3.0 AIRCRAFT - LIGHTNING INTERACTION

3.1 Introduction

This chapter addresses the circumstances under which aircraft are struck by lightning. It also describes the potential effects of lightning on the aircraft.

A considerable amount of research into the mechanisms whereby aircraft are struck by lightning have been accomplished. Much of this research has been aimed at defining the atmospheric conditions under which an aircraft may be struck by lightning, and answering the question of whether or not an aircraft can produce a lightning strike that originates at the aircraft, or if it can trigger an impending flash originating at a cloud charge region. Results of these studies are summarized in the following paragraphs.

Strike occurrence data, principally for transport airplanes, has been collected for many years and is usually summarized according to the following categories:

1. Altitude
2. Flight path; that is, climbing, level flight, or descent
3. Meteorological conditions
4. Outside air temperature
5. Lightning strike effects on the aircraft

The following specific topics are discussed:

- Definitions of Lightning attachment points
- Circumstances under which aircraft are struck
  - Altitude and flight path
  - Meteorological Conditions
  - Immediate Environment at time of strike
  - Frequence of Occurrence
- Aircraft-lightning strike mechanisms
- Electrical field effects
  - The charge stored on the aircraft
  - Triggered lightning (“Can an aircraft trigger lightning?”)
- Swept flash phenomena
- Direct effects on aircraft skins
  - Pitting and meltthrough
  - Magnetic forces
  - Pitting at structural interfaces
  - Resistive heating
  - Shock waves and overpressure
- Direct effects on non-metallic structures
- Direct effects on fuel systems
- Direct effects on electrical systems
- Direct effects on propulsion systems

3.2 Aircraft Lightning Attachment Points

A lightning flash initially attaches to, or enters, an aircraft at one spot and exits from another. Usually these are extremities of the aircraft such as the nose or a wing tip. For convenience, these are called initial entry and initial exit points.

At any one time, current is flowing into one point and out of another. The "entry" point may be either an anode or a cathode; that is, a spot where electrons are either entering or exiting the aircraft. The visual evidence after the strike does not allow one to resolve the issue and usually no attempt is made. Instead, by convention, attachment spots at forward or upper locations have usually been called entry spots and those at aft or lower locations on the aircraft have been termed exit points.

Since the aircraft flies more than it's own length within the lifetime of most flashes, the entry point will change as the flash reattaches to other spots aft of the initial entry point. The exit point may do the same if the initial exit spot is at a forward portion of the aircraft. Thus, for any one flash, there may be many "entry" or "exit" spots and the following definitions are used:

lightning attachment point: The place where the lightning flash touches (attaches to) the aircraft.

initial entry point: The place where the lightning flash channel first "enters" the aircraft (usually an extremity).

final entry point: The place where the lightning flash channel last "enters" the aircraft (typically a trailing edge).

initial exit point: The place where the lightning flash channel first "exits" from the aircraft (usually an extremity).

final exit point: The last place where the lightning flash "exits" from the aircraft (usually a trailing edge).

swept "flash"(or "stroke") points: Spots where the flash channel reattaches between the *initial* and *final points*, usually associated with the *entry* part of the flash channel.

3.3 Aircraft Lightning Experience

The following paragraphs summarize the important findings from the transport aircraft data gathering projects noted previously and describe the flight and weather conditions under which lightning strikes are most common. Knowledge of these conditions may help pilots to minimize future lightning strike incidents. Small airplanes can be expected to experience lightning strikes during the same flight and weather conditions that have existed when larger transport airplanes have been struck, although there have been no data gathering projects involving small airplanes to quantify these conditions.

Altitude and Flight Path: Fig. 3.3-1 shows the altitudes at which the reporting projects discussed above show aircraft are being struck. This data indicates that there are more lightning strikes begin experienced at intermediate altitudes than at cruise altitudes for transport airplanes. This fact indicates (1) that there are more lightning flashes to be intercepted below about 20,000 ft. than above this altitude, and (2) that jet aircraft are being struck at lower than cruise altitudes: that is, during climb, descent, or hold operations.

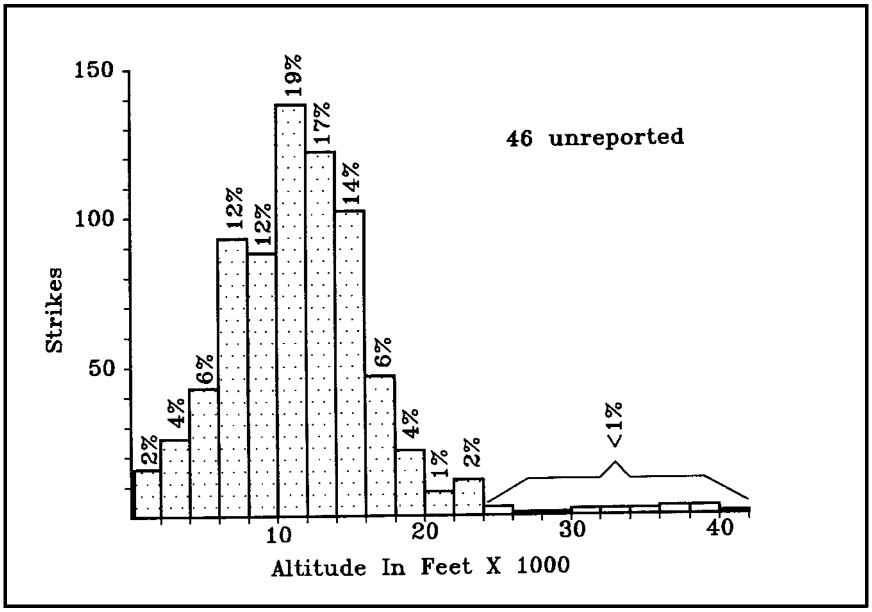

Figure 3.3-1: Aircraft lightning strikes vs. Altitude

It is generally thought that strikes which occur above about 10,000 ft. result from intracloud flashes between positive and negative charge centers in the cloud (or between adjacent clouds), whereas strikes below this level are more likely to result from cloud-to-ground flashes. Strike incidents occurring above 20,000 ft. occur less frequently because aircraft at these altitudes can more easily divert around areas of precipitation than can aircraft at lower altitudes and most pilots make an effort to avoid regions of convective activity where cumulus tops are greater than 20,000 or 25,000 thousand feet.

Synoptic Meteorological Conditions: Data discussed thus far might imply that an aircraft must be within or beneath a cloud to receive a strike and, since electrical charge separation is accompanied by precipitation, that most strikes would occur when the aircraft is within a cloud, or in or near regions of precipitation. Strike incident reports show that these conditions often do exist, but other lightning strikes occur to aircraft in a cloud when there is no evidence of precipitation nearby, and even to aircraft flying in clear air at a supposedly safe distance from a thundercloud. FAA and airline advisory procedures instruct pilots to circumvent thunderclouds or regions of precipitation evident either visibly or on radar, but strikes to aircraft flying 25 miles from the nearest radar returns or precipitation have been reported. Occasionally a report is received of a "bolt from the blue," with no clouds anywhere in sight. It is not certain that these reports are correct because it does not seem possible for electric charge separation of the magnitude necessary to form a lightning flash to occur in clear air. In most well documented incidents, a cloud is present somewhere, within 25 miles when the incident occurs.

Perhaps of most interest to aircraft operators are the area weather conditions which prevailed at the time of reported strikes. There is no universal data bank for this type of data, but several surveys have been conducted from time to time, including those of [3.1] through [3.7]. A survey involving a more limited number of strikes, but containing more weather information than the broad based surveys referenced above, is that of H.T. Harrison [3.8] of the synoptic meteorological conditions prevailing for 99 United Airlines lightning-strike incidents occurring between July 1963 and June 1964.

Harrison has drawn the conclusion that any condition which will cause precipitation may also be expected to cause lightning, although he adds that no strikes were reported in the middle of warm front winter storms. Data from the Airlines Lightning Strike Reporting Project reported by Rasch et al [3.7], show that lightning strikes to aircraft in the United States and Europe occur most often during the spring and summer months, when thunderstorms are most prevalent.

It is also important to note that many strike incidents have been reported where no bona fide thunderstorms have been visually observed or reported.

Immediate Environment at Time of Strike: Figs. 3.3-2, 3.3-3, and 3.3-4 show the immediate environment of the aircraft at the times of the 881 strikes reported in [3.7]. In over 80% of the strikes reported, each aircraft was within a cloud and was experiencing precipitation and some turbulence.

The incident reports above also show that most aircraft strikes have occurred when an aircraft is near the freezing level. Fig. 3.3-5 [3.7] shows the distribution of lightning strikes to aircraft as a function of outside air temperature. Freezing temperatures (and below) are thought to be required for the electrical charge separation process to function. Of course, strikes to aircraft at temperatures higher than 50^{o} F have occurred when the aircraft was close to (or on) the ground, where the ambient air temperature may be as high as about 77^{o} F.

Frequency of Occurrence (**Commercial aircraft):** An example of the number of lightning strikes which actually occur, as related to flight hours for piston, turboprop, and pure jet aircraft, is tabulated in Table 3-3-1 based on the data of Newman [3.1] and Perry [3.5]. From this data it follows that an average of one strike can be expected for each 3000 hours of flight for most commercial transport aircraft. This amounts to approximately one strike per year per airplane. Strike frequency data is not available for small general aviation, although on an annual basis these airplanes are probably experiencing fewer strikes since they do not usually fly as many hours per year.

Several factors may influence the apparent lower strike rate of small general aviation aircraft.

1. General aviation aircraft need not adhere to strict flight schedules or congested traffic patterns around metropolitan airports.

2. General aviation aircraft are a much smaller “target” for lightning than a large transport aircraft, probably because the electric field is not perturbed as much by the smaller aircraft, resulting in less likelihood of an aircraft initiated strike (See Section 3.4 for discussion of strike mechanisms).

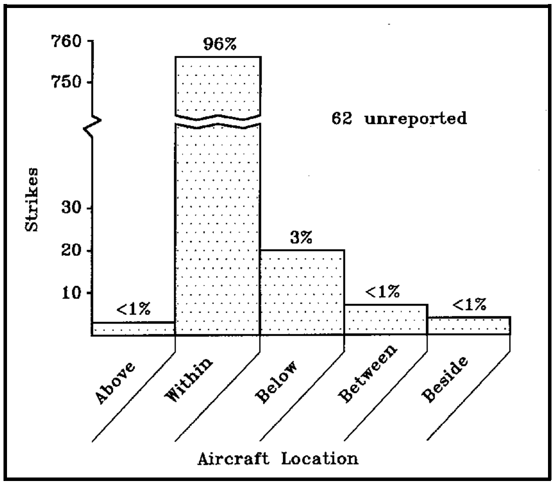

Figure 3.3-2: Aircraft location with respect to clouds when lightning strikes have occurred

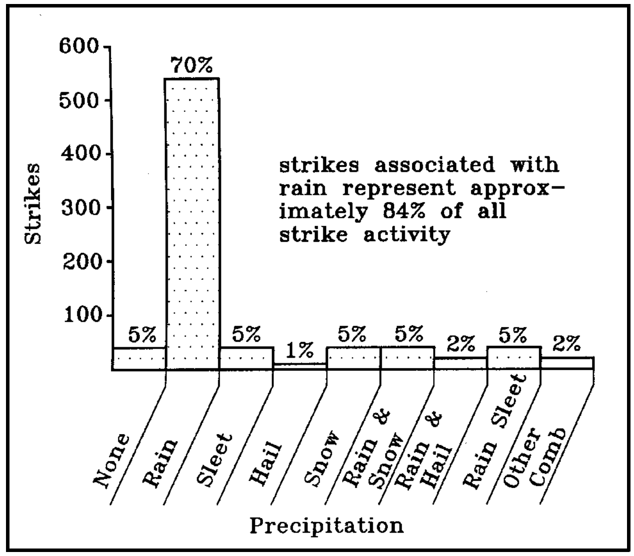

Figure 3.3-3: Precipitation at time of aircraft lightning strikes

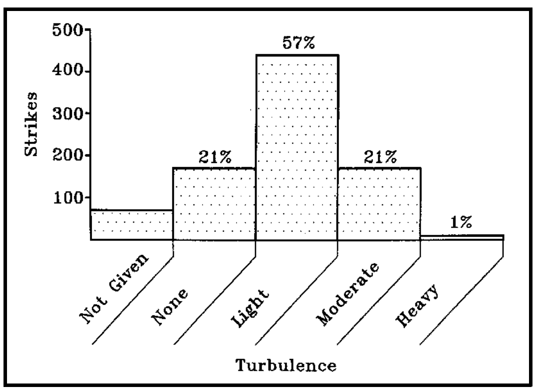

Figure 3.3-4: Turbulence experienced when lightning strikes have occurred.

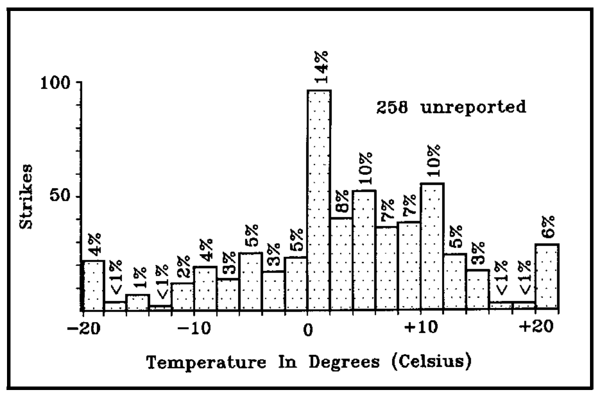

Figure 3.3-5: Outside Air Temperature during lightning strikes.

Table 3.3-1

	Newman (1950 – 1961)		Perry (1959 – 1974)		TOTALS		
	Strikes	Hours	Strikes	Hours	Strikes	Hours	No. hours per strike
Piston	808	2 000 000	–	–	808	2 000 000	2475
Turboprop	109	415 000	280	876 000	389	1 291 000	3320
Pure Jet	41	427 000	480	1 314 000	521	1 741 000	3340
ALL	958	2 842 000	760	2 190 000	1718	5 032 000	2930

3. Most transport aircraft data has been obtained via voluntary reporting of lightning strikes by pilots. The general aviation aircraft operators typically do not have a similar system in place. These operators report strike incidents to the FAA only if a major lightning related incident or accident occurs. Possibly the best source of data would be the insurance companies that usually pay for repairs when damage occurs.

Other statistics that are available, which apply to a broad category of aircraft and include data from a variety of different operators in varying geographic locations, may be misleading. For example, data shows that there is an average of 99,000 flying hours between reported lightning strikes to U.S. Air Force fighter-type aircraft. The strike experience in Europe is known to be more frequent than strike experience in the U.S. and most other parts of the world. Weinstock and Shaeffer [3.9] report 10.5 strikes per 10,000 hours for U.S. Military aircraft flying in Europe, which rate is about 5 times greater than the world-wide exposure rate for similar aircraft. The same situation pertains to commercial aircraft operating in Europe, as indicated by Perry's summary of United Kingdom and European strike data [3.6], for example. This unusually high lightning-strike exposure rates seem to result both from the high level of lightning activity in Europe compared with that in many other regions, together with traffic congestion.

Trends affecting strike rate: There are several trends in small aircraft operations which may cause greater exposure of aircraft everywhere to lightning strikes in the future:

1. Longer range capabilities of small airplanes

2. Increases in the number of small aircraft and rotorcraft equipped for instrument flight rules (IFR) flight.

3. Increasing use of radar and direct route navigation aids in general aviation aircraft, permitting IFR flight under adverse weather conditions.

These factors warrant continued diligence in the design and operation of aircraft with respect to the possible hazards lightning may present.

3.4 Aircraft Lightning Strike Mechanisms

The electrical conditions which produce lightning, together with the mechanisms of lightning strike attachment to an aircraft are discussed in the following paragraphs. While it is not impossible to anticipate or avoid these conditions all of the time, it is important to understand the strike attachment process in order to properly assess the ways in which lightning effects aircraft.

Electric Field Effects: At the beginning of lightning flash formation, when a stepped-leader propagates outward from a cloud charge center, the ultimate destination of the leader, at an opposite charge center in the cloud or on the ground, has not yet been determined. The difference of potential which exists between the stepped leader and the opposite charge(s) establishes an electrostatic field between them, represented by imaginary equipotential surfaces, which are shown as lines in the two dimensional drawing of Fig. 3.4-1. The field intensity, commonly expressed in kilovolts per meter, is greatest where equipotential surfaces are closest together. It is this field that is available to ionize air and form the conductive spark which is the leader. Because the direction of electrostatic force is normal to the equipotentials, and strongest where they are closest together, the leader is most likely to progress toward the most intense field regions.

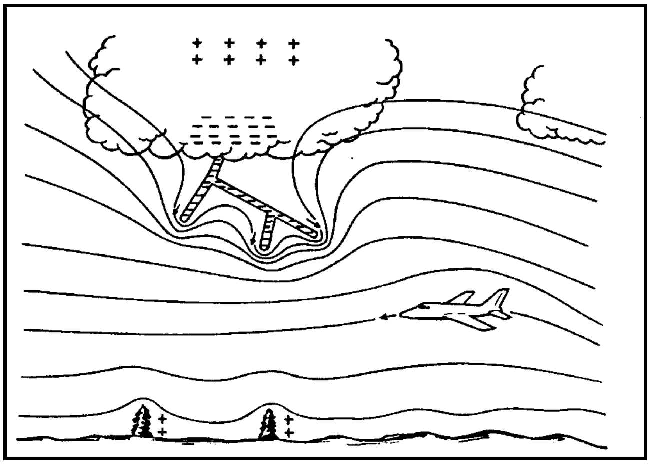

Fig. 3.4-1: Stepped leader approaching an aircraft.

An aircraft will always assume the electrical potential of its location. Since the aircraft is typically a large conductor, whose surfaces are all at this same potential, it will divert and compress adjacent equipotentials, thus increasing the electric field intensity at its extremities, and especially between it and other charge sources, such as the advancing leader. If the aircraft is far away from the leader, its effect on the field near the leader is negligible; however, if the aircraft is within several tens or hundreds of meters from the leader, the increased field intensity in between may be sufficient to attract subsequent leader propagation toward the aircraft. As this happens, the intervening field will become even more intense, and the leader will advance more directly toward the aircraft.

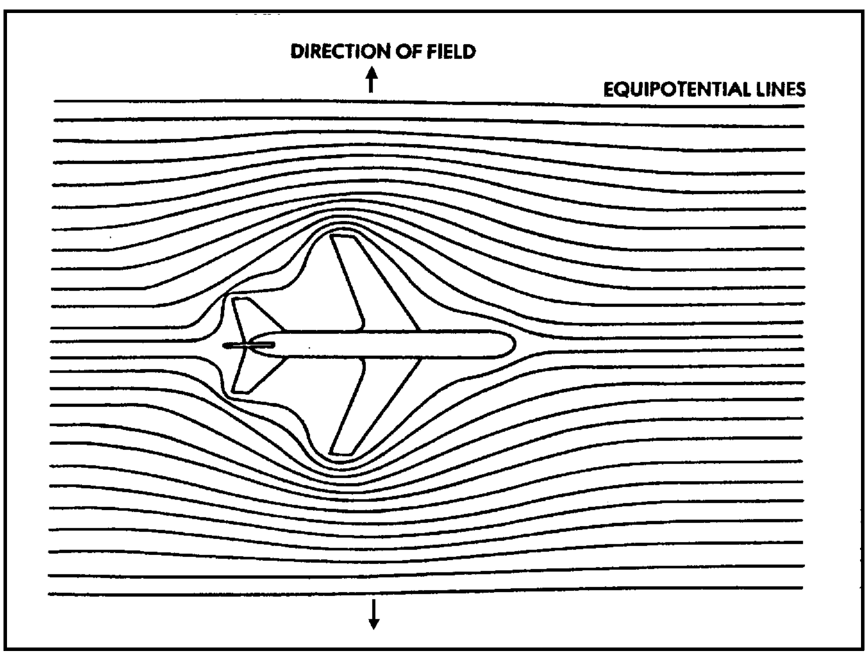

Fig. 3.4-2: Compression of electric field around an aircraft.

The highest electric fields about the aircraft will occur around extremities, where the equipotential lines are compressed closest together, as shown in Fig. 3.4-2. Typically, these are the nose, wing and empennage tips, and also smaller protrusions, such as antennas or air data probes. When the leader advances to the point where the field adjacent to an aircraft extremity is increased to about 30 kV/cm (at sea level pressure), the air will ionize and electrical sparks will form at the aircraft extremities, extending in the direction of the oncoming leader. Several of these sparks, called streamers, usually occur nearly simultaneously from several extremities of the aircraft. These streamers will continue to propagate outward as long as the field remains above about 5 to 7 kV/cm. One of these streamers, called the junction leader, will meet the nearest branch of the advancing leader and form a continuous spark from the cloud charge center to the aircraft. Thus, when the aircraft is close enough to influence the direction of the leader propagation, it will very likely become attached to a branch of the leader system.

Charge Stored on Aircraft: Streamers may propagate onward from two or more extremities of the aircraft at the same time. If so, the oncoming leader will have split, and the two (or more) branches will continue from the aircraft independently of each other until one or both of them reach their destination. This process of attachment and propagation onward from an aircraft is shown in Figure 3.4-3.

When the leader has reached its destination and a continuous ionized channel between charge centers has been formed, recombination of electrons and positive ions occurs back up the leader channel, and this forms the high-amplitude return stroke current. This stroke current and any subsequent stroke or continuing current components must flow through the aircraft, which has now become part of the conducting path between charge centers.

If another branch of the original leader reaches the ground before the branch which has involved the aircraft, the return stroke will follow the former, and all other branches will die out. No substantial currents will flow through the aircraft in such a case, and any damage to the aircraft will be slight.

Aircraft Inititiated Lightning Strikes: A question often asked is "If an aircraft cannot produce a lightning flash from its own stored charge, can it trigger a natural one?" Stated another way the question might be "Would the lightning flash have occurred if the aircraft were not present?" A second question would be "Even if aircraft do trigger lightning, would there be an impact on the criteria to which aircraft must be designed?" Some preliminary discussion of the mechanism by which aircraft triggers lightning is necessary.

There is clear evidence that lightning flashes can be triggered by research aircraft that are intentionally flown into clouds to observe lightning phenomena, but it is not clear how often aircraft in normal service trigger lightning.

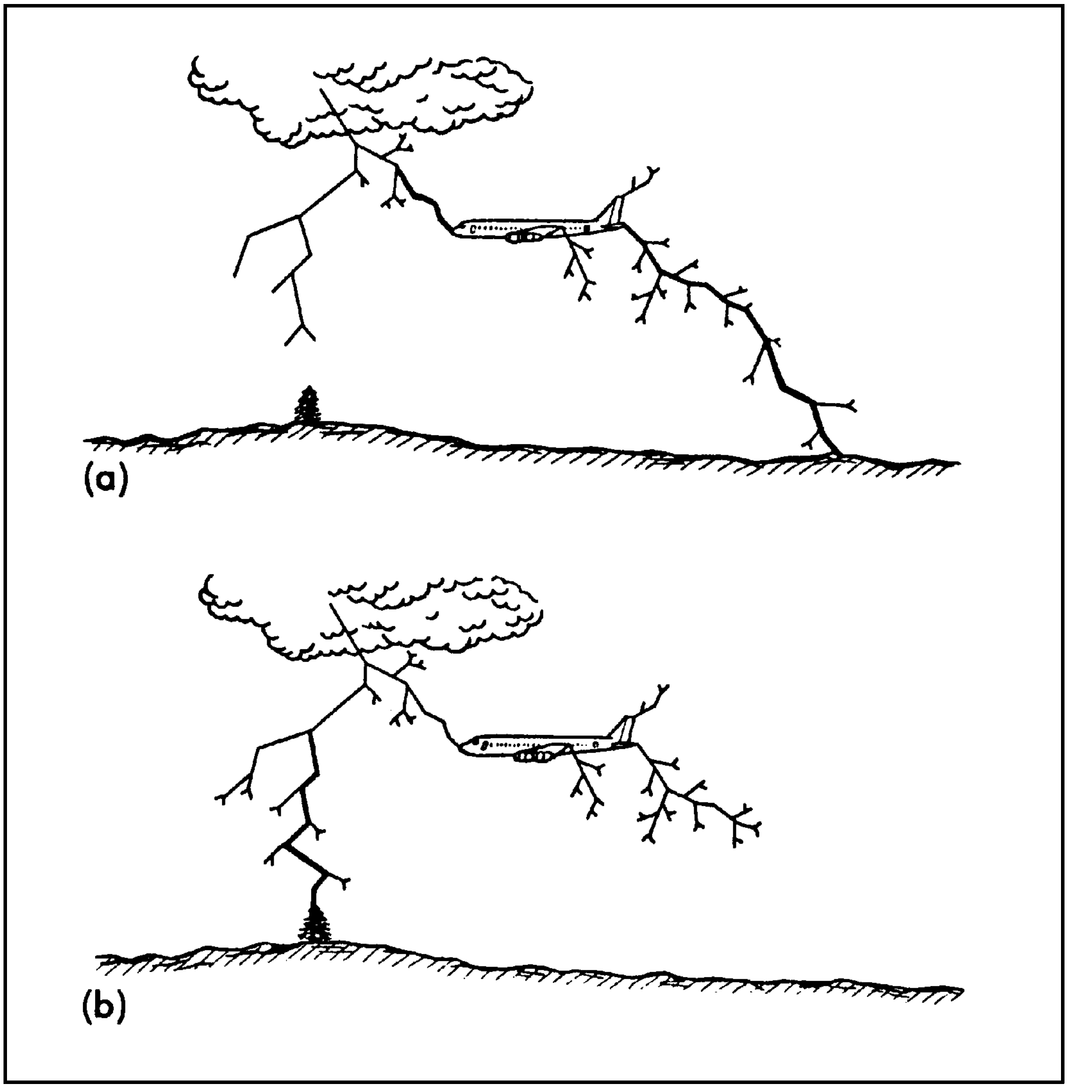

Figure 3.4-3: Return stroke paths

3.5 Swept Flash Phenomena

After the aircraft has become part of a completed flash channel, the ensuing stroke and continuing currents which flow through the channel may persist for up to a second or more. Essentially, the channel remains in its original location, but the aircraft will move forward a significant distance during the life of the flash.

Thus, whereas the initial entry and exit points are determined by the mechanisms previously described, there may be other lightning attachment points on the airframe that are determined by the motion of the aircraft through the relatively stationary flash channel. In the case of an aircraft, for example, when a forward extremity such as the nose becomes an initial attachment point, its surface moves through the lightning channel, and thus the channel appears to sweep back over the surface, as illustrated in Fig. 3.5-1. This occurrence is known as the swept flash phenomenon. As the sweeping action occurs, the type of surface can cause the lightning channel to attach and dwell at various surface locations for different periods of time.

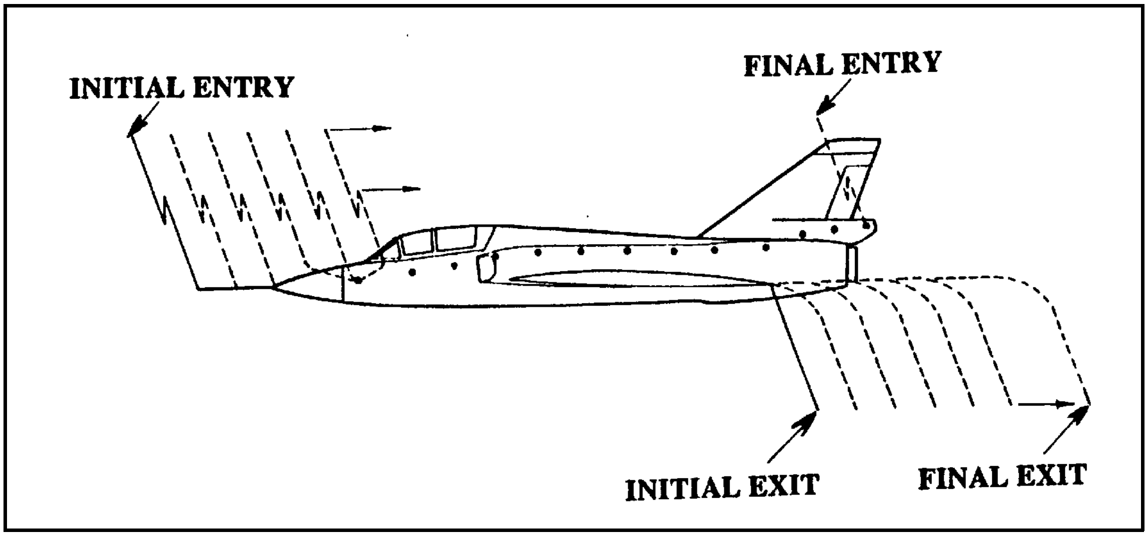

Fig. 3.5-1: Typical path of swept flash attachment points.

The aircraft does not usually fly out of, or away from, the channel. This is because the potential difference between charge centers (cloud and earth or another cloud) is sufficient to maintain a very long channel until the charges have neutralized each other and the flash dies.

3.6 Direct Effects on Skin Structures

The effects of lightning on skins, both metallic and composite include:

1. Melting or burning at lightning attachment points.

2. Resistive temperature rise.

3. Magnetic force effects.

4. Acoustic shock effects.

5. Arcing and sparking at bonds, hinges and joints.

6. Ignition of vapors within fuel tanks.

As is no doubt apparent, not all materials will suffer from these effects equally. Obviously, aluminum skins will suffer most from melting at lightning attachment points. While they will be subject, like composites, to acoustic shock damage, their greater ductility and malleability will likely enable them to survive. Composites will suffer the most from acoustic shock waves. It should be emphasized, however, that, carbon composites are conductors, albeit resistive conductors. They are therefore subject to the same influences as metal structures, although in different degree. They are, for example, subject to magnetic forces, as well as arcing and sparking at bonds and resistive heating.

Non-conductive composites, such as fiberglass and aramid fiber reinforced plastics will be subject to dielectric breakdown and puncture

Aircraft structures include the outer skins of the aircraft, together with internal framework, such as spars, ribs, frames, and bulkheads. Lightning currents must flow between lightning entry and exit points on an aircraft and tend to spread out as they flow between attachment points, using the entire airframe as a conductor. Any conductive material, metal or conductive composite with which most of these structures are fabricated becomes part of the conductive path for lightning currents.

In metal structures, the current density at any single point in the airframe is sometimes sufficient to cause physical damage between lightning entry and exit points. Only if there is a poor electrical bond (contact) between structural elements in the current flow path is there likely to be physical damage, and this may be of little consequence unless this arcing occurs in a fuel tank. On the other hand, where the currents converge to the immediate vicinity of an entry or exit point, there may be a sufficient concentration of magnetic force and resistive heating to cause damage. Discussion of individual effects follows.

3.6.1 Pitting and Melt-through

If a lightning channel touches a metal surface, melting will occur at the point of attachment. Common evidence of this is the successive pit marks often seen along a fuselage, or the holes melted in the trailing edges of wing or empennage tips. Most holes are melted in skins of no more than 0.040" (1 mm) thick, except at trailing edges, where the lightning channel may hang on for a longer time and enable holes to be burned through much thicker surfaces. Since a finite amount of time is needed for melting to occur, the continuing currents are the lightning flash components most conducive to pitting and meltthrough. Melt-through of skins is usually not a safety--of--flight problem unless this occurs in an integral fuel tank skin.

3.6.2 Magnetic Force

It is well known that parallel conductors with current traveling in the same direction are mutually attracted to each other. If the structure near a lightning attachment point is viewed electrically as being made up of a large number of parallel conductors converging to a lightning entry (exit) point, then as lightning current converges to the point, forces occur which try to draw these conductors closer together. If a structure is not sufficiently rigid, pinching or crimping may occur. The amount of damage created is proportional to the square of the lightning stroke current amplitudes and is also proportional to the length of time during which this stroke current flows. Thus the high amplitudes of stroke currents are the lightning flash components most responsible for magnetic force damage.

Besides airframe extremities, other parts which may be damaged by magnetic forces include bonding or diverter straps, or any other object which may conduct concentrated lightning stroke currents. Magnetic force damage is usually not evident during a flight, and may not be detected until the aircraft is later examined after landing. However, since overstress or severe bending of metals is involved, parts damaged by this effect may need repair or replacement.

3.6.3 Pitting at Structural Interfaces

Wherever poor electrical contact exists between two mating surfaces, such as a control surface hinge or bearing across which lightning currents may flow, melting and pitting of these surfaces may occur. In one incident, for example, the jackscrew of an inboard trailing edge flap of a jet transport was so damaged by a lightning flash that the flap could not be extended past 15 degrees.

The jackscrew in this instance was not an initial attachment point and it became an attachment point only by being in the path of a swept flash. This incident illustrates the fact that lightning channels may reach seemingly improbable locations on the surface of an aircraft, and that protection designers must look beyond obvious lightning attachment points to find potential hazards.

A second example illustrates pitting caused by arcing in a structural interface. The arcing caused damage to the chemical conversion coating in the interface, resulting in accelerated corrosion within that region.

3.6.4 Resistive Heating

Another direct effect is the resistive heating of conductors exposed to lightning currents. When the resistivity of a conductor is too high or its cross--sectional area too low for adequate current conductance, lightning currents in it may deposit appreciable energy in the conductor and cause an excessive temperature rise. Since the resistivity of most metals increases with temperature rise, a given current in a heated conductor will deposit more energy than it would in an unheated, less resistant conductor; this process in turn increases the conductor temperature still further. Most metal structural elements can tolerate lightning current without overheating, and aluminum or copper conductors of greater than 0.5 cm^2 cross-sectional area can conduct severe lightning currents without overheating. Methods for determining temperature rises in conductors of specific material or cross-sectional size are available [3.10]

Wire explosion: Resistive energy deposition is proportional to the action integral of the lightning current and for any conductor there is an action integral value at which the metal will melt and vaporize. Small diameter wires, such as AWG 22 to 16, which are of the sizes commonly used to interconnect avionic equipment, or distribute AC power to small loads, will often melt or vaporize when subjected to full amplitude lightning currents.

The damage produced by explosive vaporization of conductors is usually most severe when the exploding conductor is within an enclosure, such as composite wing tips, because then the explosion energy is contained until the pressure has built up to a level sufficient to rupture the container. Partly, the damage results because the mechanical energy of combustion that the wire releases as it burns, and this adds to the energy deposited by the lightning current.

In most cases, such wiring is installed within conducting airframes and so is not exposed to major amounts of the lightning current. Some exceptions occur, however, such as a wiring harness feeding a wingtip navigation light installed on a non--conductive, fiberglass wing tip that is not protected with metallized coating or other paths (diverters) for lightning current. In such cases, lightning strikes to the navigation light vaporize and explode the wire harness, thus allowing the lightning current path to exist in plasma form within the wing tip. The accompanying shock wave can do extensive damage to the enclosing and adjacent structures.

Exploding wire harnesses are one of the most common and damaging lightning effects. They have, as far as is known, not had catastrophic consequences because these harnesses are usually found in secondary structures that are not flight critical. If these situations are allowed to exist within unprotected fiberglass   primary structures, such as a wing, the effects could be catastrophic. There is no reason, however, to allow these situations to exist because protection is easily applied. Such protection can also minimize the possibility of conducting lightning current surges into power distribution or avionic systems.

3.6.5 Shock Wave and Overpressure

When a lightning stroke current flows in an ionized leader channel, as when the first return stroke occurs, a large amount of energy is delivered to the channel in 5 to 10 microseconds, causing the channel to expand with supersonic speed. Its temperature has been measured by spectroscope techniques to be 30,000^{o} K and the channel pressure (before expansion) about 10 atmospheres. When the supersonic expansion is complete, the channel diameter is several centimeters and the channel pressure is in equilibrium with the surrounding air. Later, the channel continues to expand more slowly to the equilibrium situation of a stable arc. The cylindrical shockwave propagates radially outward from the center of the channel, and, if a hard surface is intercepted, the kinetic energy in the shock wave is transformed into a pressure rise over and above that in the shock wave itself. This results in a total overpressure of several times that in the free shock wave at the surface.

Depending on the distance of the channel from the aircraft surface, overpressures can range up to several hundred atmospheres at the surface, resulting in implosion damage. The lightning channel does not have to contact the damaged surface, but may simply be swept alongside it. Air pressure is the direct agent of damage.

Other examples of shock wave implosion damage include cracked or shattered windshields and navigation light globes. Modern windshields, especially those aboard transport aircraft, are of laminated construction and evidently of sufficient strength to have avoided being completely broken by shockwaves and overpressures. Broken windshields resulting from a lightning strike, however, are considered a possible cause of the crash of at least one propeller driven aircraft.

Little test data exists because manufacturers have shown a reluctance to test windshields. While windshields sometimes fail in laboratory conditions, this does not seem to duplicate in-flight experience. This may be because laboratory conditions do not successfully imitate actual lightning strike conditions, or there may be some other reason not yet understood. Additional discussion about windshields are included in Section 14.

3.6.6 Direct Effects on Nonmetallic Structures

Non-metallic materials used in aircraft include fiber reinforced composites and other plastics such as polycarbonate resins. The composites are of greatest interest since these may comprise much of an airframe. Polycarbonates are employed only in windows and some fairings. Fiberglass reenforced composites are non-electrically conductive and respond to lightning in a different way than the carbon fiber composites, which are electrically conductive.

Fiberglass composites: Some of these materials have begun to replace aluminum in secondary structures, such as nose, wing and empennage tips, tail cones, wing-body fairings and control surfaces, and on several occasions the entire aircraft has been fabricated of glass reinforced composites.

Often the nonmetallic material is used to cover a metallic object, such as a radar antenna. If this covering material is nonconducting, such as is the case with fiberglass or Kevlar, electric fields may penetrate it and initiate streamers from metallic objects inside. These streamers may puncture the nonmetallic material as they propagate outward to meet an oncoming lightning leader. This puncture begins as a pinhole, but, as soon as stroke currents and accompanying blast and shock waves follow, a much larger hole may result.

Examples of punctured fiberglass honeycomb radomes are shown in section 12. Streamers propagate from the radar antenna or other conductive object inside the radome, puncturing the fiberglass--honeycomb wall and rubber erosion protection boot on its way to meet an oncoming lightning leader. Most of the visible damage is done by the stroke current.

Carbon Fiber Composites: As stated, composites reinforced with carbon or boron fibers have some electrical conductivity, because of this, their behavior with respect to lightning differs not merely from nonconductive materials, but from that of aluminum (which is much more conductive). Carbon fiber composites (CFC) are employed extensively in primary structures.

In carbon and other conductive composites, resistive heating has an entirely different effect. As temperatures rise, the resin bonding the carbon fibers begin to break down, typically as a result of burning or pyrolysis. If the gases which the burning resins give off are trapped in a substrate, explosive release may occur with attendant damage to the structure. The damage may be great enough to result in a puncture. The principal risk is structural damage, although this is normally local to the puncture, especially if the punctured skin is comprised of cloth plies. Unidirectional (tape) ply laminates may allow damage to propagate further, at least on the surface ply. Many factors influence damage, and these are evaluated in the test data in this handbook. Unlike most aluminum alloys, which are ductile and will deform, but not break, CFC materials are stiff and may shatter. This damage is usually limited to the vicinity of the lightning attachment point.

Other plastics: Transparent acrylics or polycarbonate resins are often utilized for canopies and windshields. These materials are usually found in locations where lightning flashes may attach or sweep by. Most of the polycarbonates are very good insulators, however, and so will successfully resist punctures by lightning or streamers. The electric field will penetrate the canopy and induce streamers from conducting objects inside, however if the canopy dielectric is high enough these streamers will be unable to puncture the canopy.

Pilots of small planes beneath polycarbonate canopies have often reported electric shocks indicative of streamering off their earphones or helmets, but the current levels involved have not been harmful because the streamers have not come in contact with the lightning flash. Leaders approaching the outside of a canopy travel along its surface to reach a metallic skin, or those initially attached to a forward metal frame may be swept aft over a canopy until they reattach to an aft metallic point. Sometimes this occurrence will leave a scorched path across the canopy.

3.6.7 Direct Effects on Fuel Systems

Lightning presents a potential hazard to aircraft fuel systems. An electric arc or spark conducting only one ampere of current is sufficient to ignite flammable fuel vapor, yet lightning flashes may inject thousands of amperes of current into an aircraft.

There are several dozen civil and military aircraft accidents which have been attributed to lightning ignition of fuel and there have been fires and explosions within small aircraft fuel tanks. Although the exact source of ignition in some cases remains obscure, the most likely possibility is that electrical arcing or sparking occurred at some structural joint or plumbing device not designed to conduct electric currents. Some accidents have been attributed to lightning ignition of fuel vapors exiting from vent outlets, but this has never been positively established. Lightning strikes have also melted holes in integral fuel tank skins, igniting vapors within. Streamers induced from conducting objects within tanks made of non conducting materials such as fiberglass are believed to have ignited fuel vapors.

In addition to the direct effects described above, there are several instances in which indirect effects have evidently accounted for ignition of fuel. Lightning induced voltages in aircraft electrical wiring are believed to have resulted in sparks across, for example, a capacitance type fuel probe or some other electrical object inside fuel tanks of several aircraft, resulting in loss of external tanks in some cases and the entire aircraft in others. Capacitance type fuel probes are designed to preclude such occurrences, but some of the float-type fuel level sender units employed in small airplanes have not been designed nor tested to withstand lightning-induced currents without arcing or sparking.

The accidents and incidents noted above have prompted extensive research into the lightning effects on and protection of aircraft fuel systems. Improved tank design, lightning protected filler caps and access doors, active and passive vent flame suppression devices, and safer (i.e., less volatile) fuels are examples of developments which have resulted from this research. In addition, FAA airworthiness requirements now focus attention on lightning protection for fuel systems of both small and large aircraft. As a result, lightning strikes have presented fewer hazards to the fuel systems aboard modern aircraft than to those of older aircraft. Continued changes in airframe designs and materials, however, make it necessary to consider lightning protection in small airplane fuel tank designs.

3.6.8 Direct Effects on Electrical Systems

If an externally mounted electrical apparatus, such as a navigation lamp or antenna, happens to be a lightning attachment point, protective globes or fairings may shatter and permit some of the lightning current to directly enter associated electrical wiring.

In the case of a wing tip navigation light, for example, lightning may shatter the protective globe and light bulb. This may in turn allow the lightning channel to contact the bulb filament so that lightning currents may flow into the electrical wires running from the bulb to the power distribution bus. Even if only a fraction of the total lightning current enters the wire harness, it may be too small to conduct the lightning currents involved and thus will be melted or vaporized, as described in section 3.6.4.

The accompanying voltage surge may cause breakdown of insulation or damage to other electrical equipment powered from the same source. The externally mounted component affected is disabled, and, at worst, enough other electrical apparatus is disabled along with it to impair flight safety. There are many examples of this effect, involving all types of aircraft. Susceptible components generally include navigation lights, antennas, air data probe heaters and occasionally propeller blade or windshield heaters. The latter were quite susceptible to lightning strikes, and, since these wires were too thin to conduct the lightning currents, they were usually burned away. The high frequency radio sets feeding antennas were also frequently damaged, and cockpit fires were common.

3.6.9 Direct Effects on Propulsion Systems

With the exception of a few incidents of momentary interruption, there have been no reports of adverse lightning effects on the performance of reciprocating engines. Metal propellers and spinners have been struck frequently, of course, but effects have been limited to pitting of blades or burning of small holes in spinners. Lightning currents must flow through propeller blade and engine shaft bearings, and bearings may become pitted as a result, necessitating tear down and inspection in accordance with engine manufacturer’s instructions. Wooden propellers, especially ones without metal leading edges, could probably experience more damage, but there is no published data.

Turbine stalls: Reported lightning effects on turbojet engines show that these effects also are limited to temporary interference with engine operation. Flameouts, compressor stalls, and roll-backs (reduction in turbine speed) have been reported after lightning strikes to aircraft with turbo-prop and turbo-jet mounted engines. This type includes military aircraft with internally mounted engines and fuselage air intakes, and business-jet aircraft with engines mounted on the fuselage.

There have been no attempts to duplicate engine flameouts or turbine stalls with simulated lightning in a ground test, or have there been other qualitative analyses of the interference mechanisms. It is generally believed that these events result from disruption of the inlet air by the shock wave associated with the lightning channel sweeping aft along a fuselage. This channel may pass close in front of an engine intake, and if a stroke current occurs, the accompanying shock wave is considered sufficient to disrupt engine operation. The steep temperature gradient may be important. These effects have been reported as occurring more often on smaller military or business jet aircraft than on larger transport aircraft. Thus, smaller engines seem more susceptible to disrupted inlet air than are larger engines.

Operational aspects: In some cases a complete flameout of the engine results, while in others there is only a stall or roll-back. In most instances a successful restart or recovery of the engine to full power has been made. Operators of aircraft with turbine engines (especially small engines) with inlets close to the fuselage should anticipate possible loss of power in the event of a lightning strike and be prepared to take quick corrective action.

There have been only a few reports of lightning affecting wing mounted turbojet engines. Since these are usually large engines the shock wave from a lightning flash is probably inadequate to noticeably disrupt inlet air flow, and there have been no reports of stalls or rollbacks of wing-mounted turbojet engines.