircraft can be managed. These include thunderstorm avoidance, aircraft lightning protection design, and adequate maintenance. The NASA Storm Hazards Program produced the following key results in support of these goals:

1. The thunderstorm regions with highest probability for an aircraft to experience a direct lightning strike were those areas where the ambient temperature was colder than -40°C (pressure altitudes of 38 000 to 40 000 ft), where the relative turbulence and precipitation intensities were characterized as negligible to light, and where the lightning flash rate was less than 10 flashes/min. However, direct lightning strikes were encountered at nearly all temperatures and altitudes.
2. The intensity of these high-altitude lightning strikes, however, was less than that of cloud-to-earth flashes which are encountered less frequently by aircraft operating at or below the freezing level.

3. The presence and location of lightning do not necessarily coincide with the presence or location of hazardous precipitation and turbulence. In addition, hazardous precipitation and turbulence are not necessarily related to one another.
4. Airborne lightning location devices may not provide a reliable indication of the potential for triggered lightning.
5. The entire exterior surface of this airplane may be susceptible to direct or swept lightning attachment, i.e., there is no lightning attachment Zone 3 on the F-106B airplane or on aircraft with geometries similar to that of the F-106 airplane.
6. The program demonstrated that adequate protection design can reduce or eliminate hazardous lightning effects on aircraft, even though the USAF F-106 fleet had experienced several catastrophic lightning-related accidents prior to addition of some of the protection features to the NASA F-106B airplane.
7. Careful, timely inspections and maintenance also contributed to the success of the lightning safety record of the NASA F-106B airplane. Periodic visual inspections of all lightning protection features, electrical bonding checks, and tests of electrical/electronic system protection devices identified small degradations in some of these features, and enabled appropriate maintenance to be performed.

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Table 1.- Storm Hazards Mission Summary

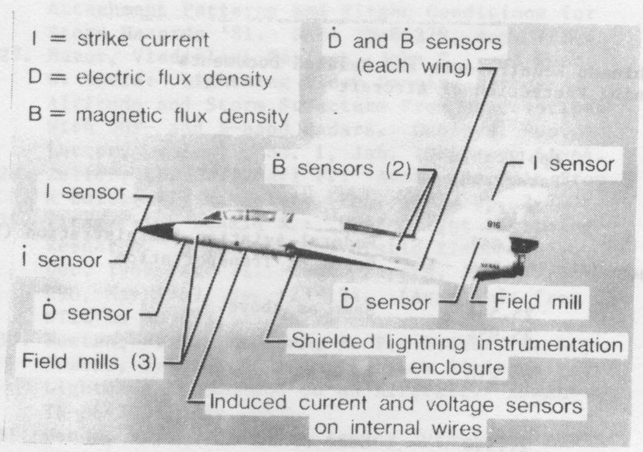
YEAR		1980	1981	1982	1983	1984	1985	1986	TOTAL
MISSIONS		19	24	35	40	38	19	9	184
PENETRATIONS:	HIGH	23	29	191	298	273	25	18	857
	LOW	46	82	50	26	136	199	100	639
TOTAL		69	111	241	324	409	224	118	1496
STRIKES:	HIGH	6	7	153	214	223	12	1	616
	LOW	4	3	3	0	24	41	23	98
TOTAL		10	10	156	214	247	53	24	714
NEARBYS:	HIGH	1	9	26	110	11	11	0	168
	LOW	5	13	0	2	0	0	0	20
TOTAL		6	22	26	112	11	11	0	188

Table 2.- U.S. Government Airworthiness Requirements and Related Documents Pertaining to Lightning Protection of Aircraft

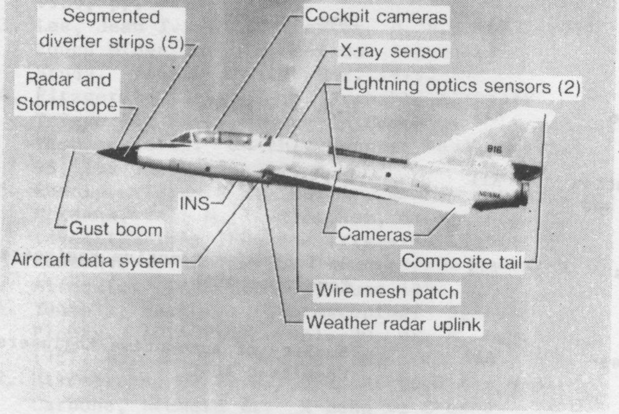
Document Identification	Title	Applicable Paragraphs	Agency
Federal Aviation Regulations, Part 23	Airworthiness Standard: Normal, Utility, and Acrobatic Category Airplanes	23.867 23.954	Federal Aviation Administration (FAA), Dept. of Transportation
Federal Aviation Regulations, Part 25	Airworthiness Standard: Transport Category Airplanes	25.581 25.954	Same as above.
Federal Aviation Regulations, Part 27	Airworthiness Standard: Normal Category Rotorcraft	27.610	Same as above.
Federal Aviation Regulations, Part 29	Airworthiness standard: Transport Category Rotorcraft	29.610	Same as above.
Advisory Circular AC 20-53A Apr. 1985	Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning	All	Same as above.
User's Manual DOT/FAA/CT-83/3 Oct. 1984	User's Manual for AC 20-53A, Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to Lightning	All	Same as above.
DOD-STD-1795 (USAF) May 1986	Military Standard: Lightning Protection of Aerospace Vehicles and Hardware	All	U.S. Air Force
MIL-STD-1757A July 1983	Military Standard: Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware	All	Dept. of Defense
Committee Report SAE AE4L June 1978	Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware	All	Society of Automotive Engineers Committee AE4L
Committee Report SAE AE4L-81-2 Dec. 1981	Test Waveforms and Techniques for Assessing the Effects of Lightning-Induced Transients	All	Society of Automotive Engineers Committee AE4L
Committee Report SAE AE4L-87-3 Feb. 1987	Recommended Draft Advisory Circular: Protection of Aircraft Electrical/ Electronic Systems Against the Indirect Effects of Lightning	All	Society of Automotive Engineers Committee AE4L

LANGLEY RESEARCH CENTER

Figure 1.- NASA Langley Research Center DHC-6 Storm Hazards research airplane used in 1978.

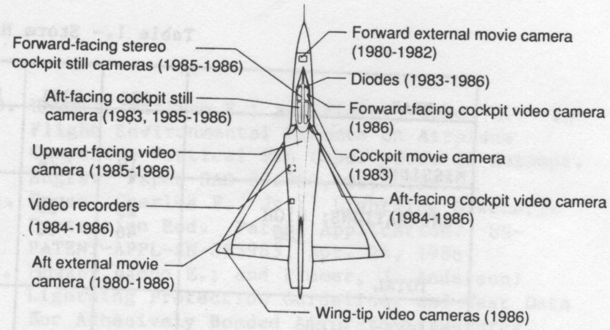


(a) Location of electromagnetic sensors.

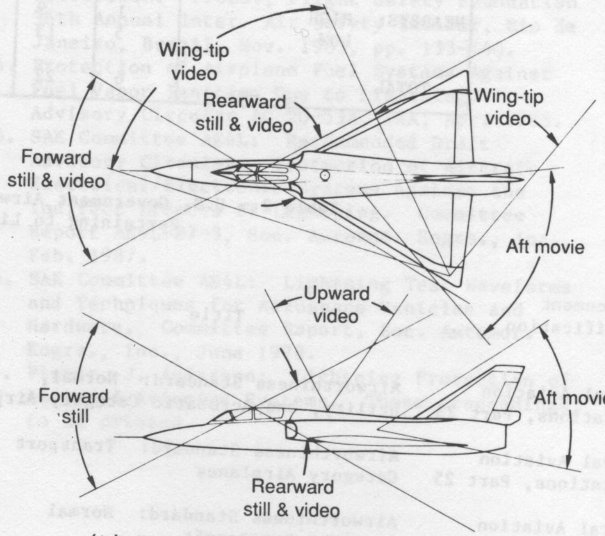


(b) Location of additional research sensors.

Figure 2.- NASA Langley Research Center F-106B Storm Hazards research airplane used from 1979-1986.



(a) Location of airborne camera systems.



(b) Photographic and video coverage during Storm Hazards '86.

Figure 3.- Airborne camera systems used on the F-106B airplane from 1980-1986.

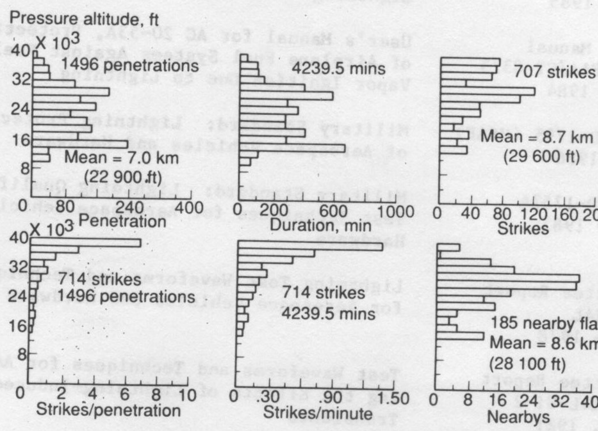


Figure 4.- Thunderstorm penetrations and lightning statistics as a function of pressure altitude for Storm Hazards '80-'86.

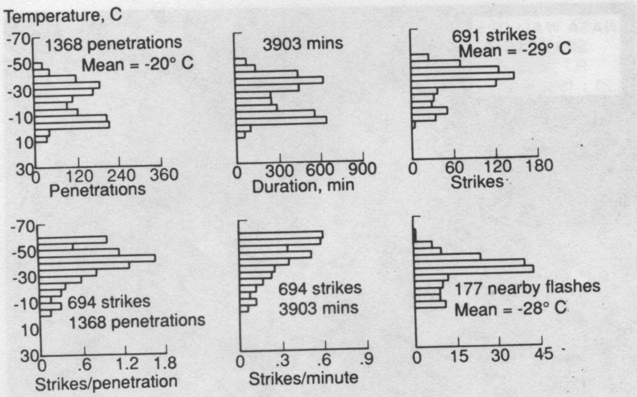


Figure 5.- Thunderstorm penetrations and lightning statistics as a function of ambient temperature for Storm Hazards '80-'86.

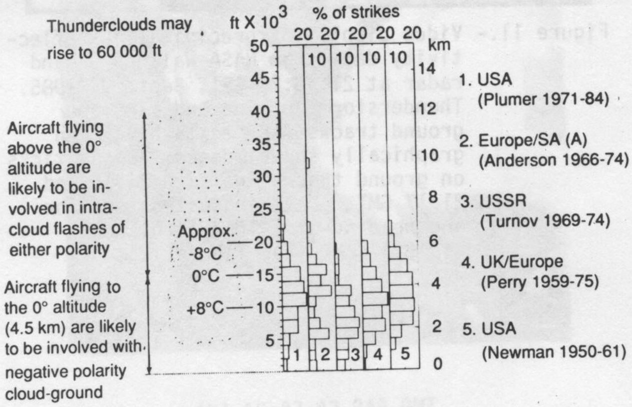


Figure 6.- Aircraft lightning strike incidents as a function of altitude. From reference 2 with updated data from reference 1.

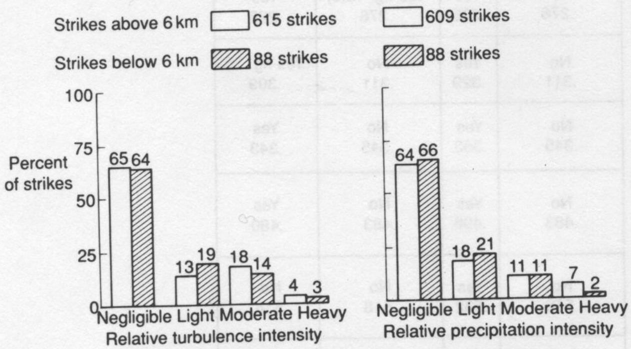
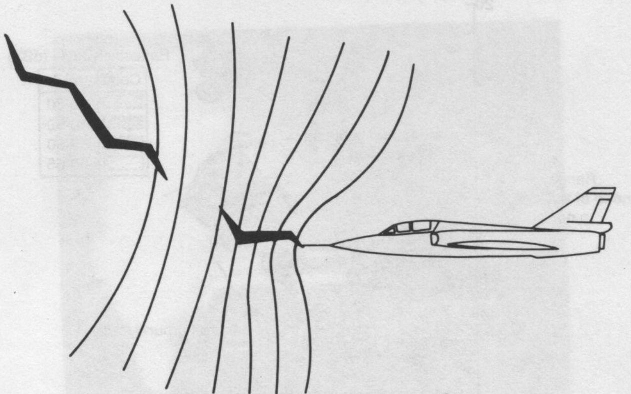
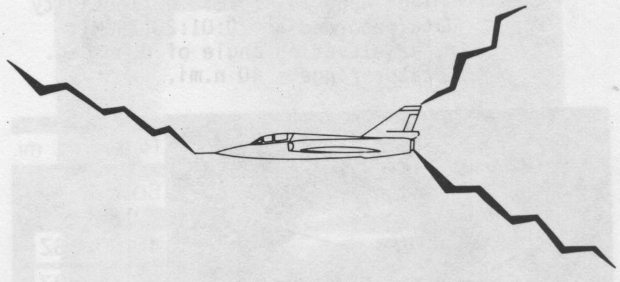


Figure 7.- Relationship of lightning strikes to relative turbulence and precipitation intensities for Storm Hazards '80-'86.



(a) Leader approaches aircraft, intensifying the electric field and inducing a junction leader from the aircraft.



(b) Leader continues from the aircraft toward a final destination.

Figure 8.- The naturally-occurring aircraft lightning strike.

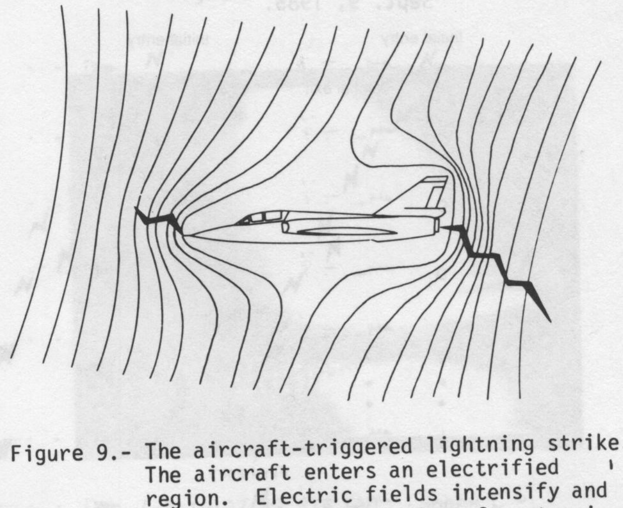


Figure 9.- The aircraft-triggered lightning strike. The aircraft enters an electrified region. Electric fields intensify and leaders originate at aircraft extremities.

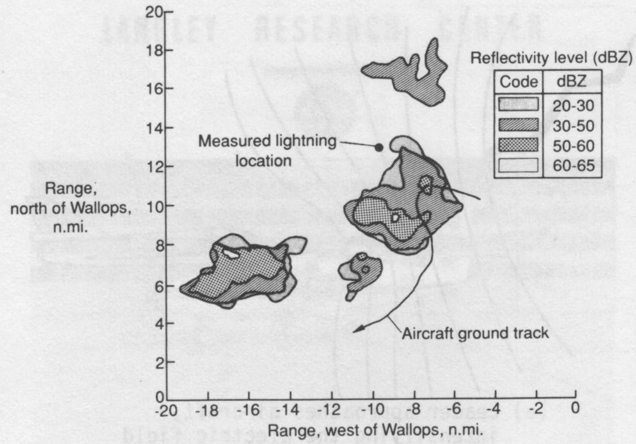


Figure 10.- Precipitation reflectivity contours from the NASA-Wallops S-band radar, airplane ground track, and airborne lightning locator point for the time interval from 20:10:45 to 20:16:30 GMT on Aug. 14, 1978. Reflectivity data recorded at 20:01:20.7 GMT; radar elevation angle of 0.38 deg. Locator range = 40 n.mi.

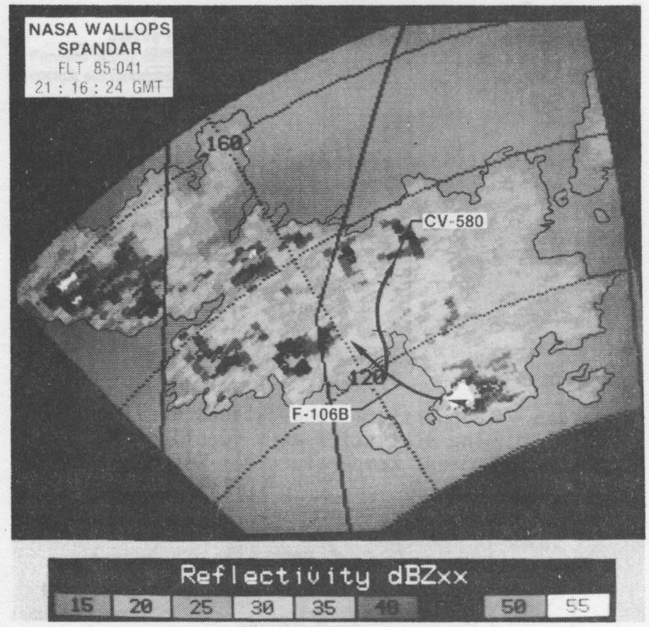


Figure 11.- Video display of precipitation reflectivity data from NASA-Wallops S-band radar at 21:16:24 GMT, Sept. 9, 1985. Thunderstorm outline and airplane ground tracks (see text) have been graphically superimposed. Cross ticks on ground tracks indicate 21:16 and 21:17 GMT. Dart indicates location and heading of F-106B airplane at 21:15:47 GMT (see figure 12).

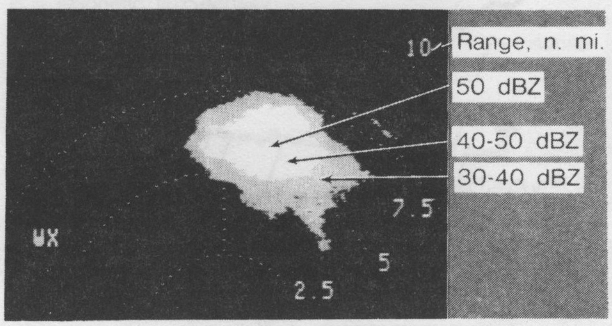
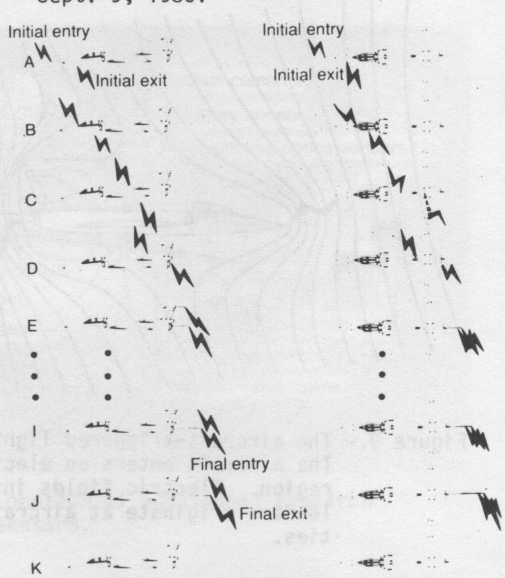


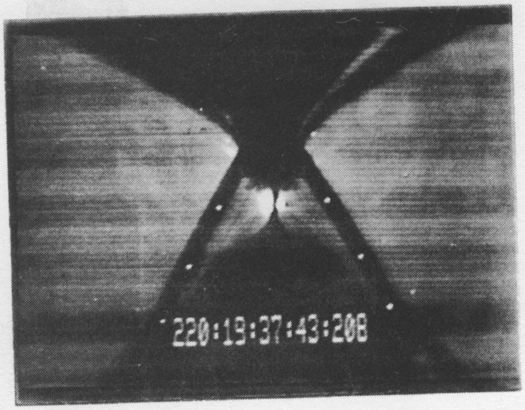
Figure 12.- Airborne x-band radar display in F-106B airplane at 21:15:47 GMT, Sept. 9, 1985.



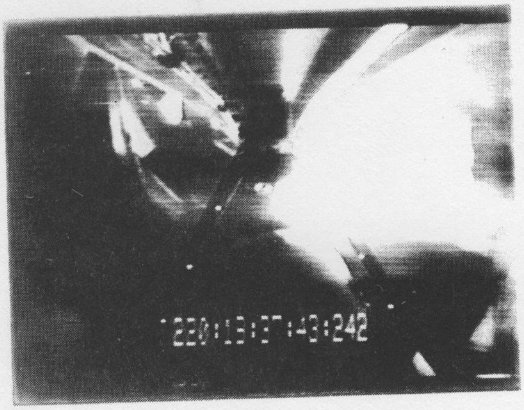
Channel seen at 19:37:43.XXX

Cockpit		Wing tip	
Fwd	Aft	Nose boom	Empennage
Yes-fig. 14(a) .208	No .227	Yes-fig. 15(a) .207	No .207
Yes-fig. 14(b) .242	Yes .261	Yes-fig. 15(b) .242	No .241
No .276	Yes .295	Yes-fig. 15(c) .276	Yes .275
No .311	Yes .329	No .311	Yes-fig. 16 .309
No .345	Yes .363	No .345	Yes .343
No .483	Yes .498	No .483	Yes .480
No .518	Yes .532	No .518	No .514
No .552	Yes .564	No .552	No .548

Figure 13.- Lightning strike scenario for strike 13 of 1986; 19:37:43.207 GMT; Aug. 8, 1986; 14,900 ft altitude over Mathews, VA. The table indicates when the lightning channel was seen by each video camera and gives the last three digits of the time code (ms) for each video frame.

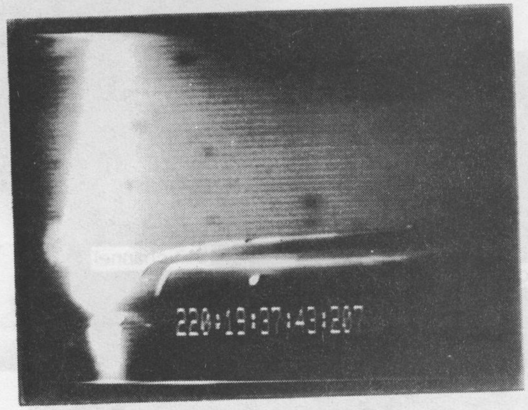


(a) 19:37:43.208 GMT.

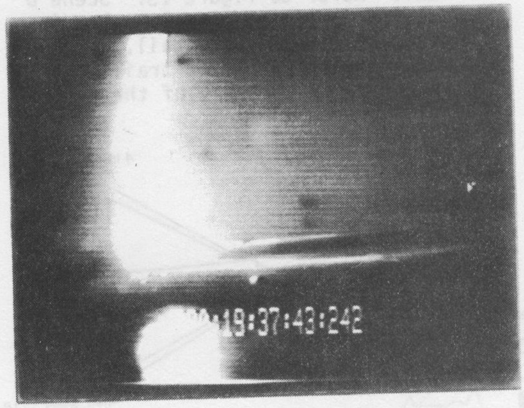


(b) 19:37:43.242 GMT.

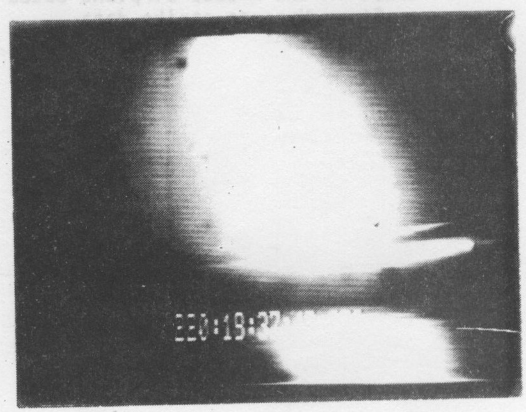
Figure 14.- Photographs from cockpit-mounted, forward-facing video camera of strike 13 of 1986. Refer to figure 13.



(a) 19:37:43.207 GMT. Scene A - channel attached to nose boom.



(b) 19:37:43.242 GMT. Scene B - channel sweeping aft along right side of canopy.



(c) 19:37:43.276 GMT. Scene C - channel sweeping aft along the top of the fuselage.

Figure 15.- Photographs from wing-tip-mounted, nose-boom-facing video camera of strike 13 of 1986. Refer to figure 13.

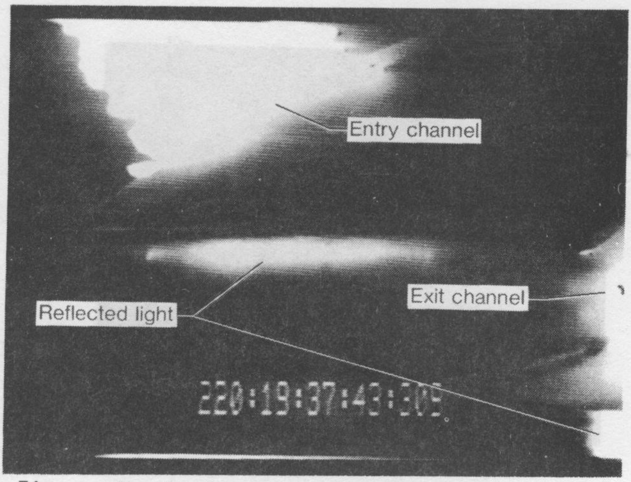


Figure 16.- Photograph from wing-tip-mounted, empennage-facing video camera of strike 13 of 1986. 19:37:43.309 GMT. Refer to figure 13. Scene D channel sweeping aft along leading edge of the vertical tail, with an additional attachment trailing aft from the exit nozzle of the engine.

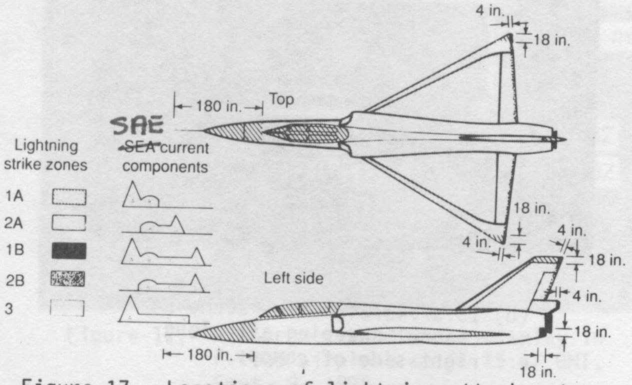


Figure 17.- Locations of lightning attachment zones on the F-106B airplane based on Storm Hazards strike data.