Lightning Direct Effects Handbook

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Chapter

1.0 INTRODUCTION

This handbook is intended to assist aircraft design and certification engineers in protecting small personal aircraft against the direct effects of lightning strikes. It is also intended to assist Federal Aviation Administration (FAA) certifying engineers in assessing the adequacy of proposed lightning protection designs. Emphasis has been given to successful test results (which have largely been condensed) in an effort to assist protection design of new aircraft through similarity to previous successful designs. This compilation of data should also allow a designer to make early decisions and minimize development testing. The design engineer will also find this handbook a means of avoiding either ineffective protection methods or the testing of previously proven techniques.

This handbook addresses the direct effects of lightning strikes. Its intent is to provide guidance and educate engineering personnel responsible for lightning protection of primary aircraft structure. The recommendations included in this document are specific to the design of small personal aircraft and may not be as applicable to large composite aircraft designs. It is intended to assist engineers with limited experience in the design of aircraft lightning strike protection. Information is included on the natural lightning environment, the interaction between aircraft and lightning, and the mechanism of the lightning strike effects on the aircraft.

Protection design guidelines in this handbook are applicable to composite airframes, (including primary and secondary structures), control surfaces, exterior skins and fuel tanks. Composite materials to be included are fiberglass, aramid fiber and carbon fiber reinforced epoxies. Boron structures are addressed only briefly, as this material is not in wide use. This handbook also includes a discussion of verification procedures for determining the adequacy of protection designs.

Included herein is design and test data accumulated from a variety of references. These include airframe manufacturers and U.S. government research and development agencies. Specific sources are referenced throughout the handbook.

This handbook will not address the protection of: a) electrical systems and components and avionics, b) fuel system and fuel system components other than tanks, c) flight control systems other than control surfaces and d) protection of personnel from electrical shock. These items usually are exposed to lightning indirect effects and require case-by-case treatment. The protection of metal skins and structures is treated only briefly since other sources of lightning protection design information for metal airframes are readily available.

Periodic updates of this handbook are anticipated as additional test data and new protection materials and techniques are developed.

The user of this handbook new to lightning protection is urged to study the introductory sections on lightning interaction and effects before utilizing the protection design sections of this handbook. Treatment of these topics begins on an elementary level and is aided by illustrations which should enable the non-specialist to proceed to an adequate understanding of important aspects. Should this discussion be inadequate to the user's needs, a more comprehensive treatment is found in, Lightning Protection of Aircraft, Fisher and Plumer et al., published by Lightning Technologies Inc., 10 Downing Parkway, Pittsfield, MA 01201, or the identical volume, under the title Aircraft Lightning Protection Handbook, 1989, DOT Report No. DOT/ FAA/CT-89/22.

The designs included in this handbook represent typical methodologies or approaches to protecting composite materials from the direct effects of lightning. The advantage of using previously tested and proven protection methods is afforded by the ability to verify adequacy of protection designs through similarity to these previously proven methods. This should reduce program costs.

2.0 The Lightning Environment

2.1 Introduction

In order to accurately assess the interaction of lightning with an aircraft, one must have some knowledge as to the physics of the lightning phenomena. This helps one to understand the conditions under which aircraft are struck by lightning.

This section will discuss the following topics:

- Origins (Where and how lightning originates)
- Cloud-to-ground flashes
  - The negative flash to ground
  - The positive flash to ground
  - Inter- and Intra-Cloud Flashes
- Flash Parameters

2.2 Origins

Lightning flashes usually originate from charge centers in a cloud, particularly the cumulonimbus cloud, although they can occur in other atmospheric conditions. The charges in clouds are produced by complex processes of freezing and melting and by movements of raindrops and ice particles involving collisions and splintering. Typically, most positive charges accumulate at the top of the cumulonimbus clouds, leaving the lower regions negative, although there may be a small positive region near the base. The result is the typical structure of **Figure 2.2-1**.

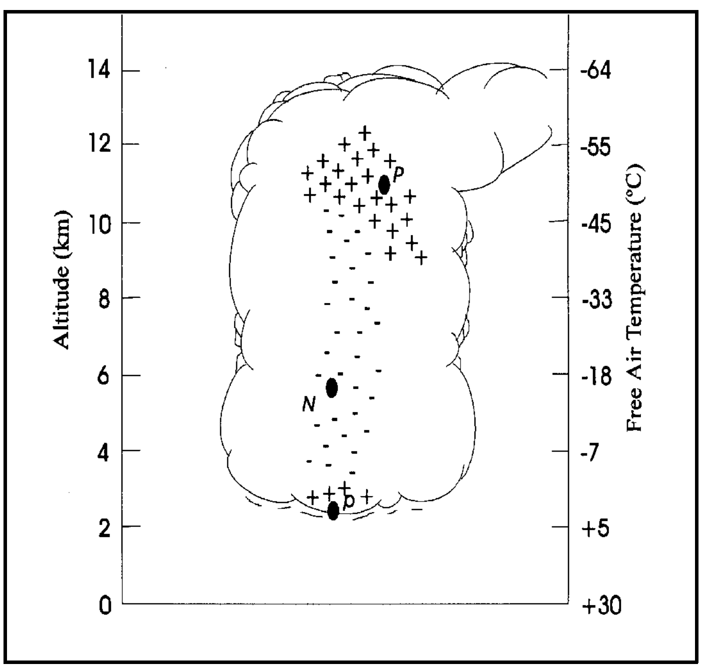


Figure 2.2-1: Generalized diagram showing distribution of electrical charge in a typical cumulonimbus cloud .

The electric charges within clouds produce electric fields which, if sufficiently intense, may ionize the air and produce electrical sparks which can develop into lightning flashes. These lightning flashes may be of three types, namely:

a) Flashes between regions of opposite polarity within a cloud (intra-cloud discharges)

b) Flashes between regions of opposite polarity in different clouds (inter-cloud charges)

c) Flashes between clouds and ground. These may originate from the cloud and propagate to ground, or originate from tall objects on the ground and propagate to a cloud.

It is believed that over 50% of all flashes are intra-cloud flashes.

2.3 Cloud-to-Ground Flashes

The process that culminates in a lightning flash begins with the formation of an ionized column called a leader which travels out from a region where the electric field is sufficiently high that it initiates progressive ionization. This occurs when the field is about 500kV/m. The leader advances in zigzag steps each about 50m long and separated by pauses of 40-100ms (hence the name stepped leader).

The diameter of the stepped leader is between 1m and 10m although the current, which is low (about 100A), is concentrated in a small highly ionized core, about 1 cm diameter. The average velocity of propagation is 1.5×10^5m/s. The leader may form branches on its downward path to the ground. When a branch is near to the ground, it causes electrical fields to intensify at projections such as trees and buildings. These fields may ionize the air and initiate junction leaders, one or more of which will make contact with the tip of the downward propagating leader. This has the effect of closing a switch and the location where the leaders connect is known as the switching point. When this occurs, charge in the leader may be conducted into the earth and the condition propagates rapidly up the leader. This is known as a return stroke, and the process discharges the leader at a velocity of about 5×10^7m/s. This initial return stroke is characterized by a current pulse of high amplitude accompanied by a bright flash.

A positive flash is one that lowers positive charge to earth while a negative flash lowers negative charge. It is common for a negative flash to discharge several charge centers in succession, with the result that the flash contains several distinct pulses of current, and these are usually referred to as subsequent strokes.

Return stroke modeling indicates that there is a decrease of the value of the return stroke current versus altitude. This is typical of a negative flash to open ground, but over mountains and tall buildings, the leader may be of the upward moving type, originating from a high point such as a mountain peak. When such a leader reaches the charge pocket in the cloud, a return stroke is also initiated and subsequent events follow the same pattern as for initiation by a downward moving leader. Thus the “switching” point is near the ground for downward leaders but near the charge pocket in the cloud for upward leaders. This can make a significant difference to the waveform and amplitude of the current experienced by an airborne vehicle which may be intercepted by a flash.

There is evidence that cloud-to-ground flashes produce more intense currents than intracloud lightning.

The negative flash to ground: An example of the return stroke current in a severe negative flash is sketched in **Figure 2.3-1**. The number of strokes in a negative flash is usually between 1 and 24, with the mean value being 3; very few flashes contain more than 24 strokes. The total duration of the flash is between about 20ms and 1s, with a mean value of 0.2s. The time interval between the strokes is typically about 60ms. There is some correlation among these parameters, the flashes with the most strokes tend to have the longest duration. The rise time of the first stroke is about 6µs, with a decay time (to half the peak amplitude) of about 70µs. Subsequent strokes in the flash tend to have higher rates-of-rise although lower peak amplitudes than the initial stroke and they can therefore be significant for inducing voltages in aircraft wiring, where the inductively coupled voltages are proportional to the rate of change of the lightning current.

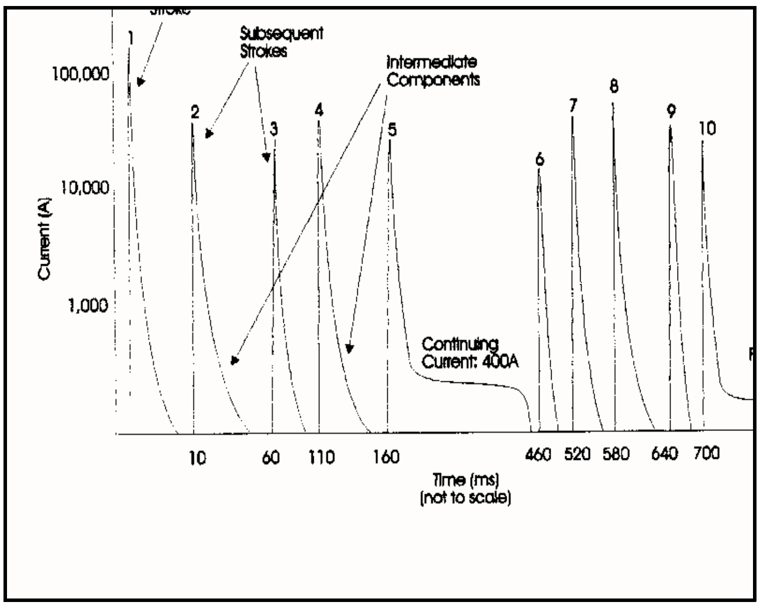


Fig. 2.3-1: Model of a severe negative lightning flash waveform.

Near the end of some of the strokes in a negative flash, there is often a lower level current of a few kA persisting for several milliseconds, known as an 'intermediate current', as shown in **Figure 2.3-1**. After some strokes a "continuing current" of 100-400A flows with a duration of 100-800ms, so that there is substantial charge transfer in this phase. It is particularly common for there to be a continuing current after the last stroke.

It is generally thought that before a restrike can occur the continuing current must cease, as illustrated after stroke 5 in **Figure 2.3-1**.

The positive flash to ground: Positive flashes to ground generally occur less frequently than negative flashes, however in certain geographic locations there may be more positive flashes to ground. Present standards have assumed an average of 10% of flashes to ground are of positive polarity. Positive flashes are usually initiated by upward moving leaders and more commonly occur over mountains than over flat terrain. Normally they consist of one stroke only followed by continuing current. Positive strokes have slower rise times than negative strokes, with higher peak currents and charge transfers. The stroke duration is longer than most negative strokes.

An example of the current in a positive flash is shown in **Figure 2.3-2**; it is a moderately severe example although not the "super flash" which occurs occasionally. Typically the rise time of a positive flash is 20µs and the total duration 0.1s. Although positive flashes are less frequent than negative, they have been considered in formulating the lightning environment for design and certification purposes.

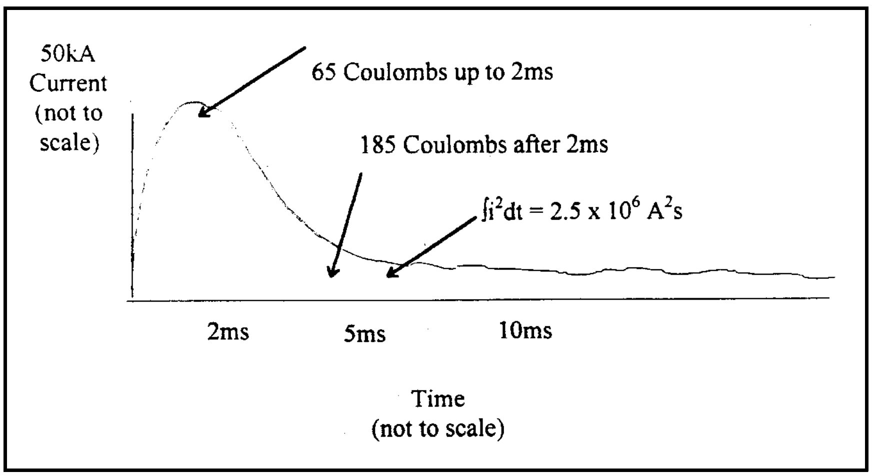


Figure 2.3-2: Typical Positive Flash

2.3 Inter and Intra-Cloud Flashes

The preceding discussion relates to flashes of either polarity to ground since most available knowledge relates to flashes of that type. Instrumented aircraft have been employed in U.S.A. and France to record the characteristics of cloud flashes. Generally speaking, the conclusion is that intracloud flashes are less severe than flashes to the ground, certainly with respect to peak current, charge transfer and action integral. However, the airborne measurements show some evidence that over a portion of some pulse wavefronts the rate-of-rise for a short time (less than 0.4µs) may be higher than the cloud to ground flashes. Short pulses of low amplitude but high rate-of-rise have been observed during intra-cloud flashes. Similar pulses due to charge redistribution in a cloud have been observed between return strokes in flashes to ground.

For intra-cloud discharges up to 60kA peak currents have been recorded, but are more typically 20-30kA. The pulses occurring during the initial lightning attachment phase occasionally occur in negative cloud to ground flashes.

For the designer of aircraft, the difference between cloud to ground and cloud to cloud lightning may be academic. Aircraft may, after all, be expected to encounter all types of flashes. Whether the high current striking an aircraft is associated with the upper end of a cloud-to-ground flash or with a intra-cloud flash makes no difference. Protection designs and test data presented here are expected to account for each of these lightning environments.

Additional data on the natural lightning environment and descriptions of the standard lightning environment for design and certification purposes may be found in "Aircraft Lightning Environment and Related Test Waveforms Standard," SAE AE4L, Committee Report AE4L-97-4, July 1997.

2.5 Natural Lightning Parameters

Most of the available statistical data are from cloud to ground and ground to cloud lightning flashes. The relevant data are presented in **Figure 2.5-1 and 2.5-2** is divided into negative and positive flashes. The tables include statistical data for the lightning currents and all related parameters of interest for the definition of the lightning environment. For a given flash or stroke parameter, the tables show that as the magnitude increases, the percentage of occurrence decreases. The extreme parameters do not occur together in one flash.

Table 2.5-1: Parameters for Positive Lightning Flashes Measured at Ground

Parameters	Unit	Lightning Parameters		
Positive Flashes		**95%**	**50%**	**5%**
Flash duration	ms	14	85	500
Total charge	C	20	80	350
Positive Stroke		**95%**	**50%**	**5%**
Peak current	kA	4.6	35	250
Peak rate-of-rise	A/s	2×10^8	2.4×10^9	3.2×10^{10}
Time to peak	µs	3.5	22	200
Time to half value	µs	25	230	2000
Impulse charge	C	2	16	150
Action integral	A^2s	2.5×10^4	6.5×10^5	1.5×10^7

–Note: The individual parameters listed above do not necessarily occur together in one flash.

Table 2.5-2: Parameters for Negative Lightning Flashes Measured at Ground

Parameters	Unit	Lightning Parameters		
Negative Flashes		**95%**	**50%**	**5%**
Number of strokes		1 - 2	3 - 4	12
Time intervals between strokes	ms	8	35	140
Flash duration	s	0.03-0.04	0.2	1
Charge in flash	C	1.3	7.5	40
Negative first stroke				
Peak current	kA	14	30	80
Peak rate-of-rise	A/s	5.5×10^9	1.2×10^{10}	3.2×10^{10}
Time to peak	μs	1.8	5.5	18
Time to half value	μs	30	75	200
Impulse charge	C	1.1	5.2	24
Action integral	A^2s	6×10^3	5.5×10^4	5.5×10^5
Negative subsequent strokes				
Peak Current	kA	4.6	12	30
Peak rate-of-rise	A/s	1.2×10^{10}	4×10^{10}	1.2×10^{11}
Time to peak	μs	0.22	1.1	4.5
Time to half value	μs	6.5	32	140
Impulse charge	C	0.2	1.4	11
Action integral	A^2s	5.5×10^2	6×10^3	5.2×10^4
Continuing current		**98%**	**50%**	**2%**
Amplitude	A	33	140	520
Duration	s	0.058	0.16	0.40
Charge	C	7	26	110

Note 1: The above lightning parameters do not necessarily occur together in one flash.

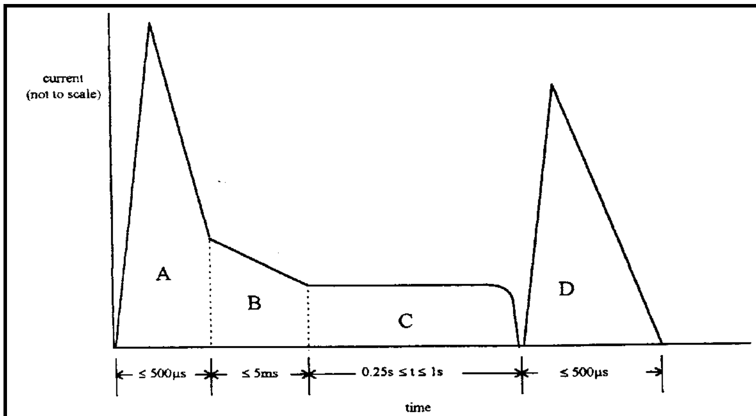
Note 2: The percentage figures represent percentiles, that is, the percentage of events having a greater amplitude than those given.

The available data indicate that the cloud to ground flashes represent the most severe lightning threat to the aircraft as regards with physical damage to composite structures. The high rate of rise pulse currents measured during the initial and the final attachment phases to instrumented aircraft may constitute a severe indirect effects threat. Similar pulses with fast rates of change have also been reported in cloud-to-earth flashes which convey negative charge to the earth.

In addition to the lightning currents, electric fields exist before and during a lightning strike event. Initially, these fields result in breakdown of the air to form the attachment and may also cause breakdown of dielectric materials on an aircraft. The magnitudes of these fields are dependent upon air breakdown thresholds and range between 400 and 3000 kV/m, with rates of rise of up to 1000kV/m/µs.

2.6 Protection Design and Verification Environment

The lightning environment for aircraft protection design and certification testing has been synthesized from negative and positive natural lightning flash characteristics and includes components designated *A, B, C* and *D.* These components are illustrated in Figure 2.6-1 and are from the document "Aircraft Lightning Environment and Related Test Waveforms Standard," Committee Report: AE4L-97-4," July 1997.



COMPONENT A (First Return Stroke)

Peak Amplitude	:	200kA (± 10%)
Action Integral	:	2 x $10^6 A^2 s$ (± 20%) (in 500µs)
Time Duration	:	≤ 500µs

COMPONENT B (Intermediate Current)

Max. Charge Transfer	:	10 Coulombs (± 10%)
Average Amplitude	:	2kA (± 20%)
Time Duration	:	≤ 5ms

COMPONENT C (Continuing Current)

Amplitude	:	200 - 800A
Charge Transfer	:	200 Coulombs (± 20%)
Time Duration	:	0.25 to 1 s

COMPONENT D (Subsequent Return Stroke)

Peak Amplitude	:	100kA (± 10%)
Action Integral	:	0.25 x $10^6 A^2 s$ (± 20%) (in 500µs)
Time Duration	:	≤ 500µs

Figure 2.6-1: Standardized Aircraft Lightning Environment

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.

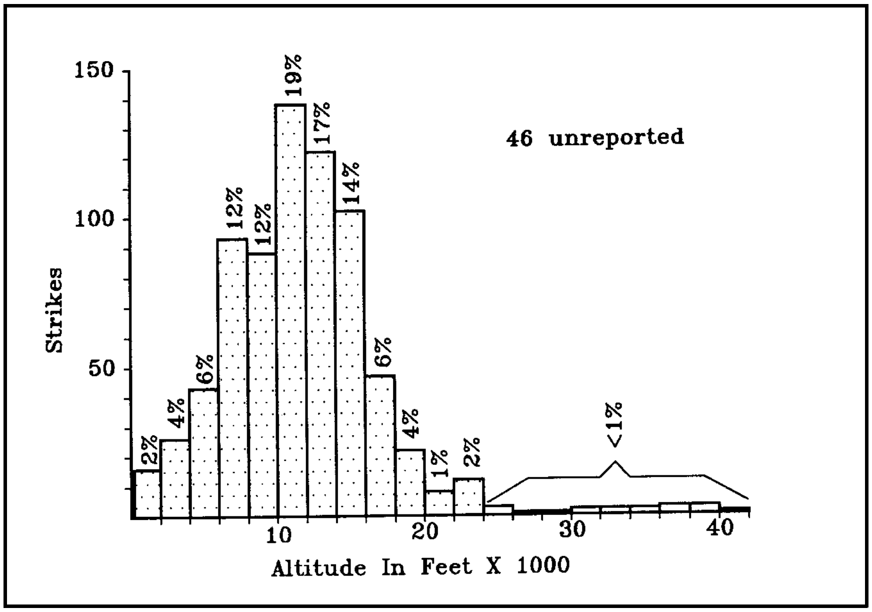


Figure 3.3-1: Aircraft lightning strikes vs. Altitude

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).

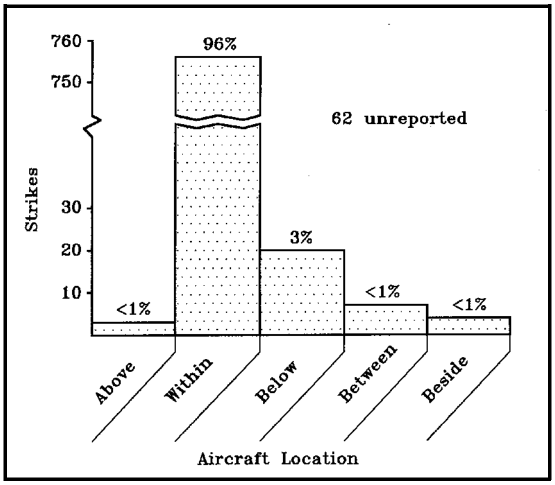


Figure 3.3-2: Aircraft location with respect to clouds when lightning strikes have occurred

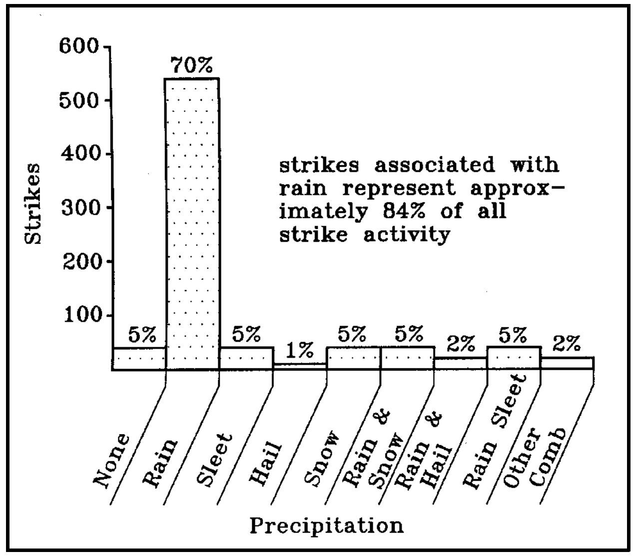


Figure 3.3-3: Precipitation at time of aircraft lightning strikes

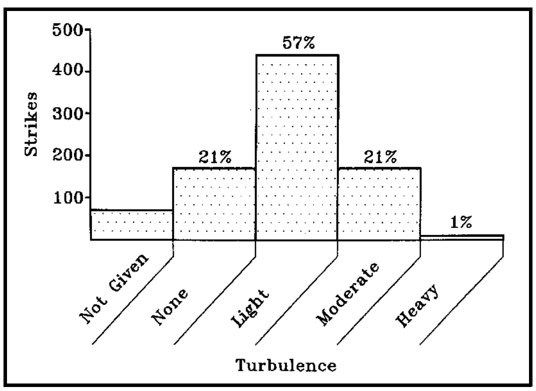


Figure 3.3-4: Turbulence experienced when lightning strikes have occurred.

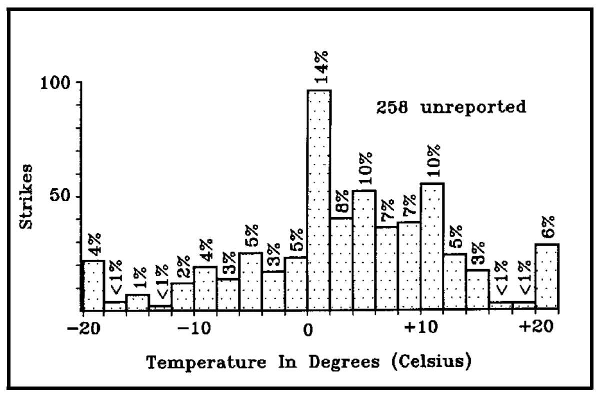


Figure 3.3-5: Outside Air Temperature during lightning strikes.

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.

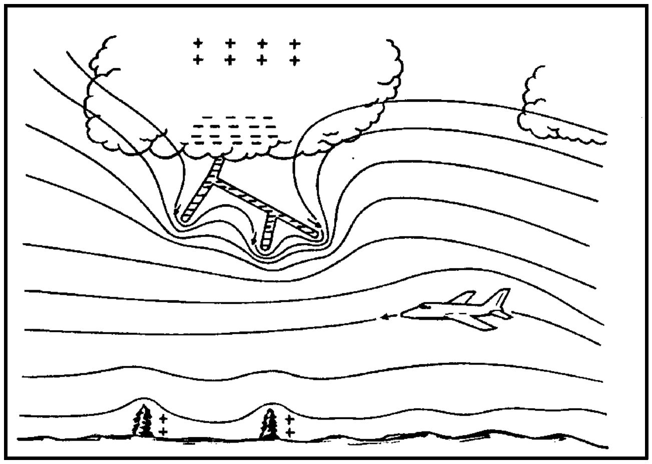


Fig. 3.4-1: Stepped leader approaching an aircraft.

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.

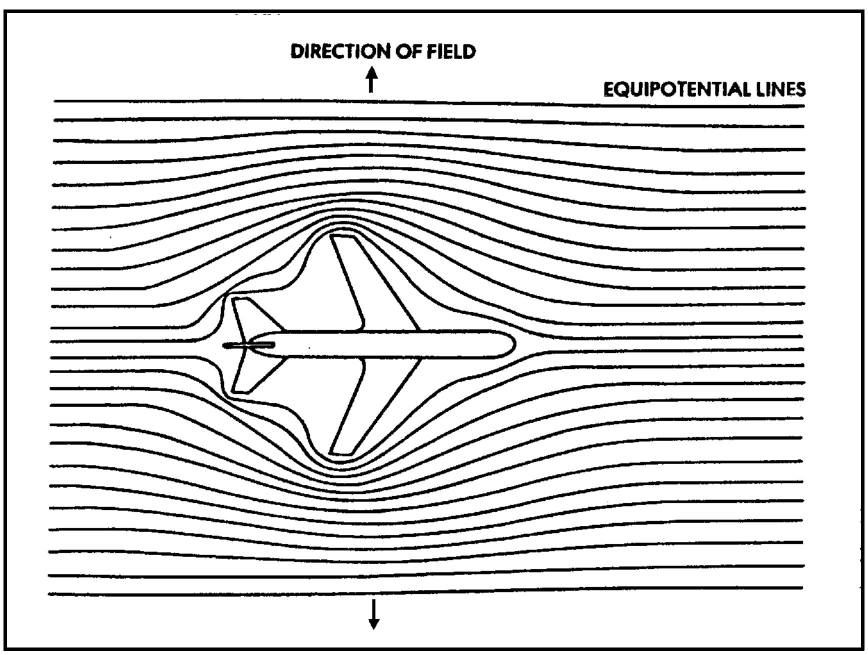


Fig. 3.4-2: Compression of electric field around an aircraft.

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.

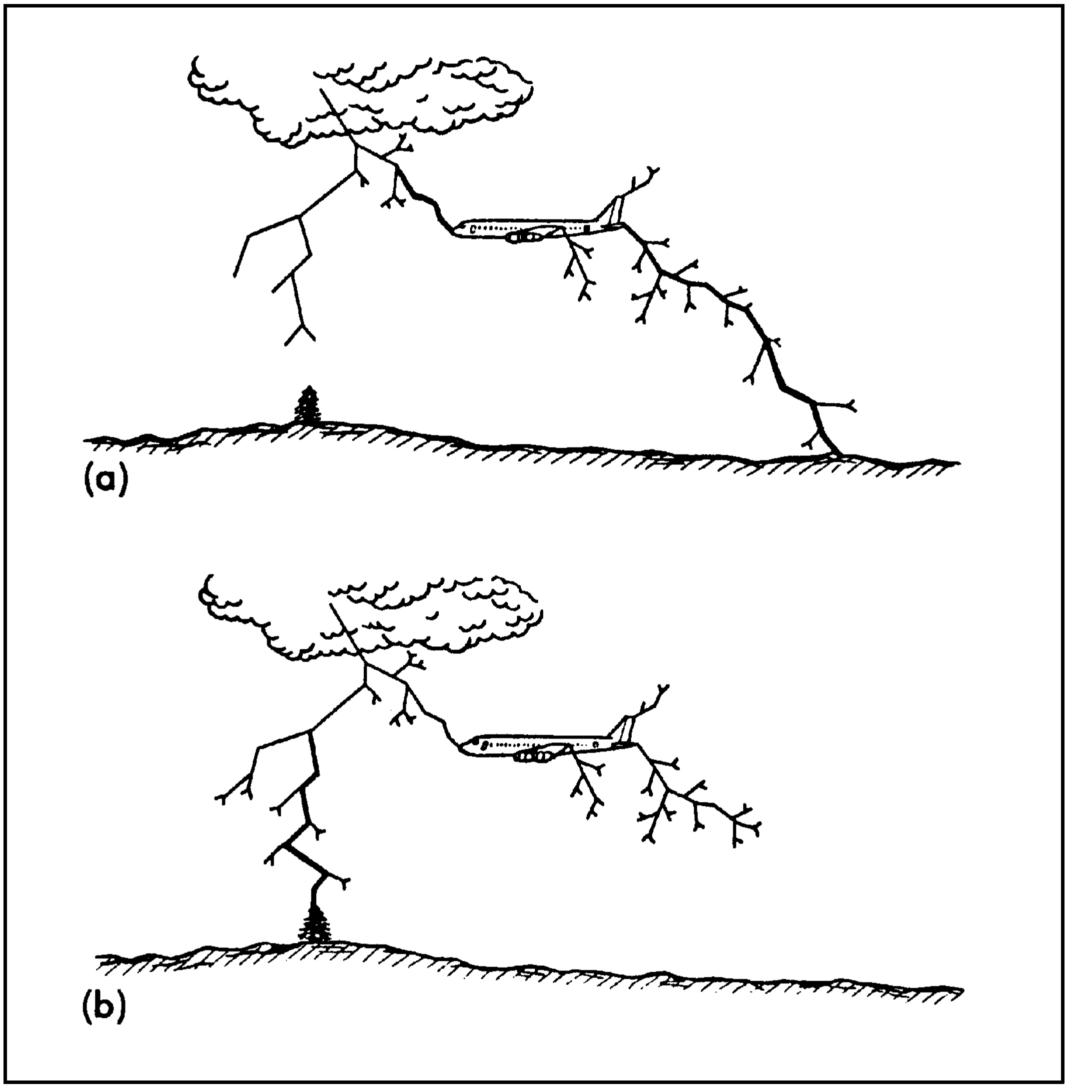


Figure 3.4-3: Return stroke paths

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.

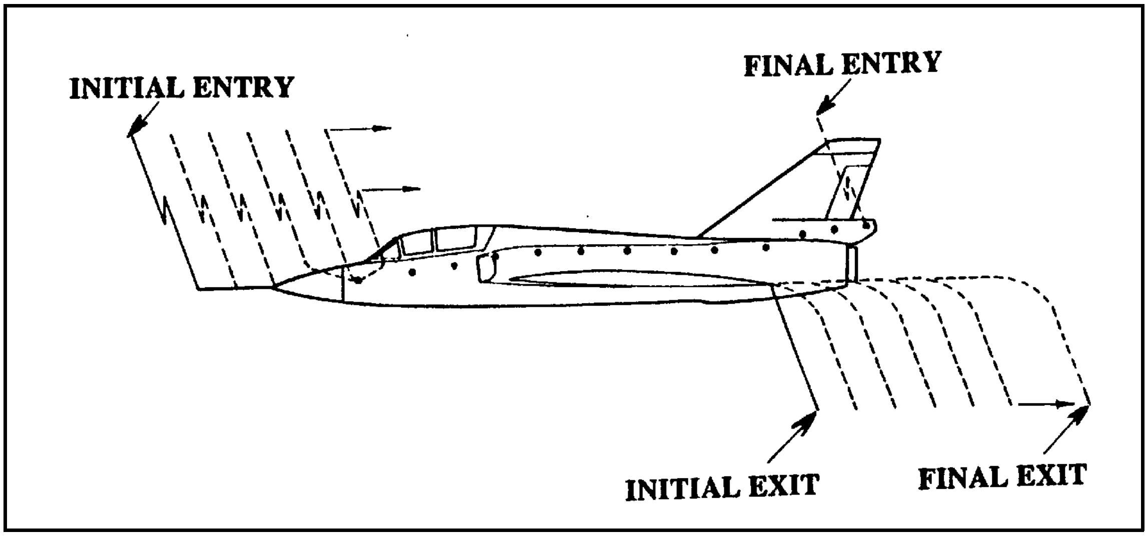


Fig. 3.5-1: Typical path of swept flash attachment points.

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.

Chapter 3 References

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4.0 THE CERTIFICATION PROCESS

4.1 Introduction

This chapter reviews the aircraft lightning protection requirements included in the Federal Aviation Administration (FAA) Federal Aviation Regulations (FAR's) and the steps that can be taken by applicants for certification to comply with these regulations. Where applicable, the role of the FAA certifying engineer or his designated engineering representative (DER) is discussed in addition to the activities of the aircraft design engineers and certification managers.

Related FAA advisory material and test standards are also described in this section. This section does not include design data or methodology. Those responsible for design and certification should be familiar with the material in this chapter before proceeding with a lightning protection design program.

Aircraft lightning protection requirements and related standards have improved substantially, to where they now address nearly all of the potential lightning hazards and incorporate the known aspects of the lightning environment. Before this, the aircraft protection requirements focused on a limited number of hazards, such as fuel tanks, access panels, antennas and other "points of entry." Regulations ignored problems such as internal arc and spark sources as well as indirect effects on electrical and avionic systems.

4.2 Federal Aviation Regulations for Lightning Direct Effects

Since lightning represents a possible safety hazard whose consequences may extend to loss of the aircraft and the lives of those aboard, the fundamental goal of aircraft lightning protection is to prevent catastrophic accidents, and to enable the aircraft to continue flying safely and be able to land at a suitable airport.

FAR's and AC's: Lightning protection requirements have therefore been included in the collection of Federal Aviation Regulations (FAR's) and Advisory Circulars (AC's) aimed at ensuring that the above goal is met for all except experimental and certain acrobatic aircraft. These regulations deal with the aircraft as a whole, and more specifically with the fuel system and other systems performing flight critical and essential functions. Specific regulations for each category of aircraft are reproduced in the following pages. As with most FAR's, they state a performance requirement, but do not include guidelines for compliance or specific technical design requirements. In this manner the FAR's allow the designer a maximum amount of flexibility. Emphasis is placed by the FAA on verification and compliance with the FAR's, in this case by demonstrating, often by test, that the designs do in fact provide the necessary protection.

Lightning protection requirements are included in the FAR's for Transport Category Aircraft (Part 25), Normal, Utility and Acrobatic Aircraft (Part 23), which are hereinafter referred to as "General Aviation" aircraft, and for both categories of rotorcraft (Parts 27 and 29), though some differences in applicable paragraph numbering and wording exist. It will be noted that the lightning protection regulations are functional requirements which are comparatively brief. The intensity of the lightning environment, the frequency of lightning strike occurrences and locations where strikes enter or exit the aircraft are not provided in the protection regulations.

The lightning environment for design and certification purposes is presented in FAA Advisory Circulars [4.1, 4.2], along with definitions of lightning strike zones and guidance for locating them on specific aircraft.

4.2.1 US Federal Aviation Regulations

The basic lightning protection regulation for airframes is the same for all vehicle categories, and appears in the FAR's for general aviation aircraft as *FAR 23*.867. Identical regulations are applicable to the other categories for aircraft:

Part 23.867 - Lightning Protection of Structure, This is the basic airframe lightning protection regulation, which requires that the aircraft be able to sustain a lightning strike without experiencing catastrophic damage. It reads:

> ***23.867 Lightning protection of structure****.*
> *(a) the airplane must be protected against catastrophic effects from lightning.*
>
> *(b) For Metallic components, compliance with paragraph (a) of this section may be shown by -*
> *(1) Bonding the components properly to the airframe; or*
> *(2) Designing the components so that a strike will not endanger the airplane*
>
> *(c) For nonmetallic components, compliance with paragraph (a) of this section may be shown by -*
> *(1) Designing the components to minimize the effect of a strike; or*
> *(2) Incorporating acceptable means of diverting the resulting electrical current so as not to endanger the airplane.*
>
> *[Amdt. 23 -7, 34 FR 13092, Aug. 13, 1969]*

Other regulations address specific systems, as follows:

Part 23.954 - Fuel System Lightning Protection

This regulation requires that fuel tanks and systems be free of ignition sources such as electrical arcs and sparks due to direct or swept lightning strikes at externally mounted fuel system components. The regulation reads:

> ***23.954 Fuel system lightning protection.***
> *The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by -*
>
> *(a) Direct lightning strikes to areas having a high probability of stroke attachment;*
> *(b) Swept lightning strokes on areas where swept strokes are highly probable; and*
> *(c) Corona or streamering at fuel vent outlets.*
>
> *[Amdt. 23 -7, 34 FR 13093, Aug. 13, 1969]*

4.2.2 Protection Design Objectives

The primary focus of the design guidelines presented in this handbook is to minimize lightning effects caused by severe lightning attachment to the aircraft and enable compliance with the lightning direct effects protection regulations described in Section 4.2.1. Following are the objectives of the lightning protection design direct effects:

1. Prevent catastrophic structural damage.

2. Prevent hazardous electrical shocks to occupants.

3. Prevent loss of aircraft flight control capability.

4. Prevent ignition of fuel vapors.

The regulations state that compliance can be shown by either bonding components to the airframe or by designing components so that a strike will not endanger the airframe. In this context the term “bonding” refers to electrical connections among components sufficient to withstand lightning currents.

At the time this basic regulation was formulated it was widely believed that hazardous lightning effects were limited to the external structure or to components directly exposed to lightning strikes and that protection from these effects could be achieved by ensuring that they were adequately bonded to the main airframe. Examples were flight control surfaces, air data probes, wing and empennage tips and other components located at extremities of the aircraft where lightning strikes most frequently occur. Adequate bonding would prevent damage to the hinges, fasteners and other means of attaching these components to the airframe.

Bonding resistance: Unfortunately, this emphasis on bonding has led some designers to conclude that bonding, by itself, will provide adequate lightning protection for an aircraft and that little else need be done. To them, a lightning protected aircraft has meant a "bonded" aircraft. Verification of this "bonded" status has, in turn, been signified by attainment of a specified electrical resistance among the "bonded" components. The industry has adapted various bonding resistance limits for this purpose, among them the US military specification *MIL-B-5087B* , which requires that components subject to lightning currents be interconnected with a "bonding" resistance not exceeding 2.5 milliohms. This is achieved by allowing metal-to-metal contact among parts and verified by a dc resistance measurement.

Criteria like the 2.5 milliohm bonding specification have taken on an importance all of their own, to the neglect of the real purpose of design. Whereas electrical continuity among metal parts of an aircraft is important, there are many other features of a successful protection design that are of equal or greater importance.

Effects within the aircraft: The focus of *FAR 23.867* on the bonding and externally mounted components has perhaps led designers to give much less attention to lightning effects occurring within the airframe, either directly from current flow among internal structural members or indirectly, from changing magnetic and electric fields interacting with electrical systems. These indirect effects have been the cause of several catastrophic accidents, brought about by electrical arcing among fuel tank components and by burnout of flight essential electronic components. More detailed discussions of these effects and related protection methods are found in the succeeding chapters.

The emphasis of *FAR 23.867* on the external and bonding aspects of lightning protection does not, of course, excuse the designer from actively identifying and addressing *all* potentially hazardous direct and indirect lightning effects.

4.3 Steps in Protection Design and Certification

Experience has shown that the most successful lightning protection design and certification programs have occurred when the work is conducted in a logical series of steps. In this case, success means achievement of a satisfactory protection design and compliance with the regulations, all with a minimum impact on weight and cost. The specific steps and order of occurrence may vary somewhat from one program to another, but most programs include the following basic steps:

4.3.1 Step a - Establish the Lightning Zone Locations

Lightning zoning is a functional step in demonstrating that the aircraft is adequately protected from both direct and indirect effects of lightning. The purpose of lightning zoning is to determine the surfaces of the aircraft which are likely to experience lightning channel attachment and the structures which may experience lightning current conduction between pairs of entry/exit points.

Zoning should be used with the aircraft hazard assessment to determine the appropriate protection for a given aircraft part or location. To determine the appropriate protection for parts and structure in a particular lightning zone, the criticality of the systems or structure in the zone should be considered.

ZONE DEFINITIONS: The surface of an aircraft can be divided into a set of regions called lightning strike zones. These zones represent the areas likely to experience the various types of lightning currents and consequently, the various components of the lightning environment. There are three major divisions representing:

1. Regions likely to experience initial lightning attachment and first return strokes,

2. Regions which are unlikely to experience first return strokes but which are likely to experience subsequent return strokes. This will happen where the aircraft is in motion relative to a lightning channel causing sweeping of the channel backwards from a forward initial attachment point.

3. Regions which are unlikely to experience any arc attachment but which will have to conduct lightning current between attachment points.

Regions 1 and 2 are subdivided into specific lightning attachment zones as follows:

Zones 1A and 2A, where long hang-on of a lightning channel is unlikely because the motion of the aircraft with respect to the channel causes the arc root to move across the surface of the aircraft in the opposite direction from the direction of motion.

Zones 1B and 2B, where the lightning channel is unlikely to move during the remainder of the flash because the location is a trailing edge or a large promontory from which the relative motion of the aircraft and channel cannot sweep the attachment point further.

Finally, an additional zone, 1C, is defined in which, by virtue of the change in current parameters along a lightning channel and the time taken for sweeping of the attachment point across the surface of the aircraft, the threat to the aircraft is reduced.

Specific zone definitions are as follows:

Zone 1A - First return stroke zone

All the areas of the aircraft surfaces where a first return stroke is anticipated during lightning channel attachment with a low likelihood of flash hang on.

Zone 1B - First return stroke zone with long hang on

All the areas of the aircraft surfaces where a first return stroke is anticipated during lightning channel attachment with a high likelihood of flash hang on.

Zone 1C - Transition zone for first return stroke

All the areas of the aircraft surfaces where a first return stroke of reduced amplitude is anticipated during lightning channel attachment with a low likelihood of flash hang on.

Zone 2A - Swept stroke zone

All the areas of the aircraft surfaces where subsequent return stroke is anticipated to be swept with a low likelihood of flash hang on.

Zone 2B - Swept stroke zone with long hang on

All the areas of the aircraft surfaces into which a lightning channel carrying a subsequent return stroke is likely to be swept with a high expectation of flash hang on.

Zone 3

Those surfaces not in Zone 1A, 1B, 2A or 2B and where any attachment of the lightning channel is unlikely, and those portions of the aircraft that lie beneath or between the other zones and conduct substantial amount of electrical current between direct or swept stroke attachment points.

The location of these zones on any particular aircraft should be agreed upon between the airframe manufacturer and the appropriate certification authority.

ZONE LOCATION PROCESS: The locations of the lightning strike zones on any aircraft are dependent on the geometry of the aircraft and operational factors, and often vary from one aircraft to another. The eight steps described below should be followed in locating the lightning strike zones on a particular aircraft.

<u>Step 1: Determination of Initial Lightning Leader Attachment Locations</u>: The first step in locating the lightning strike zones is to determine the locations where lightning leaders may initially attach to an aircraft. Analytical methods such as rolling sphere or electrical field analysis and test methods such as model lightning strike attachment tests can be used for this purpose. If initial lightning attachment data is available for an aircraft of similar geometry, this may be used in lieu of analysis or test for establishing initial leader attachment locations. Initial

attachment locations typically include extremities such as the nose, wing and empennage tips, propellers and rotor blades, some engine nacelles, and other significant projections.

Step 2: Location of Zones 1A and 1B: The second step in locating the lightning strike zones is to identify the surfaces that may experience possible first return stroke arrival. These locations will include Zones 1A and 1C. In most cases the aircraft will be moving forward when initially struck and the leader will have swept aft from its original attachment point by the time the leader reaches the earth (or other charge center) and initiates the first return stroke. The distance, d1, flown by the aircraft during this period determines the aft extension of Zone 1A surfaces, and is dependent upon aircraft velocity, aircraft altitude above the earth (for a cloud-to-ground strike), and leader velocity. Experience indicates that most severe strike encounters, which include current Component A, involve cloud-to-ground flashes that strike the aircraft at altitudes of 5,000 ft. (1500m) or less, so Zone 1A extensions can be based on this altitude.

Step 3: Location of Zone 1C: Zone 1C is applicable to surfaces aft of Zone 1A which can be reached by swept leaders at flight altitudes between 5,000 and 15,000 ft. Between 5,000 ft. and 10,000 ft., a first return stroke of lower amplitude then Component A, called current Component Ah, is applicable. The leader sweep distance associated with this altitude is designated d2. The aircraft surfaces lying between d1 and d2 are within Zone 1C. Since all aircraft fly at altitudes below 10,000 ft., the minimum rearward extensions of Zones 1A and 1C on a particular aircraft should be based on the highest velocities at which the aircraft operates for an appreciable time within these altitudes. If the aircraft never reaches one or the other of these altitudes, then its normal cruise altitudes and the highest velocities at which the aircraft operates for any appreciable time should be used. The leader velocity should be taken as 1.5×10^5 m/s.

Step 4: Further Zone 1A and 1C Extensions: In rare cases, first return strokes may occur further aft of initial leader attachment locations than is predicted by distances d1 and d2 as determined above. This possibility should be considered if the probability of a flight safety hazard due to a Zone 1A and/or 1C to a susceptible component is high.

Step 5: Location of Zones 2A and 2B: Since most aircraft can travel more than their entire length in the one or two second duration of a lightning flash, the remainder of the surfaces aft of Zone 1C should be considered within Zone 2A. Trailing edge surfaces should be considered in Zones 1B and 2B, depending on whether they can be reached by an initial strike (Zone 1B) or a swept stroke only (Zone 2B), in accordance with the zone definitions.

Step 6: Location of Lateral Extensions of Zones 1 and 2: Surfaces 0.5m (18in) to either side (i.e. outboard or inboard) of Zones 1 and 2 determined by Steps 10.1 through 10.4 should also be considered within these same zones to account for small lateral movements of the lightning channel.

Step 7: Location of Zone 3: Those surfaces not in Zones 1 or 2 and where there is a low expectation of any attachment of the lightning channel are considered to be in Zone 3. Zone 3 includes those portions of the aircraft that lie beneath or between the other zones and which conduct lightning current between areas of direct or swept-flash attachment.

In some cases a subsequent return stroke may occur in a region described as Zone 3. This possibility should be considered if the probability of a flight safety hazard due to a Zone 2A strike to a susceptible component is high.

<u>Step 8: Overlapping Zones</u>: Surfaces within Zones 1A and 1C are also in Zone 2A, as in some cases the first return stroke may occur near the initial leader attachment point, as at a nose or engine inlet cowl, with subsequent strokes occurring within the rest of the Zone 1A areas. Protection designs should be based on the worst case zones. Once the lightning strike zones have been established, they should be documented on a drawing of the aircraft, with boundaries identified by appropriate station numbers or other notations.

Examples of Zone Locations: Lightning strike zones located in accordance with the above guidelines are illustrated in Figure 4.3.1-1 for a general aviation airplane.

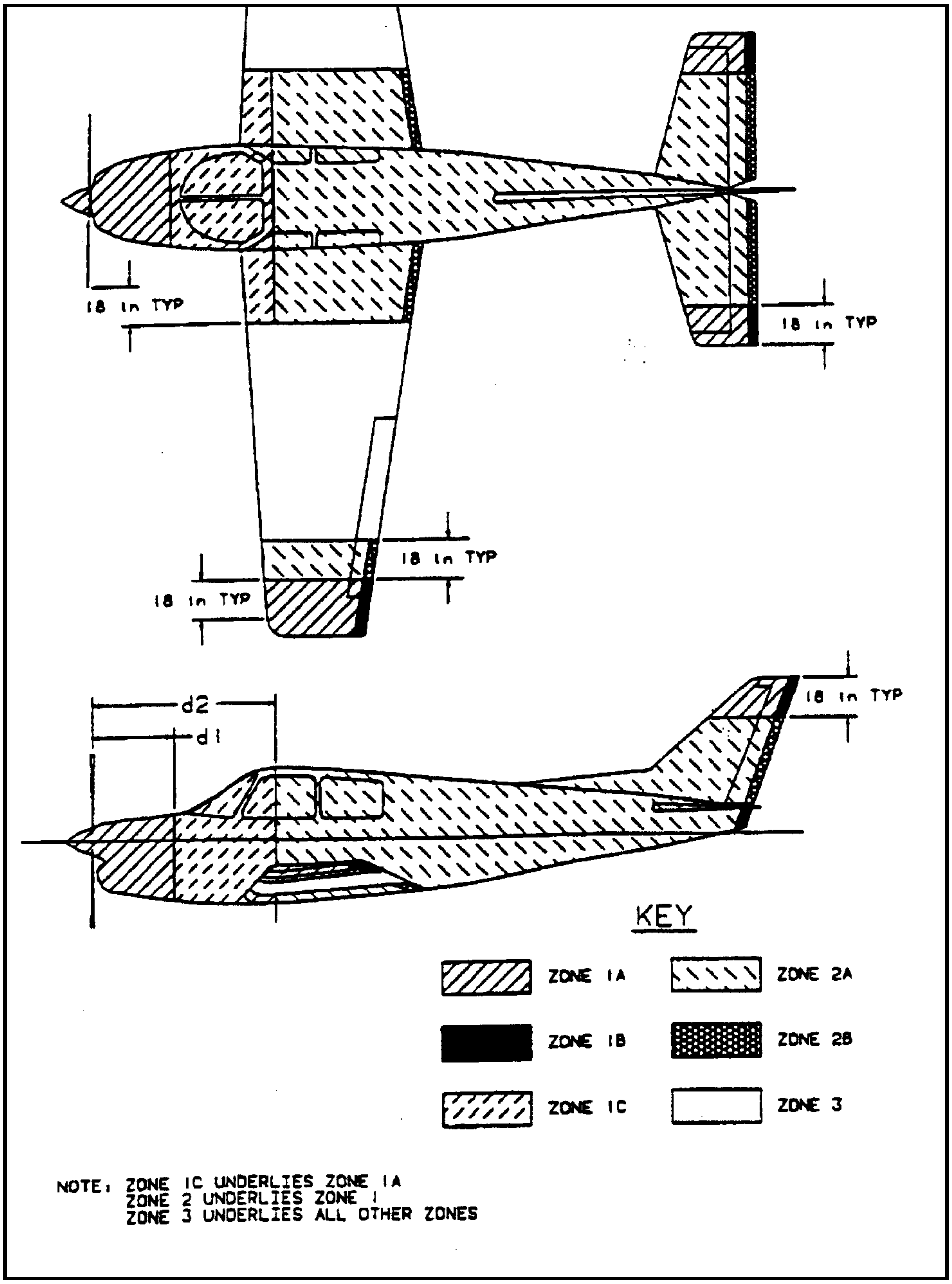


Figure 4.3.1-1: Typical General Aviation Aircraft Zone Drawing

4.3.3 Step c - Identify Systems and Components that are Performing Flight Critical or Essential Functions

Identify the aircraft systems and/or components that may be susceptible to direct and indirect effects of lightning, and whose function is critical or essential to the safe flight of the aircraft.

Determine if any of these structures and systems could be damaged or upset by direct or indirect lightning effects.

4.3.4 Step d - Establish Protection Criteria

In this step, the specific criteria for each of the structures and systems in need of protection should be decided upon. For direct effects, this will include definition of the degree of physical damage that can be tolerated by flight critical/essential structures, and establishment of ignition free criteria for the fuel tanks.

4.3.5 Step e - Design Protection

In this step, specific design additions, changes or modifications are made to the flight critical/essential structures, systems and components to enable them to meet the protection criteria established in Step d. For direct effects, this will involve a number of design techniques, ranging from selection of structural materials and manufacturing techniques to the addition of treatments or devices to improve electrical conductivity, arc or spark suppression, and shielding of electrical/electronic systems from lightning indirect effects.

4.3.6 Step f - Verify Protection Adequacy

Verification of protection can be accomplished by analysis, similarity to previously proven designs, or by test. Any of the three methods, or a combination of them, can be used, but similarity and analysis are normally considered first. If verification tests are needed, they cannot be performed until hardware has been designed, built and made available for testing. Frequently, development testing is advisable during the design process, and some of this test data may be useable for verification purposes.

Analysis: Typical analysis used for verification of direct effects protection methods include calculation of conductor temperature rises due to current, based on conductor material, cross-sectional area and action integral of the lightning current, or calculation of magnetic forces effects which are dependent upon current amplitude and geometrical factors. These analyzes are based on fundamental physical laws which can be described in mathematical terms.

Other analyzes include comparison of present designs with earlier designs for which an empirical data base exists. In this case, extensions or extrapolations are utilized to relate the existing empirical data bases to the designs of interest.

Analysis can rarely be utilized to determine the behavior of lightning currents in complex structures or components with multiple interfaces and current paths, especially when these interfaces have not been designed to conduct electric currents. Therefore, testing must frequently be used to evaluate lightning direct effects and verify protection design of structures.

Similarity: Verification of direct effects protection by similarity means that current-carrying structures and joints must be shown to have equal or greater cross-sectional areas and interface surface areas than the designs to which they are similar, and that other design features are also sufficiently similar so as not to respond differently to other lightning effects such as shock waves and magnetic forces.

Demonstration of similarity includes comparisons of detailed design drawings, parts lists and installation details, combined with such analyzes as are necessary to show that dissimilarities do not result in unforeseen hazards.

Examples of designs that may be verified by similarity are:

- Skins and structures
- Hinges and bearings
- Landing gear
- Flight control surfaces
- Windshields
- Joints, interfaces and couplings

Test: Many subsystems or components will be verified by test. The environment will be determined by the test specimen's physical location on or within the aircraft and the lightning strike zones that are applicable. More than one zone may apply; that is, components must conduct the lightning current away from the attachment point in addition to withstanding the thermal, blast and magnetic force effects of lightning attachment. Thus, all subsystems or components must usually withstand the *Zone 3* environment in addition to the surface zone environments.

Lightning direct effects are usually limited to the near vicinity of an attachment point. In most structures, the current will diffuse radially away from an attachment point and as the current density decreases, the physical damage also decreases. This indicates that the specimen size for test can be small compared to the size of the total structure or component.

4.4 Certification plans

Experience has shown, particularly on aircraft employing major amounts of composites or avionics that perform critical or essential functions, that preparation and submittal of a certification plan to the FAA early in the program is desirable. FAA concurrence with this certification plan should also be obtained. This plan is beneficial to both the applicant and the FAA because it identifies protection criteria and verification methods early in the certification process. As the process proceeds, analysis or test results may warrant modifications in protection design and/or verification methods. As necessary, when significant changes occur, the plan should be updated. The plan should include the following items:

Description of the airframe and systems to be addressed. This should include materials, installation configurations, any unusual or unique features, the operational aspects being addressed, applicable zone locations, lightning environment, and protection design level(s) (for avionics).

Description of the protection: There should be a brief description of the protection approaches. Frequently, this is subdivided to describe protection features for airframe and structures, propulsion and fuel, and electrical and avionics systems.

Acceptance Criteria: The acceptance criteria (also known as pass/fail criteria) should be identified and will apply to all parts of the lightning protection design.

4.5 Test Plans

When tests are to be a part of the verification process, plans for each test should be prepared which describe or include the following: purpose of the test; test article description and configuration (including appropriate drawing references); test setup to simulate the electrical aspects of the production installation; applicable lightning zone(s); lightning test method; test voltage or current waveforms to be applied; diagnostic methods; acceptance criteria; and the appropriate schedule(s) and location(s) of proposed test(s).

Some procedural steps that should be taken are:

A. Obtain FAA concurrence with test plans.

B. Obtain FAA concurrence on details of part conformity of the test article and installation conformity of the test setup.

   Part conformity and installation conformity should be judged from the viewpoint of similarity to the production parts and installation. Development parts and simulated installations are acceptable provided they can be shown to adequately represent the electrical and mechanical features of the production parts and installation for the specific lightning tests. Adequacy should be justified by the applicant and receive concurrence from the FAA.

C. Schedule FAA witnessing of the test(s).

D. Conduct testing.

E. Submit a final test report describing all results.

F. Obtain FAA approval of the report.

5.0 Protection Methodology

5.1 Introduction

This chapter describes generic protection methods. The effectiveness of these methods on specific airplane skin and structural materials, determined by lightning tests, is described in subsequent chapters.

Topics discussed in this section are:

- Skin and surface protection
- Composites, mechanism of damage
- Protection of composites requiring radar transparency
  - Solid bar diverters
  - Segmented diverters
- Protection of composites with conductive applications
  - Thermal sprayed metals
  - Woven wire fabrics
  - Solid metal foils
  - Expanded metal foils
  - Aluminized fiberglass
  - Conductive paints
  - Metalized fabrics
  - Interwoven wires
- Comparative weights of protection systems.

5.2 Skin and Surface Protection of composites

Composite materials are employed extensively in small aircraft design. For the purposes of lightning protection, composites may be divided into the categories of electrically conductive and non-conductive composites. The most common conductive composite is carbon-fiber reinforced composites (CFC), sometimes referred to as graphite epoxy (GR/E). The non-conductive composites generally include fiberglass and aramid fiber reinforced plastics.

Non-conductive composites are electrical insulators and cannot conduct lightning currents. Anti-static paints applied to some frontal surfaces, such as radomes, also have insignificant conductivity for lightning currents. Lightning electric fields will penetrate these materials without attenuation.

Conductive composites, such as CFC have adequate conductivity to prevent electric field penetration and prevent internal streamers. Non-conductive composites with conductive coating will also prevent electric field penetration when coatings approach 100% coverage.

5.2.1 Non-Conductive Composites

The non-conducting materials include aramid fiber and fiberglass. Non-filled resins, such as polycarbonates and acrylics are sometimes included in this classification. Glass employed in windshields, is also non-conductive.

Non-conductive composites are employed in many secondary structures such as radomes, wing and empennage tips, fairings and fins. These composites are also employed where skins must be transparent to radio and radar waves. Polycarbonates, acrylics and glass are used for canopies and windshields and view ports where optical transparency is desired.

5.2.2 Damage Mechanisms

Non-conductive composites are prone to punctures by lightning initiated streamers since electric fields are able to penetrate these skin materials and induce streamers from conductive objects within. Therefore, when employed as an exterior skin, they may be punctured by a lightning flash that contacts a conductive object beneath the skin. The high amplitude return stroke currents can then result in significant damage to these materials. Unprotected airframe skins fabricated of fiberglass or other non-conductive composites are subject to such puncture and damage.

Punctures of these composites can be prevented by providing external conductors called diverters to intercept the lightning flashes and divert them to the surrounding metallic structure. Design of such conductors requires some understanding of the mechanism of puncture and this is reviewed in the following.

Lightning produces damage to a non-conducting skin by puncturing these skins. Intense overpressures associated with stroke currents through the puncture may cause extensive damage to the composites.

Electric fields: Electric fields result in the formation of corona and streamers which propagate outward from enclosed conductors such as antenna elements. Fig. 5.2.1-1 shows a sketch of the process. Whether the streamers from the aircraft are induced by the electric field of an approaching lightning leader or whether they occur due to presence of the aircraft in a pre-existing response to an electric field, resulting in an aircraft initiated strike is rather academic; the point is that the streamers may puncture non-conducting composites.

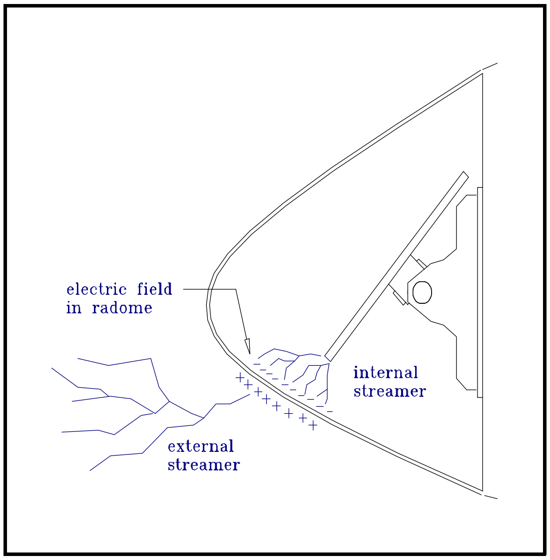


Fig. 5.2.1-1 Mechanism of puncture of a radome

In this process, the streamers will originate from the internal metallic objects and contact the internal surface of the skin, depositing electric charge there. The streamers spread electric charge in much the same way that a water hose would spread water around on the internal surface.

Puncture is more likely to occur with a composite material than a homogeneous plastic such as polycarbonates because composites have microscopic holes (porosity) and material interfaces through or along which an electric discharge can propagate. The field required to puncture a given thickness of fiberglass or aramid fiber composite is, in fact, only slightly greater than that required to ionize a similar thickness of air. A measure of the ability of a non-conductive material to resist puncture is its dielectric strength. Homogeneous materials, such as acrylic and polycarbonate sheets, have very high dielectric strengths and are more resistant to puncture.

Unprotected radomes are most often punctured, partly because of the low dielectric strength of non-conductive composites and partly because the radar antenna must, of necessity, extend beyond any adjacent metal structure. This, in turn, means that the electric field is concentrated around the metal structure of the radar and that electrical streamers can most easily form there.

There are two basic ways of providing protection for non-conductive composites. One employs diverter strips or bars on the exterior surface to serve as preferred streamer initiation points and intercept lightning flashes, while allowing the skin to be transparent to electromagnetic waves. This is the approach used for protection of radomes and some antenna fairings. The other method is to apply an electrically conductive material over the exterior of the structure. This latter method provides the most effective lightning protection and should be employed whenever possible. It also provides improved protection of enclosed systems against lightning indirect effects. Both of these approaches are discussed in the following paragraphs.

5.3 Protection of radomes and antenna fairings

These structures must remain electromagnetically transparent to permit radio and radar operation and are known as radio frequency (RF) transparencies. Therefore, in most cases, only diverter strips may be utilized for lightning protection if the transparent region is otherwise large enough to allow puncture by the lightning channel.

There are two types of diverter strips: solid and segmented. If properly applied, either type significantly reduces the number of lightning related punctures (of a radome for example), but they are not 100% effective. Occasional punctures of protected radomes occur. Application of diverters will be discussed with particular emphasis on radomes, because that is where they are most commonly used, but the discussion is equally applicable to any RF transparency, such as an antenna fairings.

Solid diverters: Solid diverters are continuous metal bars fastened to the outside of a skin to intercept a lightning flash and conduct the current to an adjacent metallic structure. Solid bars also provide some electrostatic shielding from the external electric field for objects under the skin. Thus they tend to inhibit the growth of streamers from internal objects.

Solid diverters should be designed to conduct the lightning current of the zone in which the part is located, typically 200 kA, for diverters on a nose radome in *Zone 1A*, and are usually made of aluminum, with a rectangular cross section sufficient to permit conduction of the current without excessive temperature rise or mechanical distortion. For

mechanical reasons, and to prevent fastener holes from unduly reducing the cross-sectional area, most diverters have cross-sectional areas of about 0.5 cm. sq., (0.08 in. sq.) though some are larger. A common design is 0.125-in. thick by 0.50-in. wide. The diverters are usually attached to the composite skin with screws spaced approximately 6 in. apart. It is important that the diverters be securely fastened to the radome or fairing to prevent their loss due to rain erosion and lightning magnetic force effects, and possible injection into engine inlets.

Some manufacturers of radomes install metal diverters that are not designed to conduct a severe lightning stroke and may be vaporized when exposed to a severe stroke current. These diverters are sometimes considered sacrificial, and are effective for only the first strike and may not provide protection for a subsequent lightning attachment to the same area. This is often a tradeoff of weight and costs versus the probability of a severe strike to a smaller aircraft.

Segmented diverters: Solid diverter bars tend to degrade RF transmission efficiency of radomes and fairings. To minimize this, segmented diverters, also called "button strips," may be utilized. These consist of a series of thin, conductive segments, interconnected by a resistive material, and fastened to a thin fiberglass strip which can then be adhesive bonded to the surface to be protected.

Segmented diverters provide many small airgaps that ionize when a lightning electric field is applied. Since the small gaps are close together, the resulting ionization quickly becomes continuous to guide the lightning flash across the protected surface.

Spacing between diverters: The maximum spacing between segmented diverters, and the minimum permissible spacing to underlying conductors, is dependent upon the amount of voltage required to ionize the segmented strips, the thickness of the radome skin, and the proximity of conducting elements behind the skin. Spacings typically range between 6 and 18 inches. Thin skins and/or close proximities require closer diverter spacings.

The length of a segmented diverter must also be factored into the protection design. It takes a certain amount of voltage per linear inch to break down the diverter. As the diverter gets longer and longer the voltage breakdown level becomes higher and higher. The diverter may get so long and take such a high voltage breakdown that it becomes ineffective.

Often to overcome this inherent problem of length, a combination of solid and segmented diverters have been used on larger structures.

5.4 Protection of Other Composite Skins

Where RF transparency is not required, or conductive structural materials are utilized, a conductive coating can be applied to the exterior surfaces of composites to prevent electric field penetration, and puncture, and to conduct lightning currents. Protective materials include arc or flame sprayed metals, woven wire fabrics, expanded metal foils, aluminized fiberglass, nickel plated aramid fiber and metal loaded paints. Some of these systems can also be used to protect CFC materials, as described. All of these approaches must be applied to the exterior surface of a composite skin, and there should be only one layer of protective material.

5.4.1 Arc or flame sprayed metals

Solid metal coatings applied by spraying molten metal onto the surface to be protected, or into the mold of a manufactured part can provide effective lightning protection. The protected skin material may be fiberglass or Kevlar-epoxy composites. The most common sprayed metal is aluminum.

Sprayed metal thicknesses range from 0.004 - 0.008 in. The metal solidifies on the exterior surface of the composite, resulting in a hard, stiff, conductive layer capable of conducting *Zone 1A* or *2A* currents with very little damage. The sprayed metal can be coated with paint, but paint thicknesses should be minimized, as thick primers and/or paints will intensify damage at lightning strike attachment points. Coatings sprayed on manufactured parts may have a somewhat rough finish and may require smoothing. This can be avoided by spraying the metal into a mold, after which the composite plies are laid in and cured. In this case the exterior metal finish will be smooth.

The advantages of arc or flame-sprayed metal are:

- Excellent protection for all strike zones
- The ability to cover complex shapes that might be difficult to cover with wire meshes or expanded foils.

Disadvantages are:

- Cost of process
- Weight
- Difficulty of mold separation

Some users have also reported cracking of the metal spray surface, probably due to differences in co-efficients of thermal expansion between metal and composite, or flexing of the composite skin under flight loads.

5.4.2 Woven wire fabrics

Metallic fabrics woven from small diameter wires of aluminum or copper can provide effective protection for non-conductive surfaces. The metal fabrics most commonly applied are woven of aluminum wires spaced 60 to 200 wires per inch. Wire diameters range from 0.002 - 0.004 in. These fabrics are identical to filter screens commonly used in the chemical and water processing industries.

Woven wire fabrics do not drape well over surfaces with compound curves and this is especially true of tightly woven fabrics. They must be cut and lapped to fit. Woven fabrics can readily be co-cured with a composite laminate since the resin can flow around the individual wire strands. They can also be cemented onto a previously manufactured surface, though care should be taken not to let a film of adhesive build up over the wires.

The lightning protection effectiveness of woven wire fabrics comes from the improved electrical conductivity of the metal wires as compared with the composite, and the period “holes” and “ridges” in the weave which intensifies local electric fields that enable dielectric breakdown of primers and paints at a multiplicity of points in the vicinity of the lightning attachment. This divides the lightning arc into many conductive filaments of low intensity, thereby dispersing the lightning energy over a wider area and reducing damage.

.
Advantages of wire fabrics include:

- Ability to co-cure with the composite laminate
- Effective protection for all strike zones
- Flexibility
- Light weight

Disadvantage is:

- Difficulty in draping over compound curves. This may require the fabrics to be cut into gores and lapped to fit.

An analysis of comparative weights of protection methods will be found at the end of this chapter.

5.4.3 Solid Metal Foils

Early use of foils as a protection method was limited to the use of unperforated, solid foils, much like that used in a household kitchen.

Metal foil can be adhesive bonded to non-conducting surfaces to provide a conducting layer. Metal foils of 0.001 in. or greater provide protection for the composite that is about the same as that provided by wire meshes, however, a substantial amount of foil will be melted away at the point of lightning attachment.

Manufacturing concerns have limited the application of solid metal foils. These foils do not drape smoothly over a compound curve. Solid foils must be cut and spliced to prevent wrinkles and this results in seams which might arc and delaminate when conducting lightning currents. Solid foils also have smooth, impervious surfaces, which makes them difficult to bond to the composite surface. Unbonded areas may allow the foil to become delaminated and to confine moisture, which can corrode the foils. Because of these difficulties solid metal foils are less commonly employed as compared with other protection options.

5.4.4 Expanded metal foils: Expanded foils are fabricated by a milling process that perforates and stretches a solid metal foil. The expanded foils have the superficial appearance of a woven wire mesh, yet are fabricated of one piece of metal, and thus have somewhat better electrical conductivity than metal fabrics which depend on contact between wires. Protection is effective for all lightning strike zones and is about the same as for woven wire meshes and sprayed metals.

> The physical description of expanded foils is often given in weight, rather than thickness. The number cited is in pounds per square foot; a foil referred to as 0.016 is, therefore, not 0.016 inches, but 0.016 pounds per one square foot of application. The weight cited is for the foil alone and does not include adhesive. Comparative weights of protection methods are given at the end of this chapter.

Expanded foils are better than wire fabrics at draping over compound curves since they can be stretched somewhat. They can be bonded to composite laminates as well as wire fabrics and, like fabrics, tend to promote arc root dispersion. Thus, much less expanded foil will be burned away at a strike attachment point than would be the case for an equal thickness of solid foil. Thermal and shock wave damage will also be less.

The primary difference between types and thickness of expanded metal foils is in their ability to carry highly concentrated lightning currents, such as along cabin door and window frames or other narrow paths. The lightest commercially available expanded foils will usually provide adequate protection for nearly all composite skin configurations when applied over wide surface areas, (i.e. over 12 inches wide) but however weight foils mus usually be employed along narrower current paths. Table 5.4.4-1 shows current carrying capabilities of typical foils. The selection criteria for any region of the aircraft should include current density in order to prevent vaporization of protective foils and loss of electrical continuity from one to another.

Advantages of expanded metal foils include:

- Ability to co-cease with the composite laminate
- Effective protection for all strike zones
- Excellent conductivity, especially at overlap region when co-cured
- Ease of application (including adhesion and cocuring) and draping
- Flexibility
- Light weight
- Ability to drape over compound curvatures

Disadvantages may be:

- Cost

Note: Expanded foils are a popular form of lightning protection for fiberglass and CFC composites.

Table 5.4.4-1 provides information pertaining to the current carrying capability of commercially available expanded metal foils.

Table 5.4.4-1: Current Carrying Capabilities of Foils

Material			Current Density Capability (kA / inch)
Style	**Weight or Thickness**	**Solid or Expanded**	
Aluminum	0.016 lb/ft^2	Expanded	8 - 12
Aluminum	0.028 lb/ft^2	Expanded	18
Copper	0.029 lb/ft^2	Expanded	7
Aluminum	0.001"	Solid	8
Aluminum	0.002"	Solid	14
Aluminum	0.003"	Solid	20
Aluminum	0.006"	Solid	35

5.4.5 Aluminized fiberglass

Glass fibers can be coated with aluminum and woven into fabrics with significant electrical conductivity. An individual coated filament has a nominal resistance of 2 ohms/cm. Preimpregnated fabrics (“prepreps”) made from aluminized fibers are available commercially.

A virtue of the material is that the outer ply of a fiberglass laminate can be replaced by a ply made from the coated fibers. Individual fibers can carry significant amounts of electric current because of the excellent thermal coupling between the aluminum and the glass. The glass provides a heat sink, enabling the aluminum coating to carry twice the current that could be normally carried by this much aluminum by itself.

At the point of lightning strike attachment, some volume of aluminum will be explosively vaporized, the area affected depending on the intensity of the current and the amount of aluminum on the prepreg. If the coated fiberglass material is covered by fillers or paints, the expanding gasses will be mechanically contained and more of the explosive force will be directed into the composite material, the added amount of damage being related to the mass of covering material. Paint and primer, thicknesses of less than 0.007 in. are usually not sufficient to cause any significant damage, but larger thicknesses can result in damage to several plies of fiberglass below the aluminum coated ply.

The increased damage caused by confinement of arc products is associated with any protective material. Confinement by surface finishes does, however, seem to promote more extensive damage to laminates protected with aluminized fiberglass than to those protected with woven wire fabrics or expanded metal foils.

5.4.6 Conductive paints

Adding conductive particles, such as carbon, copper or aluminum, to a paint results in a surface that has a certain amount of conductivity and some ability to provide lightning protection. This protection is marginal, however, since the conductive particles make only random contact with each other. As a result, the coating has a much lower conductivity than the metal meshes, foils or sprays.

No practical thickness of paint is sufficient to provide conduction of concentrated lightning currents. Instead, when current density exceeds the paints' ability to conduct, the paint acts to guide a flashover across the coated surface and the lightning current is then carried more in the resulting arc than in the conductive paint.

Conducting paint films are least effective if there is some conducting object beneath the surface of the insulating surface being protected. In such a case, the arc voltage might be high enough to cause a puncture through the insulating surface to that object. Damage will also be found to be greater if as in CFC materials, the composite itself has some conductivity.

Conducting paint does have the virtue that it can be applied to an existing surface, even one of complex shape. Copper paints have been the most widely used. One of the most successful applications of copper loaded paints has been in the protection of helicopter rotor blades fabricated of non-conductive composites. A coating of conductive paint approximately 0.003 - 0.005 in. applied under the finish coat of paint has been shown to prevent punctures of the blade skin. Paints have been less successful on blades with metal spars or embedded heater wires because sufficient voltage builds up along the conducting paint to puncture to the internal conductors. Resulting damage in these situations may be sufficiently extensive to represent a safety of flight hazard.

Conductive paints are the least desirable of lightning protection methods, partly because of this voltage buildup problem and also because they are subject to erosion from intense rain or hail. Also, such points would have to be present throughout the life of the aircraft.

5.4.7 Metalized carbon

Metalized carbon fibers have recently been made available by the industry. Available in both nickel coated and copper coated fiber, only the nickel coated variety has been tested. Protection for thin laminates has generally been disappointing, but protection for CFC laminates on the order of 10 plies (0.080" thick) has been promising.

This material is sometimes been used for electromagnetic shielding purposes, rather than lightning protection, especially on internal composite panels within cockpits and equipment bays.

5.4.8 Interwoven Wire

This method protects CFC laminates by the addition of fine metal wires woven into the outer ply of a CFC laminate. The wires do not degrade the mechanical properties of the CFC. They are typically woven bi-directionally among the outer layer of graphite fibers. Wire diameters have been in the range of 0.0005 in. To 0.02 in., although mostly in the range of 0.001 in. to0.010 in. Wires are positioned within the ply in such a way that there is often one wire per tow, resulting in 8 to 12 wires per inch. Although a number of metal wires have been tested, the most successful has been aluminum, possibly because of the lower melting point as compared with other metals. The wires installed must be incorporated in the outer structural ply. Additional layers of interwoven wire plies have a tendency to increase the degree of damage.

Tests show that interwoven wires provide a significant reduction in damage incurred by lightning strikes. Compared with an unprotected panel, which suffered a 6 to 8 inch puncture (*Zone 1A*) throughout all plies, a similar panel with interwoven wire suffered damage to the exterior ply (containing the wires) only.

Advantages of interwoven wires include:

- Ease of manufacture, maintenance and repair
- Negligible weight penalty

disadvantages may be:

- Potential for corrosion of the wires when exposed to moisture. Aluminum wires are most susceptible to this.

The protection effectiveness of interwoven wires is due to the arc root dispersion provided by he wires which appear periodically at the surface of the laminate, and promote primer/paint breakdown and multiple lightning attachment points. Additional attachments occur as wires vaporize when they attempt to conduct lightning current away from the lightning attachment areas. The vaporization products burst through the surface finish, creating additional arc roots.

5.5 Weights of Protection Materials

There is always some weight penalty associated with lightning protection materials. The interwoven wires in CFC have the least impact, while weights of other materials are dependant on thicknesses, and adhesion methods. Wire fabric alone weighs about 2 lbs./100 sq. ft. and when cocured, the total weight is about 3 lbs./100 sq. ft. Secondary bonding with additional adhesive can increase weight to 5 lbs./100 sq. ft. Table 5.5-1 provides a summary of typical weight penalties that may be expected:

Table 5.5-1 : Weights of Protective Coating Systems

Coating Material	**Weight** (lbs per 100 sq. Ft.)
Interwoven Wire (aluminum)	.024
Expanded Aluminum Foil	1.6 to 6 (2.9 typical)
Woven Wire Mesh	2.4 to 5
Wire Fabric	3-5
Thermal Spray (aluminum)	5.75 to 8
Conductive Paint (silver)	8
Aluminum Foil (solid)	8.5

6.0 Aircraft Skin Protection Effectiveness

The designer will find the following compilation of data useful for selection of candidates for lightning protection of the aircraft skins. This chapter provides further discussion of protection effectiveness based on previous test data. This chapter primarily addresses composite materials, since most aluminum skins are inherently self protecting; however, protection of aluminum integral fuel tank skins from melt-through is also addressed. This section includes discussions pertaining to the following topics:

- **Aluminum Skin Melt-through**
- **CFC Skin Protection**
- **Non-Conductive Skins Protection**

Protection Methods Examined: Several protection effectiveness data for methods of protection for aircraft skins are presented in this chapter. The most common method for protection of composite skins involves the application of a “protection ply” comprised of a metallized coating on the outer surface of the composite laminate. This process is referred to as “metalizing.” These coatings provide varied amounts of protection, and direct comparisons can, and should be made by lightning tests of skin specimens of similar construction and different protection systems. Many of the skin protection methods discussed in Chapter 5 of this handbook have been included.

The effectiveness of composite skin protection methods discussed in this chapter have been evaluated on various laminates including conductive carbon layups, non-conductive fiberglass and aramid fiber laminates. The success of the protection material may be influenced by the total thickness of the laminate and any core materials. Other conditions such as the thickness of paint and surface finishes, can also influence protection effectiveness. Attempts to weigh these factors were made during the selection process and notations are added where appropriate.

> The most effective way to successfully protect an aircraft from direct effects is to apply one or more of the protective layers described in Chapter 5 to the exterior surfaces of the aircraft. By so doing, the majority of the lightning currents will flow on the outside of the aircraft. Keeping the lightning currents on the outside of the aircraft will significantly minimize effects to systems and personnel.

> Dielectric coatings cannot protect the entire aircraft from a lightning attachment. On the contrary, the dielectric may actually increase damage at locations where the attachment occurs. Dielectrics should only be used to provide protection for small regions or components of the aircraft.

6.1 Aluminum Skins

Aluminum skins provide a high degree of conductivity, but may experience melt-through and physical deformation. Melt-through is predominately a concern for integral fuel tank design, but other, light-weight metal components such as control surfaces may experience deformation.

This section provides test data which will help to define the type of damage that may be expected when lightning attaches to painted aluminum skins of various thicknesses. The data will evaluate several thicknesses of skins and illustrate the effects of the various current components of lightning.

Melt-through: Studies have shown that the volume of metal melted away at a lightning attachment point is closely related to the charge carried into the point by the lightning arc, at specific current amplitudes. A nearly linear relationship exists between the amount of charge delivered to an arc attachment spot and the amount of metal melted from it. In determining the minimum amount of charge and current required to melt aluminum skins, the effects depend on current amplitude as well as charge, as shown in Figure 6.1-1.

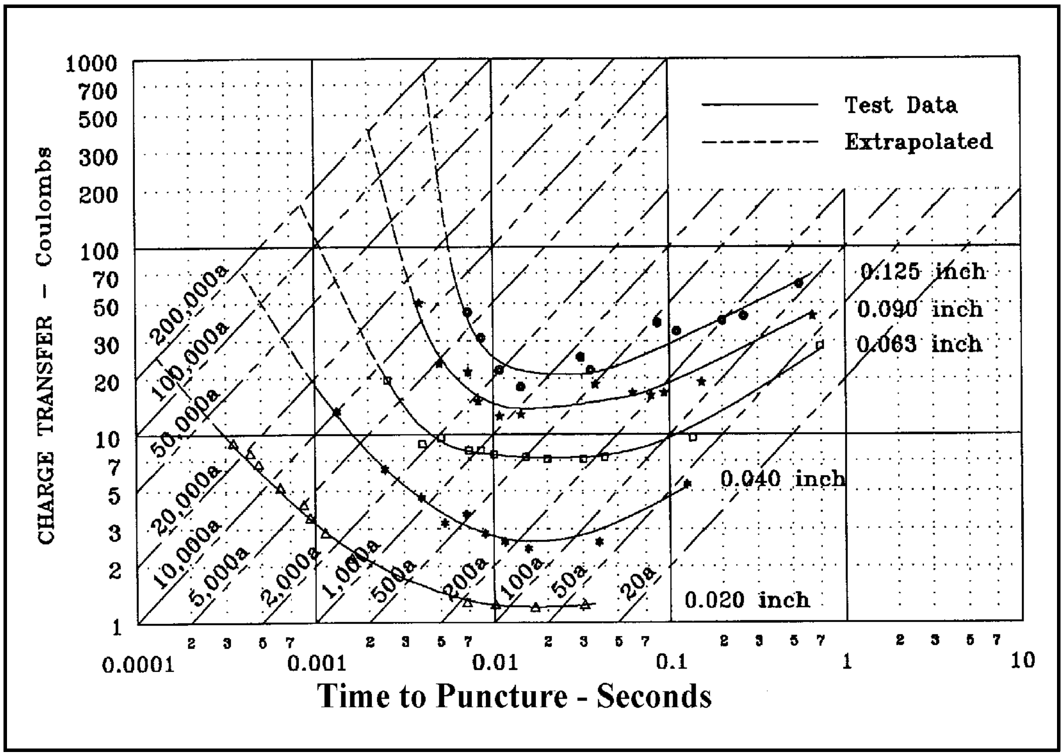


Fig. 6.1-1: Time to melt-through on aluminum skins

Figure 6.1-1 provides guidance on the amount of coulombs and time required to melt through an aluminum skin, which may be considered to be the time at which fuel vapor ignition may occur as the hot lightning arc may then be presumed to be in contact with fuel vapor. The data also explores the average current amplitude versus time. It has been shown that over 22 C, when delivered by a current of 200 A was enough to melt completely through a skin of 0.080 inch thickness. As little as 2 C, when delivered by about 130 A, melted a hole completely through a skin sample of 0.040 inch thick aluminum.

The 100,000 A stroke current do not typically melt-though aluminum skins as their time duration and charge transfers are too low. Intermediate (component B) and continuing currents (component C) remain attached to a spot long enough to melt-through.

Whether melt-through occurs or not depends on the time that a lightning arc remains attached to a single spot. This is called the “dwell time”. Dwell times on painted skins have been determined to be less than 20 milliseconds, whereas dwell times on unpainted aluminum skins are less than 5 milliseconds. Skins in zones 1A or 2A must tolerate current Component B and, if the dwell time exceeds 5 milliseconds, also a portion of continuing currents, Component C. Component B by itself delivers 10 coulombs of charge, but Component B (5 milliseconds) plus Component C for a additional 15 milliseconds delivers 6 additional coulombs (at a rate of 400 A) for a total of 16 coulombs. Figure 6.1-1 shows that 10 coulombs melts through 0.040 in. of aluminum in 5 ms, but 16 coulombs melts through 0.080 in. thick skins. Flight experience has shown that 0.080 in. thick skins have resisted in melt-through, whereas thinner skins have been melted through; corroborating the data of Figure 6.1-1.

Few small airplanes can tolerate the weight of 0.080 in. skins on integral fuel tanks, nor require skins this thick for structural purposes. Therefore, other approaches need to be considered for lightning protection of small airplane skins.

Unpainted aluminum skins 0.040 in. survived and greater have resisted melt-through under the *Zone 1A* or *2A* lightning environment. The unpainted surface allows the lightning channel to attach to a subsequent point sooner than when a dielectric paint covers the aluminum, keeping dwell times less than 5 ms. This shorter “dwell time” results in less coulomb transfer, therefore less chance of skin melt-through.

Protection from Melt-Through for Metal Skins: The protection of thin aluminum skins (0.020-0.060) have utilized a variety of methods for improving resistence to melt-through. Typically four methods have been implemented in designs;

a. Increased metal skin thickness: This method is the least desirable because of the additional weight that may not be needed for structural reasons and is only there for melt-through protection. Whereas an aluminum unpainted skin of 0.060" may be adequate to prevent melt-through, a painted skin may need to be greater the 0.080" thick as shown in Figure 6.1-2(a).

b. Add a dielectric barrier to the inner surface: In regions of a limited area, adhesives or polysulfide-type fuel tank sealants have been added to create a barrier between the metal skin which may melt the fuel cell vapors. This method does necessitate controlling the thickness of the sealant over protected areas. Other approaches that provide similar results for fuel cells are bladder installations and internal thin-walled plastic fuel tank enclosures that are becoming increasingly popular with small aircraft designs.

c. Addition of conductive particles within the exterior surface paint: The function of these particles is to reduce arc dwell time and improve the arc root dispersion, which allows multiple conduction paths through the painted surface. The technical reasoning behind this concept is sound, however verification testing is difficult unless the facility has the ability to test in a moving air stream or with the test article moving to verify decreased dwell times. Figure 6.1-2(b) illustrates the concept of improved arc root dispersion.

d. Laminated aluminum skins: The key to the success of this technique is to insure that a thermal barrier exists between the aluminum skin and the inner layer. Adhesive films have provided a sufficient barrier to prevent arc attachment to the inner aluminum skin. The arc remains attached to the edges of the hole melted in the exterior layer instead. A condition of an 0.020 in. (external) and a 030 in. (internal) aluminum ply, of total aluminum thickness 0.050 in. has successfully withstood the painted surface (i.e. 16 coulombs) zone 1A or 2A lightning environment. Figure 6.1-2(c) illustrates this protection concept.

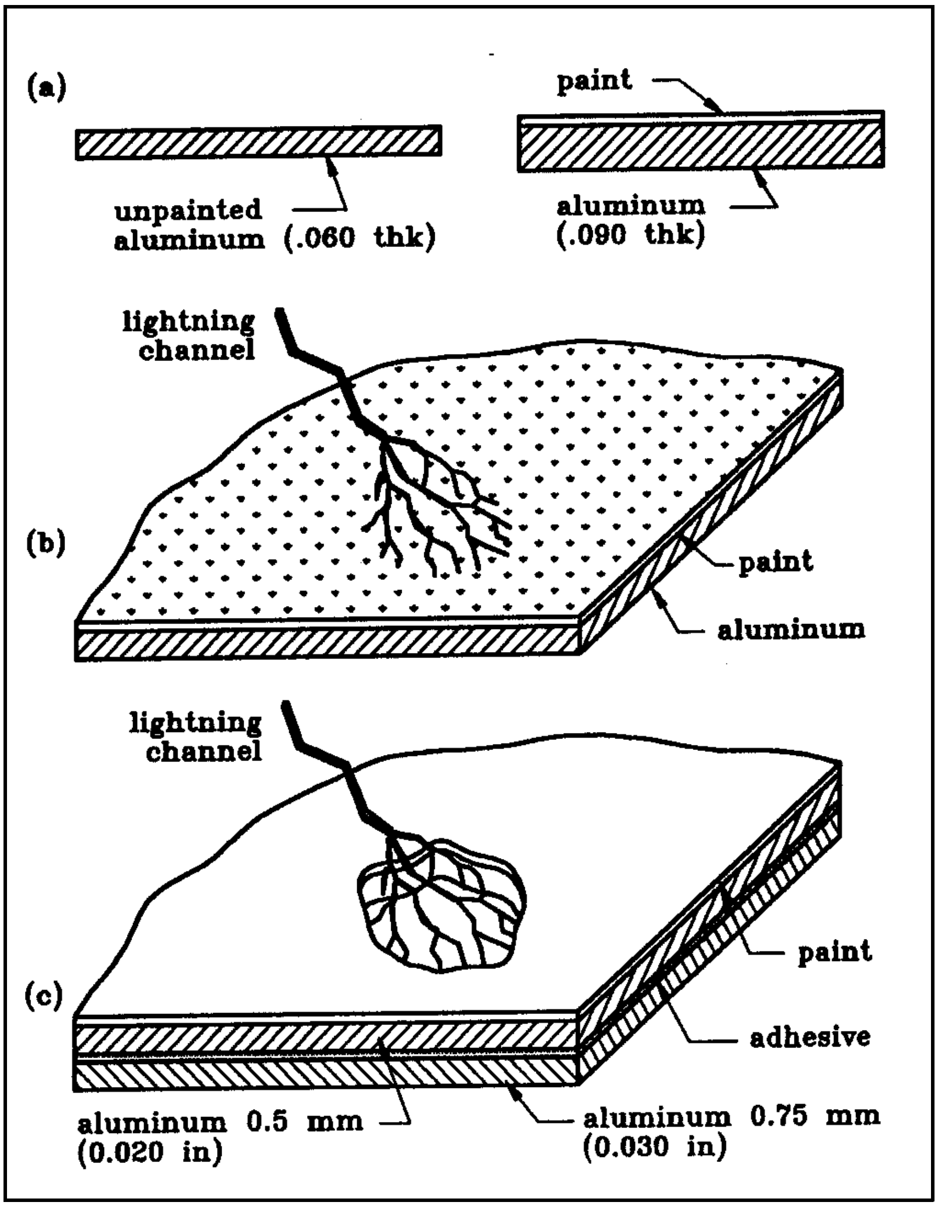


Fig. 6.1-2: Methods for protecting against melt-through.
a) Increasing skin thickness
b) Arc root dispersion / Decreasing dwell time
c) Laminated skins.

Aluminum Skin Test Data: Lightning testing of aluminum skin panels has demonstrated the shock wave effects of stroke currents and the relationship of *Component B and C* charge transfer and melt-through. Panel thicknesses of 0.032, 0.040 and 0.080 were evaluated for lightning melt-through tolerance.

Table 6.1-1 lists typical test results. A *Zone 2A* strike of 5 ms dwell time (Components D and B only) will generally melt through a panel less than 0.080 inches thick. Even the 0.080 panels may show resolidified metal on the interior surface. Figures 6.1-3 through 6.1-5 show typical damage to aluminum skins caused by Zone 1A and 1B test currents.

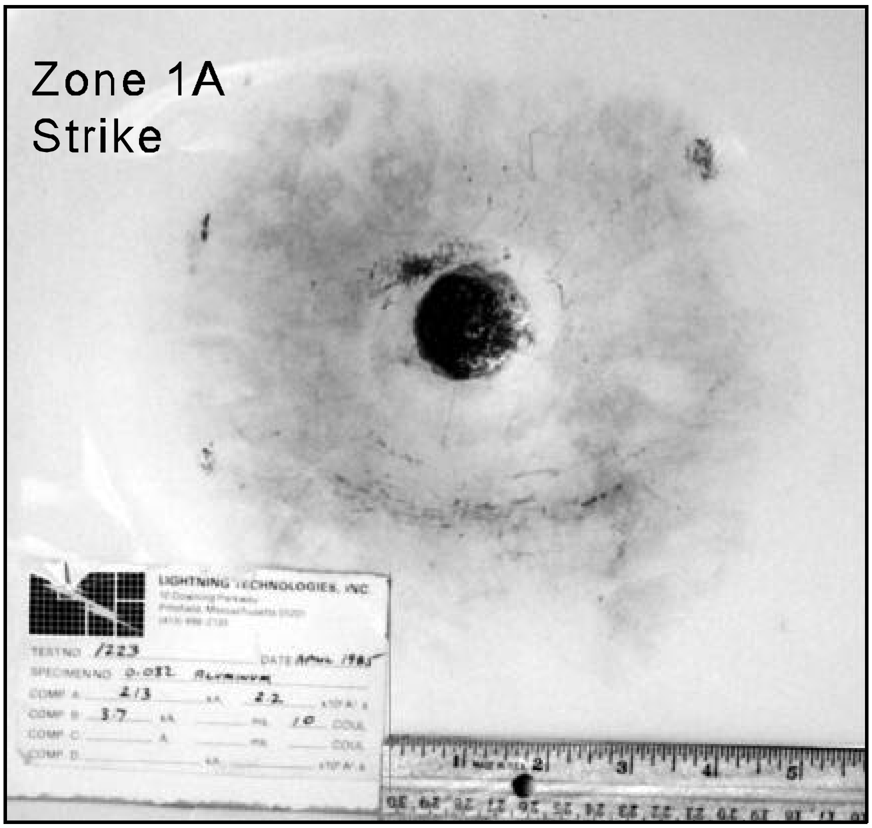


Fig. 6.1-3 : Aluminum panel (0.032" thick)
darkened area is a 2" in. diameter dent to a depth of 1"
no melt-through.

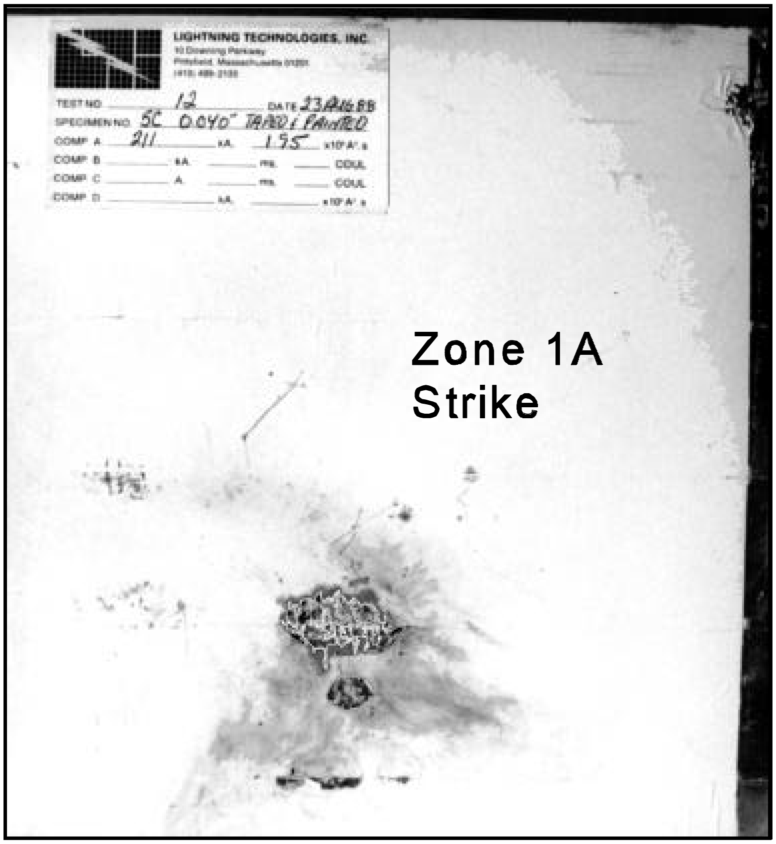


Fig. 6.1-4: 0.040" painted aluminum panel covered by aluminum tape; melted hole 0.2" through panel, foil loss 1" dia. minor indentation

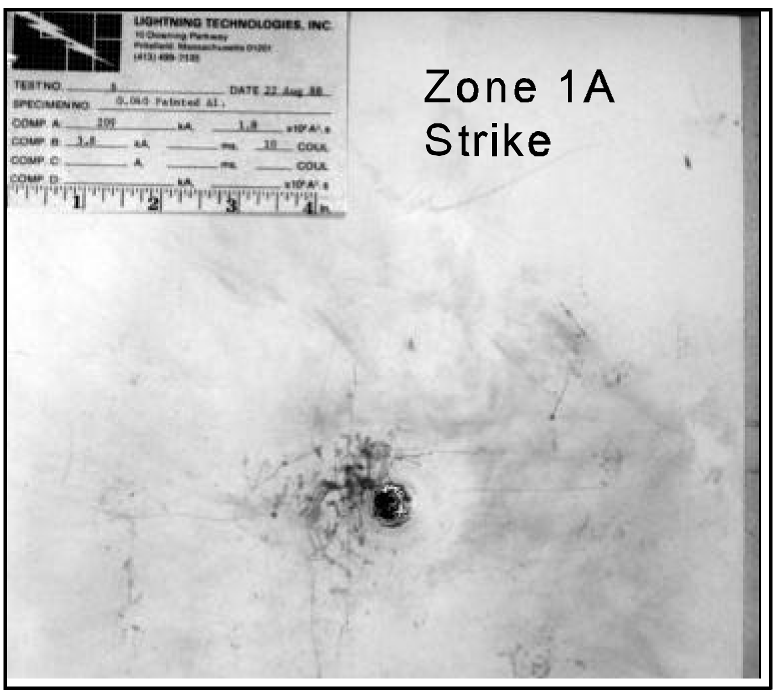


Figure 6.1-5 : 0.040" dent, small hole aluminum panel with Zone 1A Strike

Table 6.1-1: Typical Aluminum Skin Test Data

Panel No.	Panel Thickness (in.)	Comp. A (kA)	Comp. B (C)	Comp. C (C)	Zone	Affects
1	0.032 Unpainted	213	10	none	1A	1" Dent., pitting >2 in., shown in fig. 6.3-1
2	0.040 Primer	215	3.5	none	1	Primer burned, surface melting, metal splatter, no hole
3	0.040 Painted	209	10	none	1A	Dented and pitting, hole 0.1 in. dia., fig. 6.3-3
4	0.040 with Al tape	211	none	none	(a)	Tape evaporated over irregular area, scorching and pitting beneath, small dent
5	0.040 with Al tape	none	3.80	none	(a)	.25 in. pitting and burn, .10 in. hole
6	0.080 Unpainted	none	10.2	none	(a)	Slight cosmetic damage no melt-through
7	0.080 Unpainted	none	10.0	26	(a)	Slight cosmetic damage no melt-through
8	0.080 Painted	none	10.2	None	(a)	Slight cosmetic damage no melt-through

Notes: (a) No zone definition is possible, current components were applied as specified in the table for evaluation purposes.

6.2 Carbon Fibers Composites

The designer must decide what composite structures will require additional protection, since lightning damage to some aircraft surfaces may be safety tolerated surfaces and these may not require additional protection. The test data in this section illustrates damage that can be expected of both unprotected and protected, CFC laminates typical of small aircraft skin applications.

6.2.1 Unprotected CFC

The three examples selected for this section were fabricated of an 0.040 in. thick CFC laminate comprised of four, 0.010 in. fabric plies with no core or lightning strike protection on the exterior surface.. The panels were tested to Zone 1A and 2A lightning environments..

Zone 1A - Unpainted: Figure 6.2.1-1 shows that the 0.040 in. thick unpainted CFC panel has very good tolerance to a lightning strike when surface treatments, such as paint, are eliminated. The laminate was undamaged except for minor, cosmetic loss of surface resin. There was no delamination and no puncture.

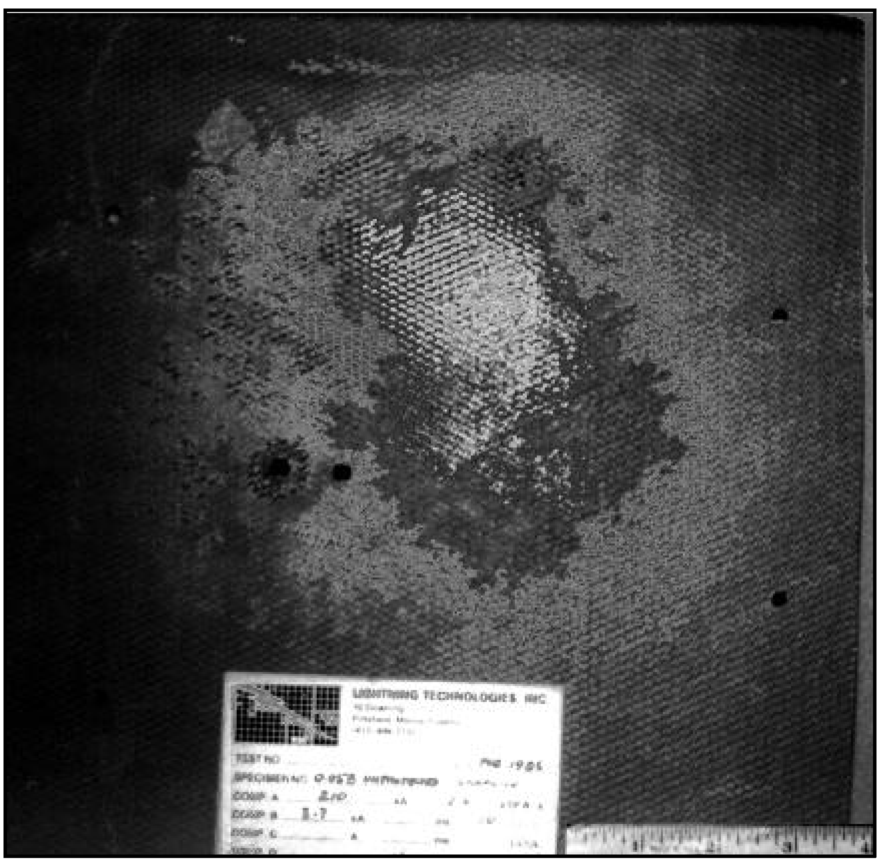


Fig. 6.2.1-1, Unprotected and unpainted CFC panel subjected to a Zone 1A strike

The unpainted panel in figure 6.2.1-1 illustrates the effects of non-conductive surface treatments on the CFC laminate. This is a typical illustration of the importance of allowing the arc root of the lightning channel an opportunity to spread out over a larger region. Although an unpainted carbon structure is not realistic, the importance of keeping surface treatments to a minimum thickness, even on protected composites, are important in minimizing damage.

Zone 1A - Painted: Figure 6.2.1-2 shows the results of a Zone 1A lightning strike to a 0.040 in. thick painted CFC panel. The laminate was damaged over a regions of 30 to 40 square inches of the laminate. The laminate was also punctured on the back side of the panel.

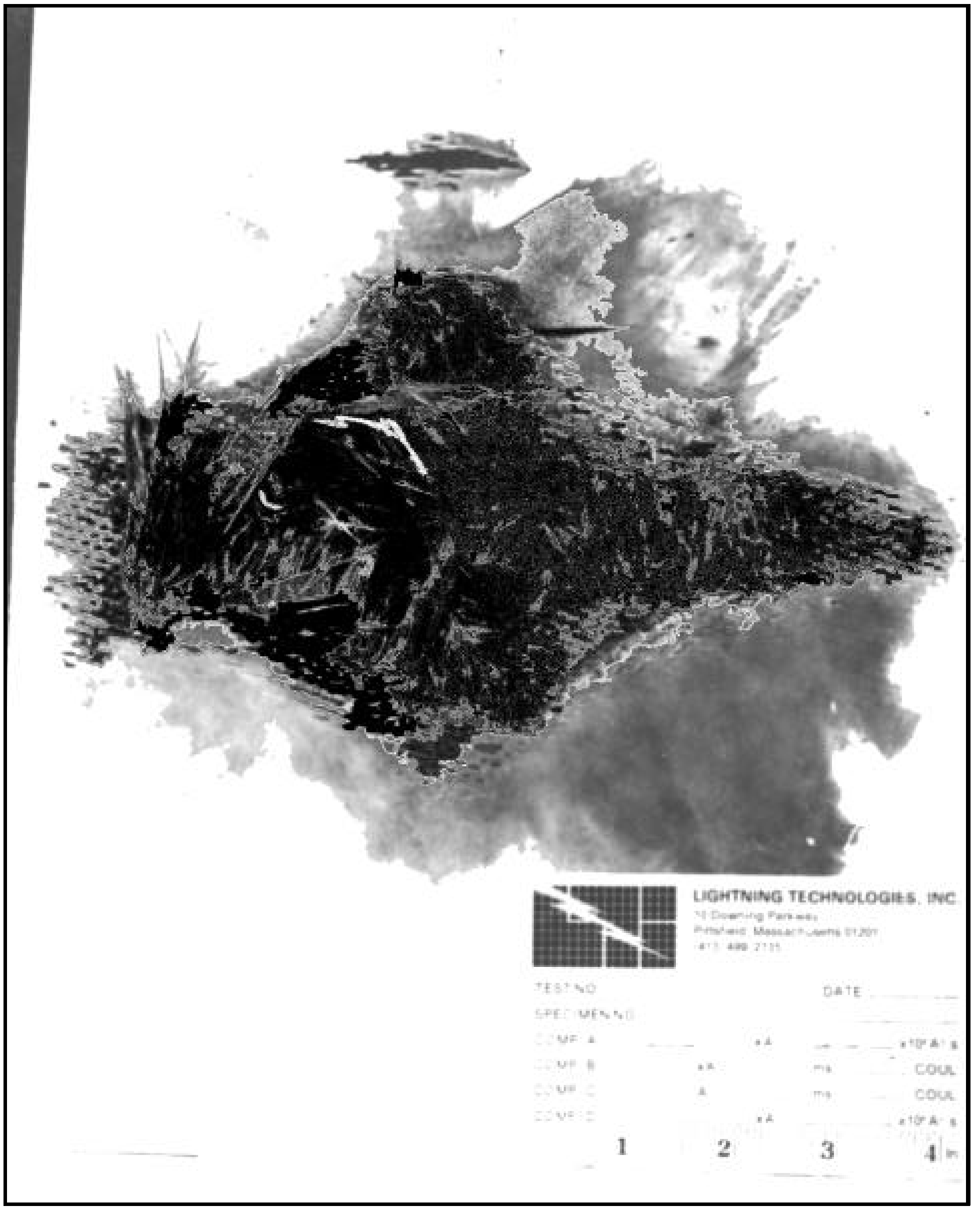


Figure 6.2.1-2 : Zone 1A stirke to a painted exterior surface of unprotected 4 ply 0.052 in. CFC laminate of woven cloth plies.

Zone 2A - Painted: Figure 6.2.1-3 shows the results of a Zone 2A lightning attachment to an unprotected 0.040" thick painted CFC panel. The laminate was damaged over a regions of 3 square inches. The inner ply laminate was also fractured over the approximate same area as the exterior surface, although the resin was not pyrolized on this ply.

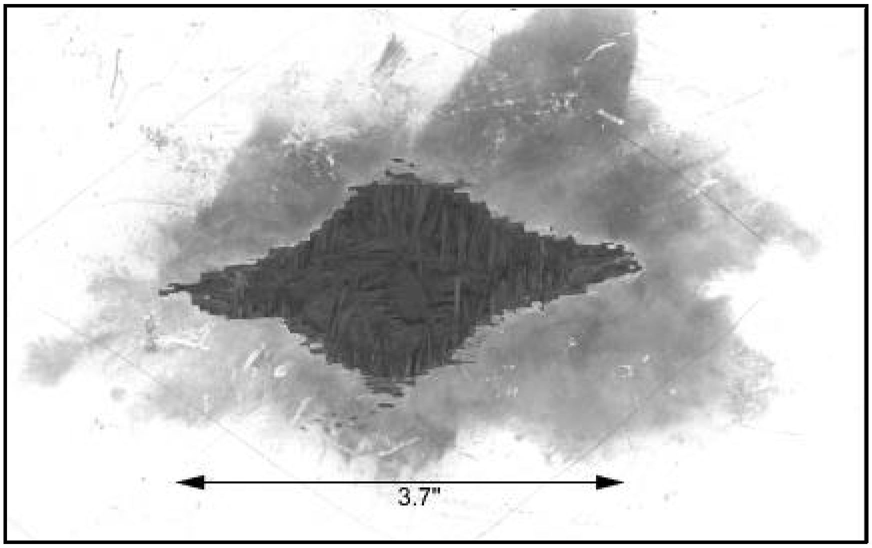


Figure 6.2.1-3 : Zone 2A strike to exterior surface of unprotected 4 ply 0.052 in. thick laminate of woven cloth plies.

6.2.2 Protected CFC Panels

Tables 6.2.2-1 and 6.2.2-2 provide additional data of protected CFC panels test data. The tables are accompanied by photographs of the post-test condition of the panel.

Table 6.2.2-1 : Carbon Fiber Composites: with foam Core

Protection	Zone	Laminate thickness		Delamination Region on Laminate	Punctured Area of Laminate		Protection Ply Loss Region	Ref. / Figure
		Outer	Inner		Outer	Inner		
Nickel Coated Carbon Fiber, outer ply only, foam core								
NCC	1A	0.016	0.008	6" dia	6"	3"	7" dia	Ref: b, Fig. 6.2.2-1
NCC	2A	0.016	0.008	4" dia.	3"	1"	3.5" dia	Ref: b, Fig. 6.2.2-2
Expanded Aluminum Foil, foam core								
EAF 0.016	1A	0.032	0.016	2" dia.	3"	none	4.5" dia.	Ref: a, Fig. 6.2.2-3
EAF 0.028	1A	0.032	0.016	1" dia.	none	none	3.5" dia.	Ref: a, Fig. 6.2.2-4
Expanded Copper Foil, foam core								
ECF 0.029	1A	0.016	0.008	6" dia.	none	none	9" dia	Ref b, Fig. 6.2.2-5
ECF 0.029	2A	0.016	0.008	1" dia	none	none	6" dia.	Ref b, Fig. 6.2.2-6

References:

a) Lightning Technologies, Glasair III Lightning Protection System Development Report, LT-92-782, 1992.
b) Lightning Technologies, Lightning Tests on the Model LC40 Aircraft Components, LT-97-1398, 1997.
c) Lightning Technologies, Lightning Strike Tests on Cycom MCG Fiber Protected Panels, LT-83-145, 1983.

Analysis: Expanded copper foil demonstrated the best protection for both zones, being marginally better than expanded aluminum foil. Nickel coated carbon fiber permitted puncture in both zones.

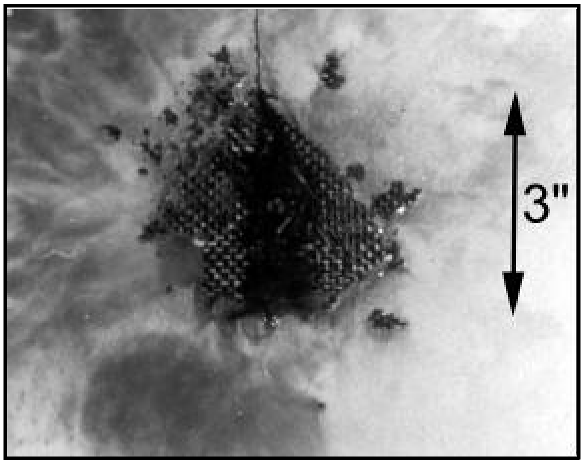


Fig. 6.2.2-1 : Ni CFC Panel,
Zone 2A, Ref b, Test No. 4

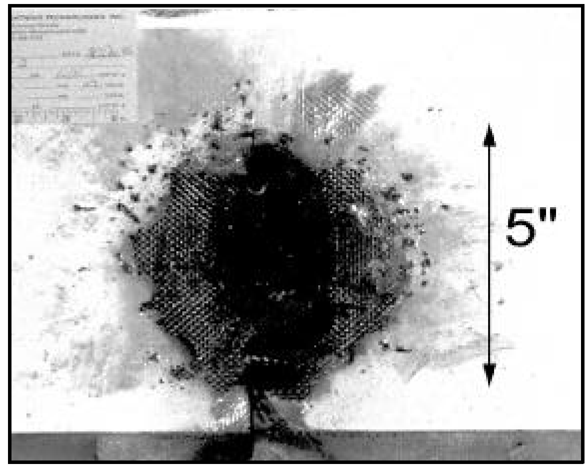


Figure 6.2.2-2 : Ni CFC Panel
Zone 1A, Ref b, Test No. 12

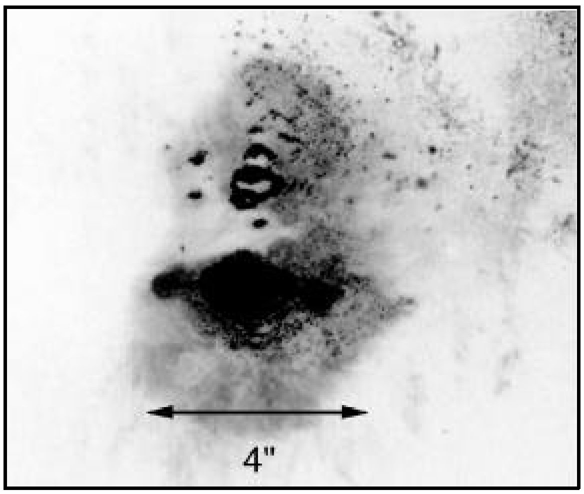


Figure 6.2.2-3 : EAF/CFC Panel
Zone 1B, Ref a, Test 5

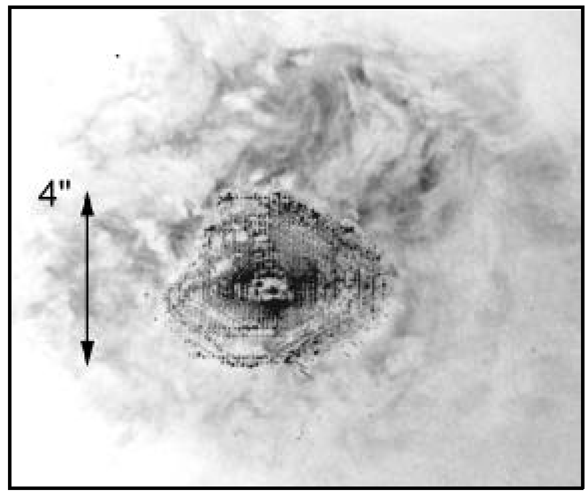


Figure 6.2.2-4 : Al CFC Panel
Zone 1A, Ref a, Test No 40

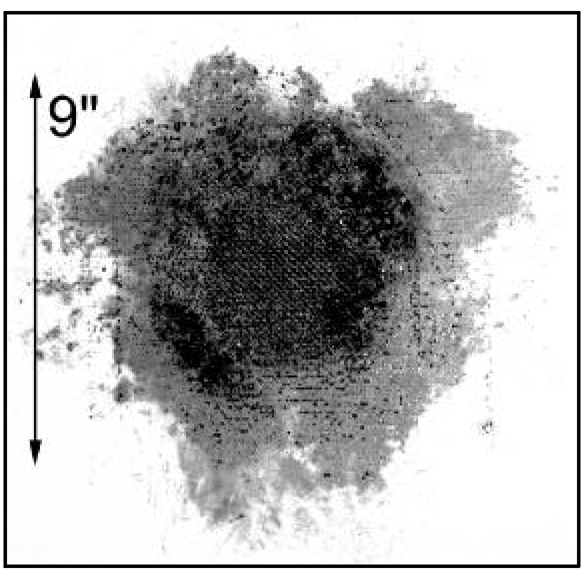


Figure 6.2.2-5 : Cu CFC Panel
Zone 1A, Test No. 10

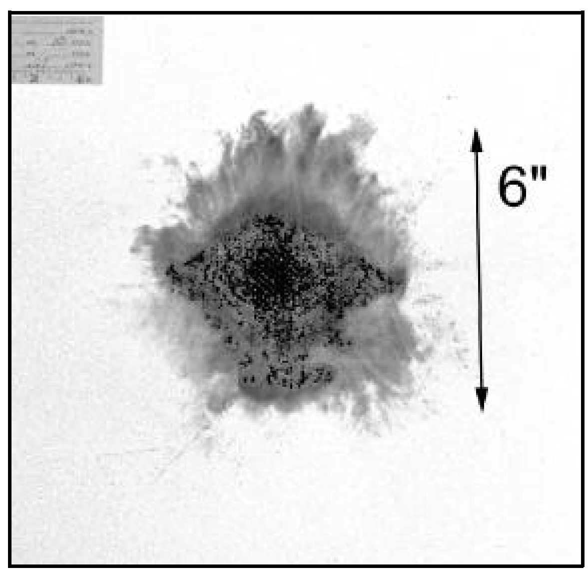


Figure 6.2.2-6 : Cu CFC Panel
Zone 2A, Test No. 7

6.2.2.-2 Carbon Fiber Composites: No Core

Protection	Zone	Laminate thickness	Delamination	Inner Ply Fracture	Test Report Ref.	Ref. Report Figure
Expanded Copper Foil (ECF)						
ECF 0.029	1A	0.024, 3 plies	none	none	b	Fig. 6.2.2-7
ECF 0.029	2A	0.024, 3 plies	none	none	b	Fig. 6.2.2-8
Interwoven Aluminum Wires (IAW) 8 to 10 wires per inch for each direction						
IAW 1 ply	1A	4 plies total	1 ply	none	d	Fig. 6.2.2-9
IAW 1 ply	2A	4 plies total	1 ply	none	d	Fig. 6.2.2-10
Woven Wire Mesh (WWM) (200 x 200 mesh)						
WS	2A	4 plies total	none	none	d	Fig. 6.2.2-11

References:

b) Lightning Technologies, Inc. Report: Lightning Tests on the Model LC40 Aircraft Components, LT-97-1398, 1997.

d) Lightning Technologies, Inc. Report: Learfan Development Tests, no released report

Analysis: ECF exhibited best protection both zones. Interwoven aluminum wire in the outer ply of carbon resulted in a localized region of delamination of the outer ply.

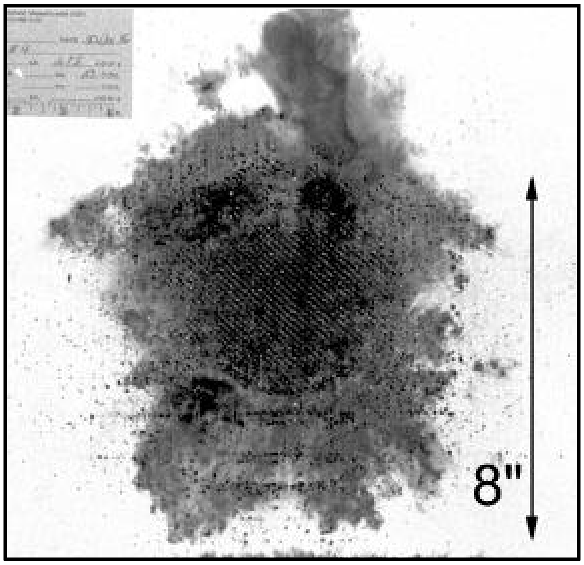


Figure 6.2.2-7 : Cu CFC Panel, no core
Zone 1A, Test No. 9

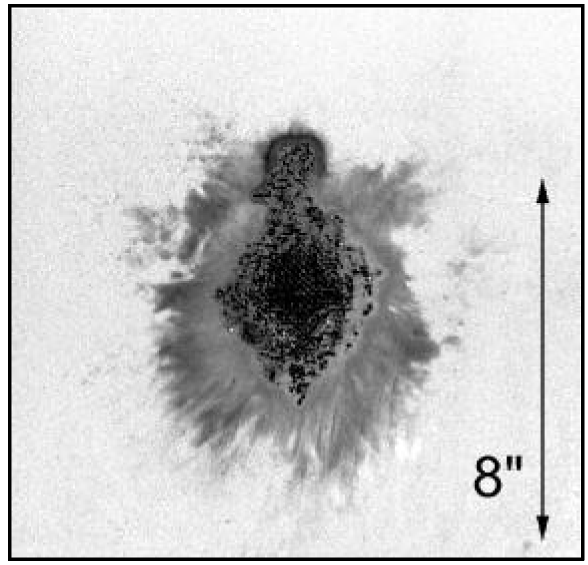


Figure 6.2.2-8 : Cu CFC Panel, no core
Zone 2A, Test No. 6

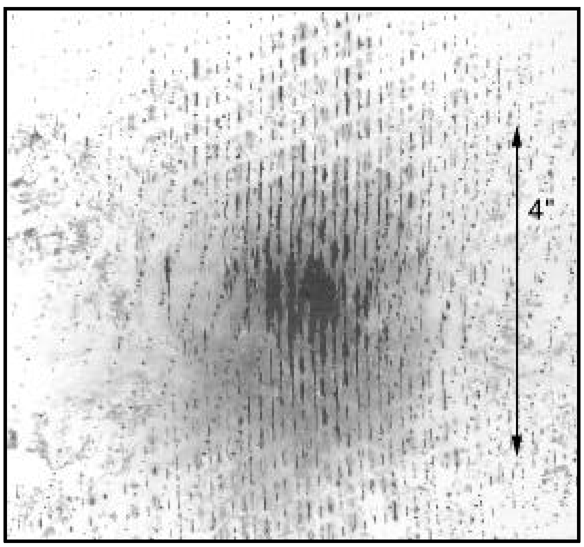


Figure 6.2.2-9 : IAW CFC Panel, no core
Zone 1A

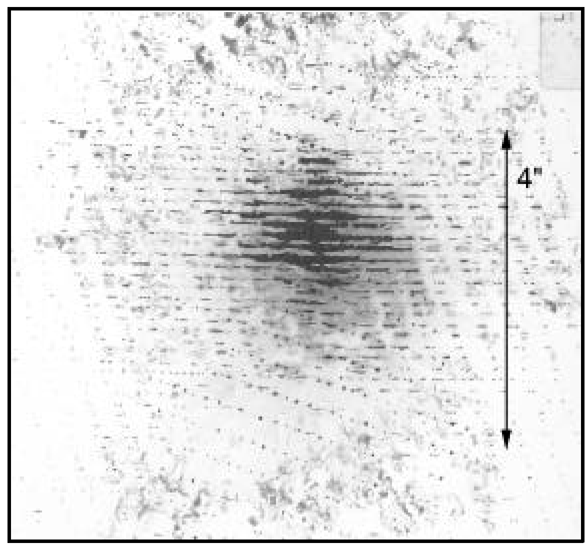


Figure 6.2.2-10 : IAW CFC Panel, no core
Zone 2A

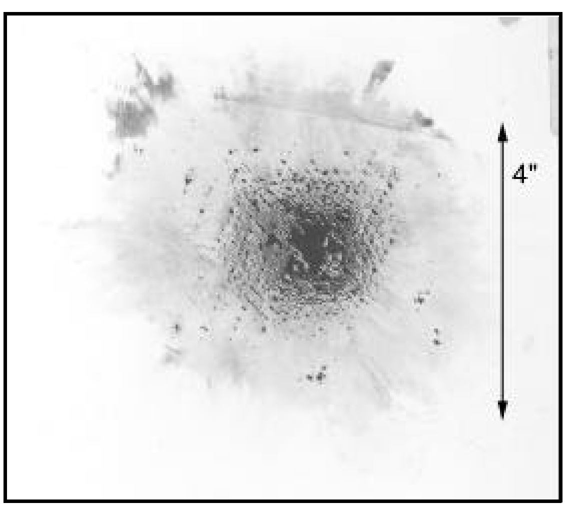


Figure 6.2.2-11: WS CFC Panel, no core

6.2.3. Carbon Fiber Composite (graphite) Panels

The following test panels were done for the US Air Force (Quinlivan, J. T., Kuo, C. J., Brick, R. O., *Coatings for Lighting* (sic) *Protection of Structural Reinforced Plastics, AFML-TR-70-303 Pt.1*, 1971). The tests were a Zone 2 strike, however due to the old nature of the test procedures the action integral is not known. The language used to describe the damage is that of the original document. Dimensions are 6" by 12", and foils are unperforated and unexpanded.

Table 6.2.3-1 AFML Test Data for CFC (No Core)

Test No.	Panel Matl.	Protection Method	Discharge Current (KA)	Waveshape (μs)	Results / Figure No.
019	CFC	AF 1-mil	94	18 x 30	No damage to the substrate, loss of most foil material in region of strike / Figure 6.2.3-1
021	CFC	AF 3-mil	94	18 x 32	Damage to the substrate outer ply, loss of foil over a 1.5 in. dia. area / Figure 6.2.3-2
023	CFC	AF 3-mil	94	18 x 30	No damage to the substrate, loss of foil over a 1.5 in. dia. region / Figure 6.2.3-3
044	CFC	AF 6 mil	95	18 x 28	Burn marks on substrate, AF burned away over a 1 in. dia. area / Figure 6.2.3-4
61	CFC	Cu Paint	110	14 x 28	Substrate severely damaged over a 3 to 4 in. region / Figure 6.2.3-5
68	CFC	Alum. Plasma Spray	94	15 x 26	Two plies of substrate delaminated, aluminum coating cracked locally / Figure 6.2.3-6

Abbreviations: CFC = Carbon Fiber Composite (graphite), AF = Aluminum Foil, CF = Solid Copper Foil, WM = Wire Mesh, AS = Aluminum Strips, CFB = Copper Fabric

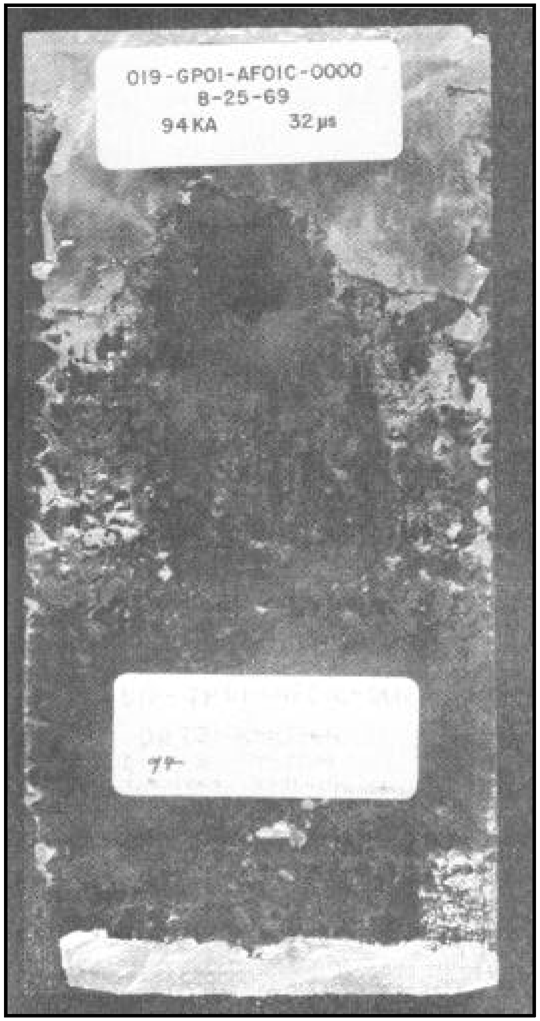


Figure 6.2.3-1 :

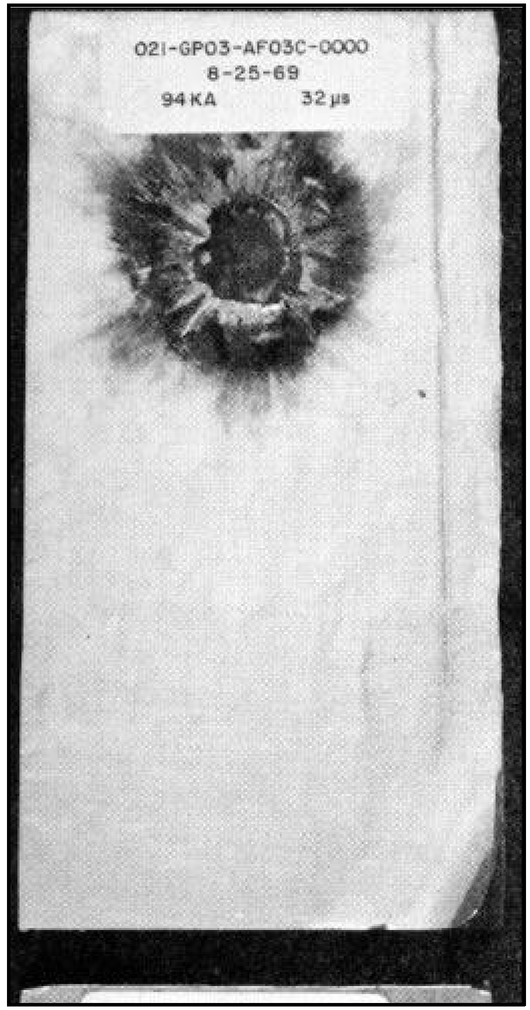


Figure 6.2.3-2 :

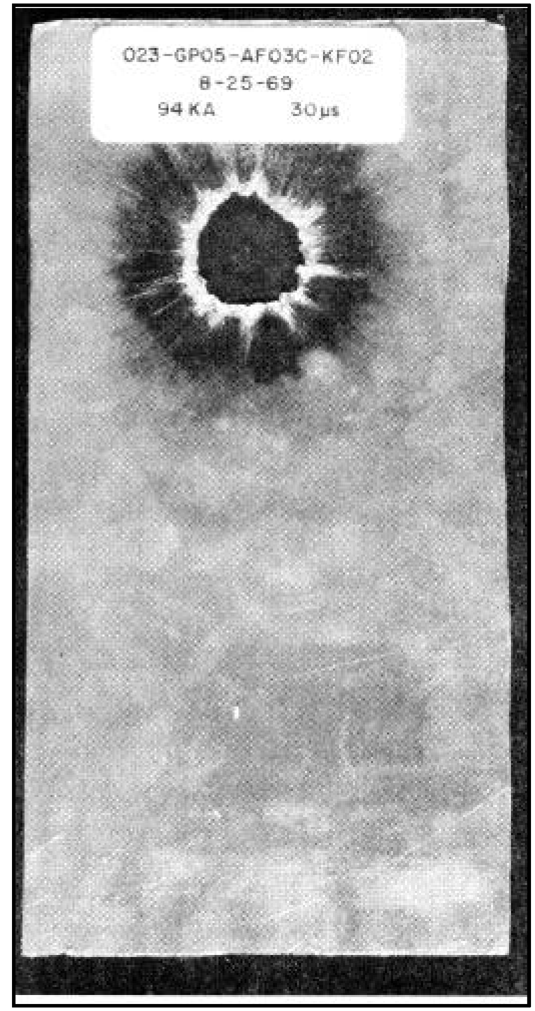


Figure 6.2.3-3 :

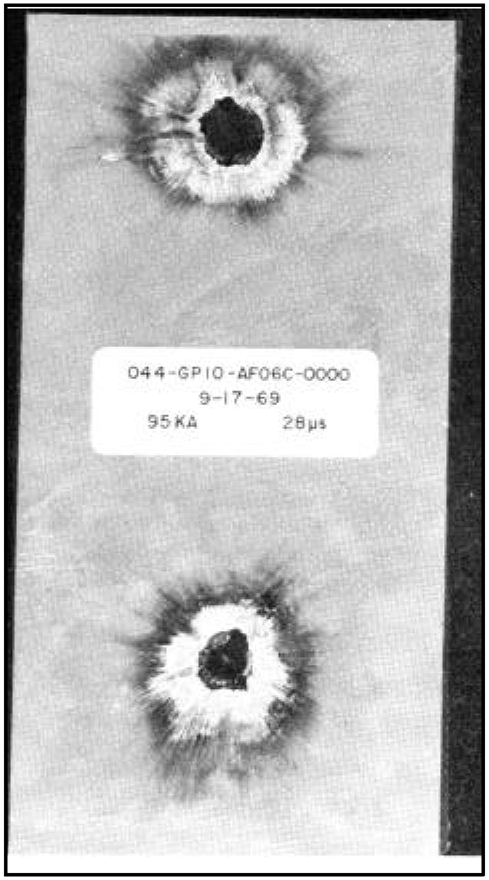


Figure 6.2.3-4 :

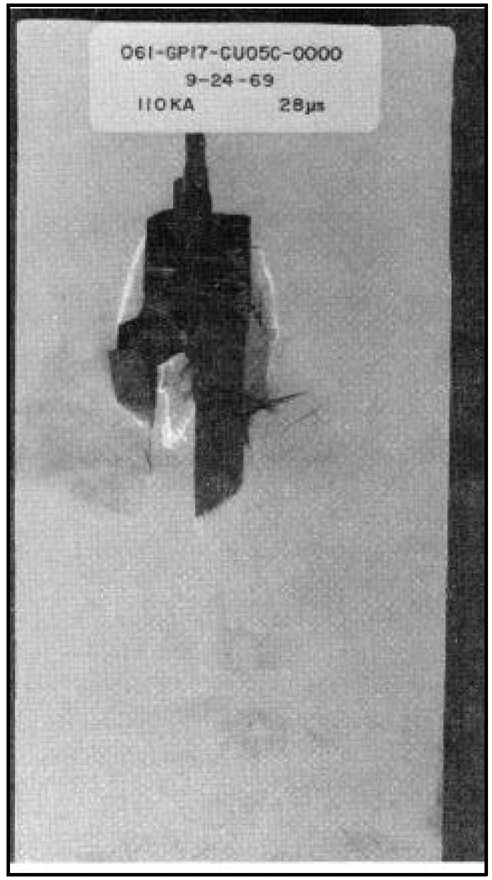


Figure 6.2.3-5 :

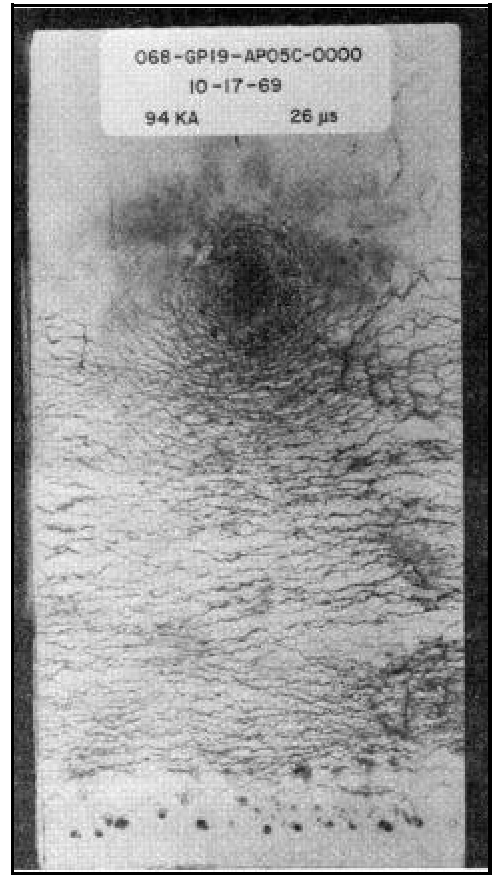


Figure 6.2.3-6 :

Analysis of CFC panel test data:

1) Conductive paints do little to protect against a severe strike with a conductive composite beneath.

2) Unperforated (solid) foils work well in aluminum, copper or the more resistive nickel. Application and maintenance problems persist however. Most designers will prefer the perforated and expanded variety.

3) Typically, protection from less conductive materials (such as nickel or stainless steel) will not perform as well as more conductive materials. There is likely to be little difference in maintenance, apart from galvanic concerns. There is also likely to be little difference in application.

4) A layer of significant dielectric strength placed over a conductive layer (such as carbon-based composites like graphite) will typically increase damage to the conductive layer when attachment occurs.

6.3 Non-Conductive Composites

The following examples show typical protection methods for non-conductive composites and define the magnitude of dmage that can be expected for Zone 1 and 2 lightning attachments.

Table 6.3-1 - Non-Conductive Composite with Fiberglass and Core

Protection	Zone	Lamination Thickness		Delamination Region on Laminate	Puncture Area of Laminate		Protection Ply Loss Region	Reference / Figure.
		Outer	Inner		Outer	Inner		
Thorstrand Aluminized Fiberglass	1A	0.016	0.016	7" dia.	none	none	8" dia.	Ref. a, Figure 6.3-1
120x120 Woven Wire Mesh	2A	0.024	0.024	1.5" dia.	1" dia.	none	2" dia	Ref. a, Figure 6.3-2
LDS 50-212 Alum Foil Perforated	1A	0.024	0.024	4" dia	none	none	8" dia	Ref a, Figure 6.3-3
EAF 0.028	1A	0.024	0.024	1"	none	none	5" dia	Ref a, Figure 6.3-4
ECF 0.029	1A	0.016	0.016	1"	none	none	10" dia	Ref b, Figure 6.3-5
ECF 0.029	2A	0.016	0.016	none	none	none	4" dia	Ref b, Figure 6.3-6

References:

a) Lightning Technologies, Glasair III Lightning Protection System Development Report, LT-92-782, 1992.
b) Lightning Technologies, Lightning Tests on the Model LC40 Aircraft Components, LT-97-1398, 1997.

Analysis: None of the fiberglass non-conductive panels showed puncture when protected by expanded foils of either copper or aluminum.

Figure 6.3-1 : Thorstrand protected fiberglass panel

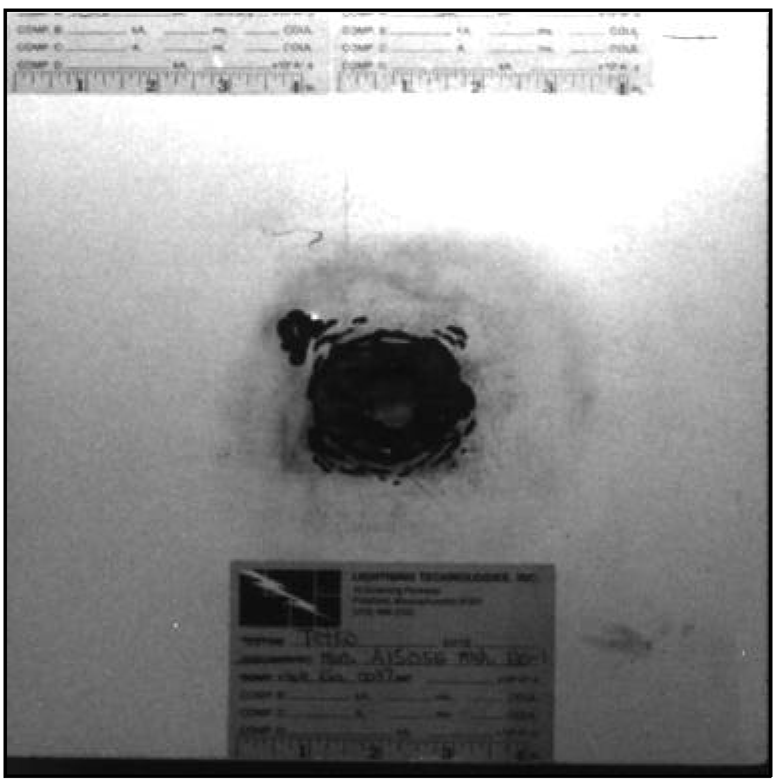


Figure 6.3-2 : 120 x 120 woven wire mesh
protected fiberglass panel

Figure 6.3-3 : LDS 50-120 Alum. Foil
protected fiberglass panel

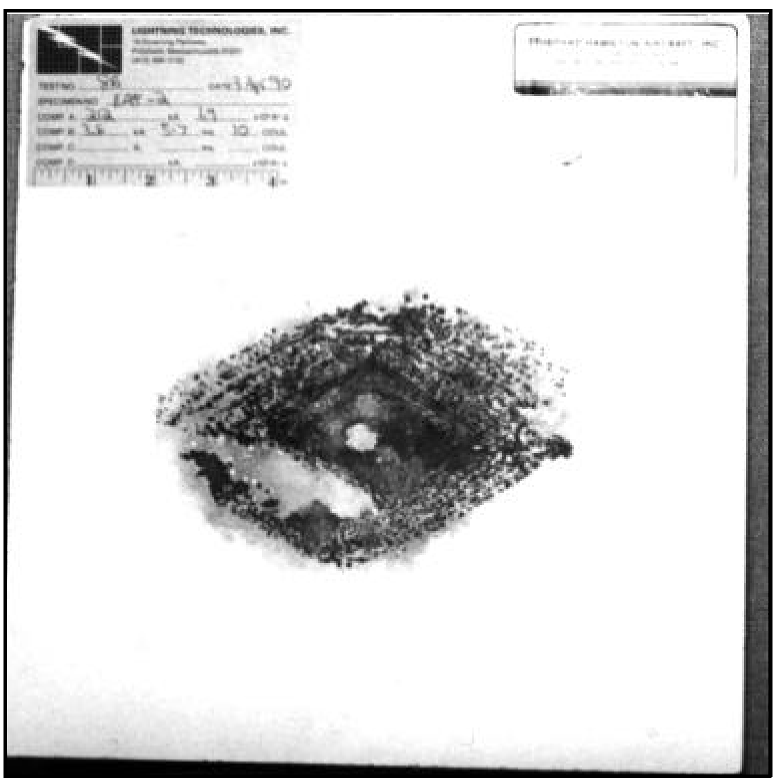


Figure 6.3-4 : 0.028 EAF protected fiberglass panel

Figure 6.3-5 : 0.029 ECF protected panel, Zone 1A

Figure 6.3-6 : 0.029 ECF protected panel, Zone 2A

7.0 Windshields and Similar Assemblies

Windshields, canopies, and side windows are often located in direct and/or swept stroke attachment regions, *Zones 1A* or *2A*. Lightning damage to windshields has not been frequent, but at least one accident in the 1930s has been attributed to such damage. There are several aspects of windshield and canopy designs which could make them susceptible to damage and designers should verify that these conditions do not result in safety or flight hazards.

Windows and windshields are usually fabricated from glass, acrylic, polycarbonate, or combinations of these materials. These materials generally have high dielectric strengths especially when compared to air or even many fiberglass or aramid fiber type non-conductive composites. Generally, if conductive objects are not be positioned close to the inside surface of windshields, there will be little tendency for a lightning flash to puncture the windows. However, the likelihood of lightning punctures increase when conductive films or wires are embedded in the windshield laminate.

<u>Electrically heated windshields</u>: Electrical heating elements embedded within laminated windshields are used to clear icing and fogging. Typical configurations are shown in Fig. 7.0-1. Heating elements are either fine metal wires or metal films, powered by the aircraft electrical power systems.

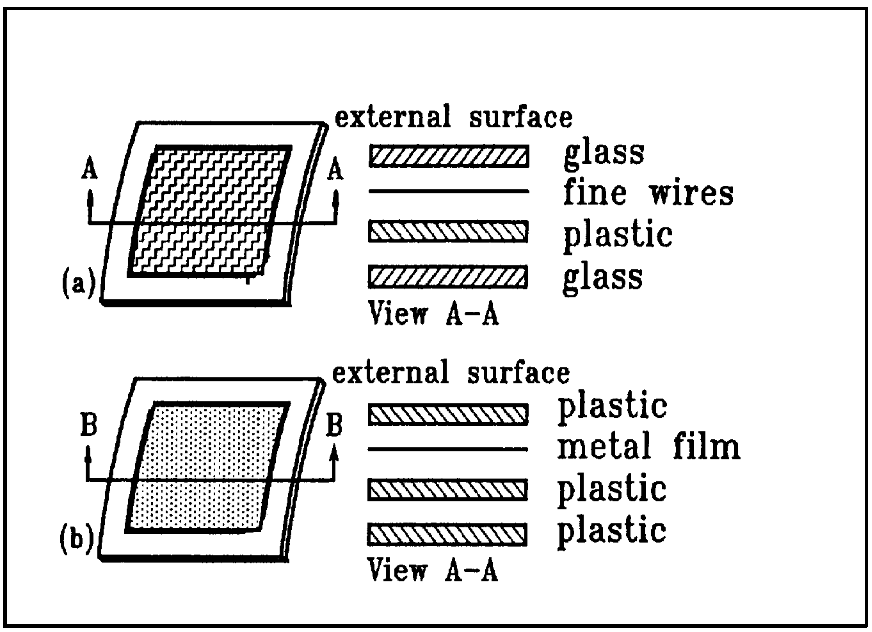


Fig. 7.0 - 1 Electrically heated windshields
(a) Fine wires in glass/acrylic sandwich
(b) Metal film in acrylic or polycarbonate sandwich

Since the wires are of small diameter and arranged in zig-zag patterns, an electric field directed through the glass is concentrated at those wires which may result in a puncture of the outer glass ply and conduction of lightning currents directly into the heating elements and the power circuits. Electric fields can be produced either by an approaching lightning leader or by electrical charge that collects on the outside of the window as the aircraft flies through precipitation. It is generally thought that punctures of the outer glass may be less likely with metal film heating elements because the uniform conductive film helps to prevent e-field concentration at localized spots of the windshield.

The over-pressures created by the expanding lightning channel may present a similar hazard by cracking the outer laminate, which then allows direct attachment of the lightning channel to the heating element. The subsequent vaporizing of the thin wires or metal film of the heating element results in an explosive over-pressure and damage to inner and outer laminates of the windshield as illustrated in Fig. 7.0-2. The loss of integrity of the windshield may result in sudden loss of cabin pressure and the chance of glass being ejected into the face of the pilots or passengers.

A secondary hazard of the lightning attachment to the heating element is the direct injection of very high surge currents into the aircraft's electric power distribution system, often resulting in damage to electrical loads powered from the same distribution bus.

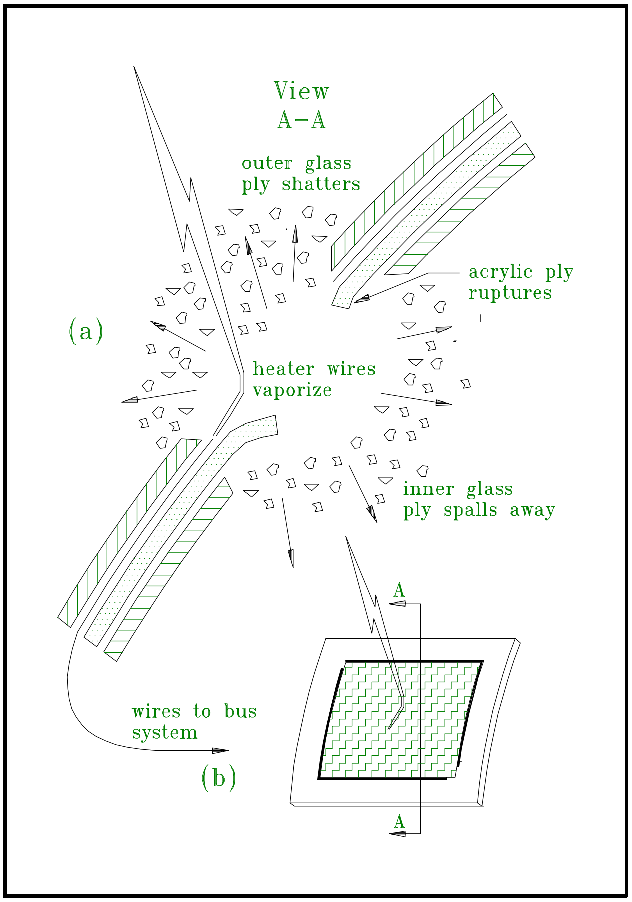


Fig. 7.0-2 Lightning damage to heated windshield.
A)Shock wave damage to laminate
B) Surge current into power system

__**Protection methods**__: One method of eliminating these problems is to de-ice the windshield with hot air instead of electrical heating elements. Removing the heating elements eliminates the possibility of windshield puncture.

The following design approaches can be followed to minimize the lightning related hazards if electrical heating elements are present:

a) Utilize a tough center ply of urethane or polycarbonate. These materials are usually and tolerant of shock wave or impact damage. Some specifications require that windshield structures be able to survive the impact of a 2 kg (4 lb) bird at 200 knots. Such windshields have sometimes been capable of tolerating the effects of *Zone 1A* punctures through the outer ply. Since failures can also result from tearing at the interface between the laminate and the frame, as well as by puncture of the laminate itself, this part of the design must also be considered. Approaches that successfully tolerate bird strike requirements may also be likely to meet lightning requirements.

b) Utilize a metal film heating elements instead of fine embedded wires. The films may be less conducive to puncture by the lightning channel.

c) Since windshields, canopies and other windows are usually flight critical items, candidate designs should be tested. This is especially true of the newer, lighter-weight windshields. Databases relating to these newer, high strength, light weight laminate designs do not exist.

The foregoing protection methods are applicable to bubble-type canopies and side windows, as well as to frontal windshields, though windshields represent the most likely lightning related problem.

Canopies rarely employ de-icing elements and are fabricated most often of polycarbonate resins which have very high dielectric strengths. This is also true of side windows. Sometimes metal films are deposited on the interior of bubble type canopies to shield the pilot from strong electric fields that would otherwise cause electric shocks. These films typically have not promoted punctures to canopies fabricated of polycarbonate resins.

Anti--static coatings: Electrical charges that accumulate on frontal windshields and canopies can be bled away by electrically conducting surfaces. To remain optically transparent, these films must be very thin resulting in conductivity values that are inadequate to conduct lightning currents.

The most common coating in present use is indium tin oxide (ITO) and it is preferred for its comparative durability against erosion.

Flash blindness: If a lightning strike occurs at night in front of a windshield the bright flash might temporarily blind the pilot, making it difficult or impossible to read instruments.

The flash blindness may last for a minute or two and several accidents have resulted when the aircraft was on final approach to an airport or in IFR conditions.

No windshield treatment has been found to prevent this effect without impairing normal visibility. When there are two pilots, one of them should focus on the instruments and avoid looking out the windshield during conditions that might lead to a lightning strike. Cockpit instrument lights and display intensities should also be kept at maximum brightness.

Failure and Test Implications: While windshields usually fail when tested under laboratory conditions, it is rare for such structures to fail under real life conditions. It has traditionally been assumed that laboratory conditions fail to duplicate some aspect of real life conditions. There have been a variety of explanations, none entirely satisfactory. It seems likely, however, that the lightning often attaches to the adjacent airframe structure, rather than the windshield itself.

For such reasons such as these, manufacturers have often been reluctant to either test windshields or release the results of such testing. Therefore little data has accumulated. Before testing any windshield or windshield-structure, manufacturers are urged to contact experienced test personnel for suggestions and test method recommendations.

Experimental Test Example: The following data was developed from a series of tests conducted for Stoddard Hamilton (Lightning Technologies*, Glasair III Lightning Protection System Development Report, LT-92-782*, *1992*). The tests evaluated the acrylic windshield and canopy side windows. A mannequin was placed in the front seat of the aircraft to simulate a passenger or pilot. Cameras were placed behind the mannequin to witness streamers or arcing to the head region. Figure 7.0-3 shows a typical high voltage discharge to the windshield and canopy region.   In all cases the lightning channel attached to adjacent airframe structure with no evidence of dielectric breakdown or punctures of the windshield or canopy. Figure 7.0-4 shows a photograph of the mannequin's head during a high voltage test.

Figure 7.0-3 : High voltage attachment testing to windshield and canopy

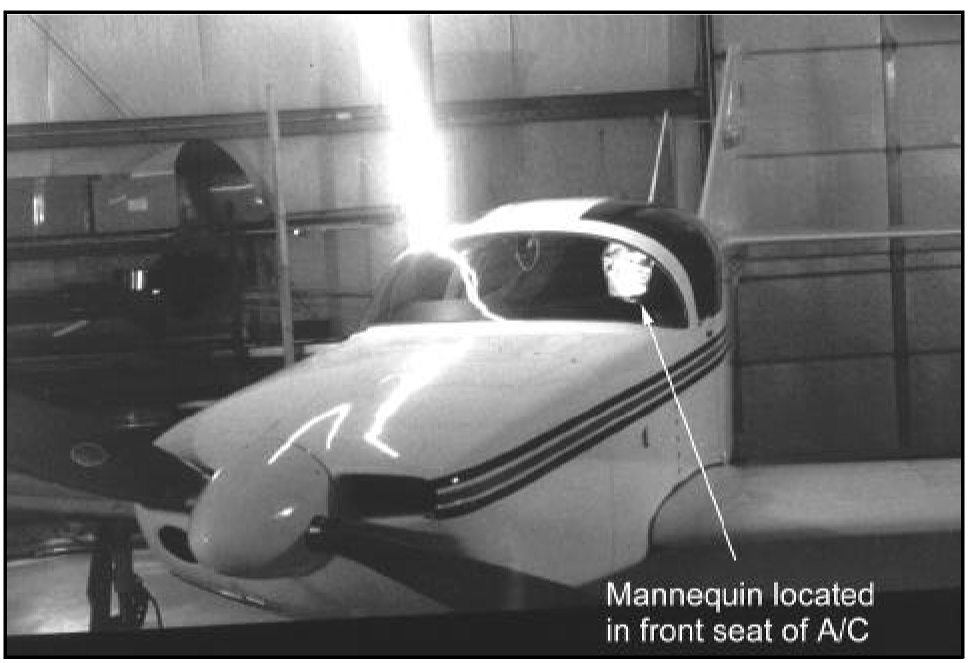


Figure 7.0-4 : Photograph of mannequin during testing.

The tests shown above were performed on a complete aircraft. Test conditions can be set up to simulate a canopy or windshield and tests performed on a specimen basis as shown in Figure 7.0-5, shown below. In the example shown below the canopy window, comprised of acrylic was able to withstand the high voltage thread even with a conductive object in close proximity to the inside surface.

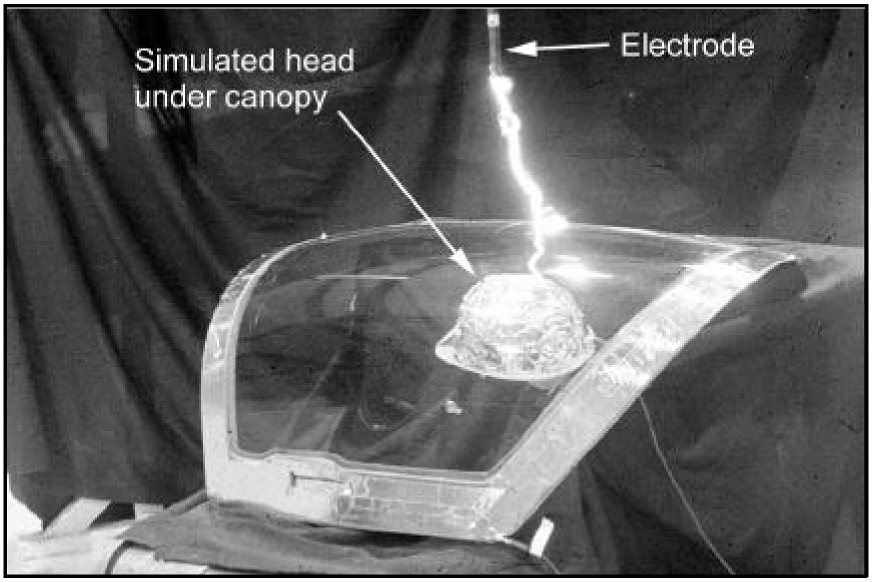


Figure 7.0-5 : High Voltage to Canopy, Component Test

8.0 Control Surfaces

This section provides design guidance for composite control surfaces. It also includes the results of lightning verification testing to several composite control surfaces.

8.1 Design Guidance and Considerations

Control surfaces will usually be located in *Zones 1B or 2B.* The designer will need to remember that current densities in these areas are likely to be high, not merely because of the type of attachment, but because control surface cross sectional areas are likely to be small. Control surfaces, whether composite or metal, are typically fabricated from thin and light weight materials. As with any hinge installation, care must be taken to insure that the hinge to structure connection must remain structurally sound.

The small aircraft designer will find the lightning protection requirements for control surfaces to be a challenge in a number of areas. Among these are: control surface skins, trailing edges, internal structural members (including ribs, spars and their interfaces), and hinge interfaces.

The protection of external skin surfaces have been dealt with at length in Chapters 5 and 6 of this document, but there are additional design guidelines for control surfaces.

a) The best way to protect control surfaces is typically to metalize all surfaces. That is, insure maximum conductivity with some form of metal protection, be it foil, metalized fibers or other technique. In so doing, the designer will help to ensure that a majority of the current remains on the outside of the control surface.

b) The designer may alternatively make the entire control surface, as well as internal support structures of a non-conductive material such as fiberglass. Although, the control surface is fabricated of non-conductive materials, streamers could form internal to the control surface and result in lightning channel formation internal to the control surface. In these cases, exterior surface protection may still be required and some verification testing may be required.

c) Control surface interfaces at ribs, spars, and hinges can often be damaged due to arcing at adhesive bondlines that result in disbond. The designer is wise to provide redundancy, probably in the form of mechanical fasteners, in addition to adhesives. Testing will often be required to verify the adequacy of the design.

d) Control surfaces will more often than not require some form of protection, particularly at the trailing edge, where composite surfaces are usually secondarily bonded, and the composite structure is thin. This secondarily bonded trailing edge interface are likely to disbond during a lightning attachment the trailing edge. Several options can be considered, such as a secondarily bonded wrap-around of foil or screen, a sheet metal wrap-around or a metal inserts. Metal fasteners often are required to provide mechanical support in the event the adhesive bondline fails.

e) In carbon fiber composite control surfaces, the assembly may be cocured, that is, constructed as a single unit, thus maximizing conductivity. The technique is sometimes referred to as resin transfer or unitized construction.

f) Ribs and spars may be composed of a non-conductive composite, providing the lightning with no current path. Since the lightning currents are not transferred through those adhesive bondlines of the ribs and spars, the likelihood of damage is minimized.

Hinges: Hinge brackets to control surface structural interfaces must be carefully reviewed. In considering these interfaces, note that adhesive bondlines often fail, for the same reason other non-conductive adhesive bonds fail. The current density may cause mechanical fasteners to loosen. Lightning protection is, therefore, likely to be a design challenge at these locations. Testing is often necessary in these instances.

In addition to these difficulties, the designer will need to remember that multiple hinges are not sufficient to insure adequate conductivity. The current will choose the shortest path, typically delivering a majority of the current to one hinge. This phenomenon will be most likely to occur with conductive composites and to a lesser amount on control surfaces with aluminum skins. In a three hinge installation, it is not uncommon for one hinge to carry seventy percent of the lightning current. Even higher currents are possible, depending on where the strike attaches and electrical qualities of the control surface. Even when the control surface is neither an attachment or an exit point, hinges and control surface will serve as a parallel conductive pathway. Additional data on the effect of lightning on hinges or bearings will be found in Section 9.

8.2 Control Surface Test Results

The following paragraphs provide some examples of tests performed on several control surface designs.

8.2.1 Fiberglass Flap

A flap assembly fabricated of fiberglass was subjected to a Zone 2 lightning attachment. The flap received only cosmetic damage to the expanded foil protection ply along a 4 inch area of the trailing edge and localized foil loss near the hinge locations. The fiberglass structure remained intact with no apparent disbonds or damage that would endanger continued sage flight to landing. Figure 8.2.1 shows the area of damage to the flap trailing edge.

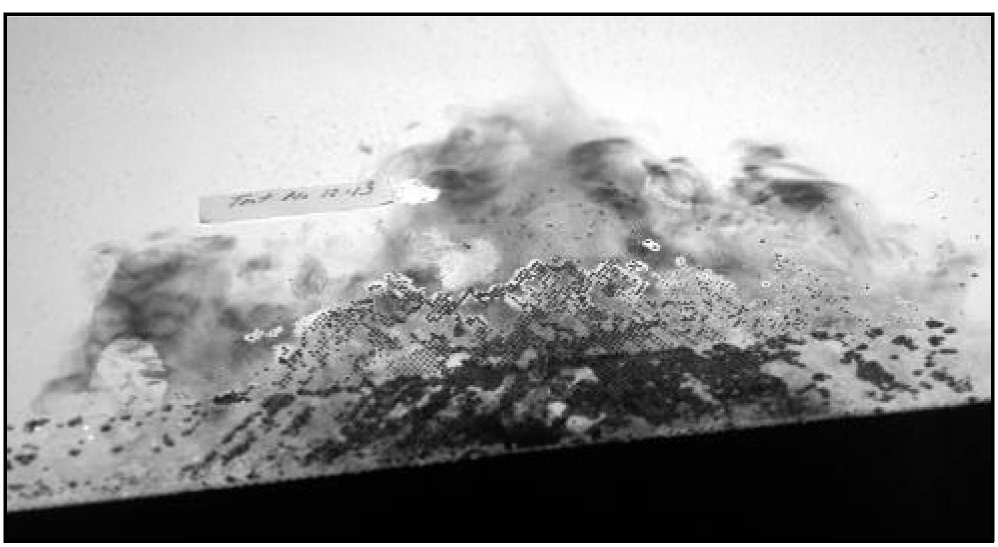
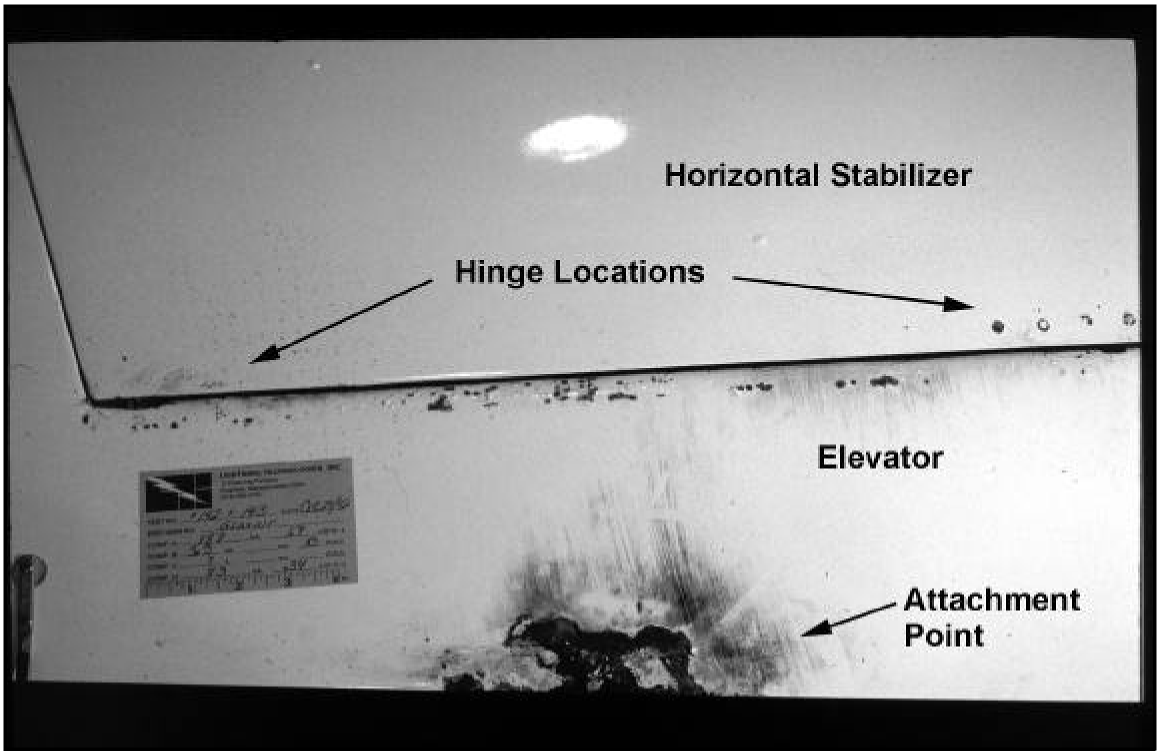


Fig. 8.2-1 - Flap trailing edge, *Zone 2* attachment, Glasair IIILP.

8.2.2 Fiberglass Elevator Installation

This example shows the results of a Zone 1B attachment to a fiberglass elevator that was protected with expanded aluminum foil. The elevator assembly was connected to a horizontal stabilizer which provided a realistic current distribution to the hinge interfaces. The test resulted in loss of expanded foil at the attachment point and at hinge locations where current density was high. The fiberglass structure of the elevator was not damaged by the test series. Figure 8.2.2-1 provides a photograph of the elevator post test condition.



8.2.3 Carbon Fiber Rudder

The testing to the carbon fiber rudder assembly evaluated the ability of the rudder to sustain a Zone 2 lighting strike. The rudder skins and spars were assembled utilizing a co-cured laminate process which eliminates the necessity of assembly with secondarily bonded joints. The rudder trim tab was fabricated from fiberglass composites and attached to the rudder with a piano hinge.

The rudder hinge brackets were attached to the rudder with bolts. The rudder carbon fiber skins were sandwiched between load bearing metal doublers. The rudder had three hinges attached similar to the aircraft installation.

The test currents were injected on the trailing edge of the rudder and removed by hard-wire connections to the rudder hinge brackets. The first test evaluated a Zone 2 strike to the rudder trailing edge and the second test evaluated a strike to the fiberglass trim tab.

Figure 8.2.3-1 shows the post test photograph of the rudder.

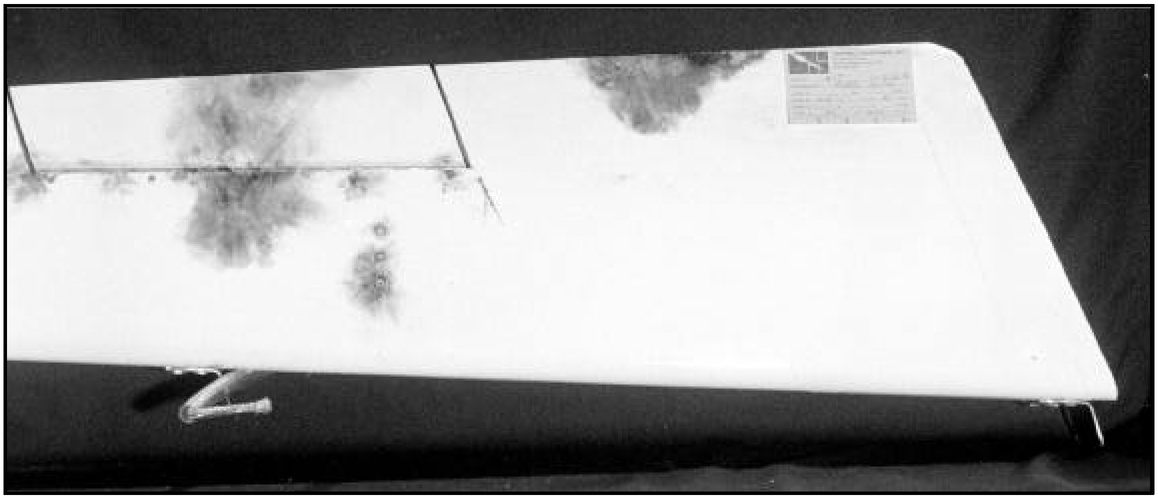


Figure 8.2.3-1 - Post test photograph of rudder test article

Figure 8.2.3-2 shows a closeup photograph of the Zone 2 attachment to the trailing edge.

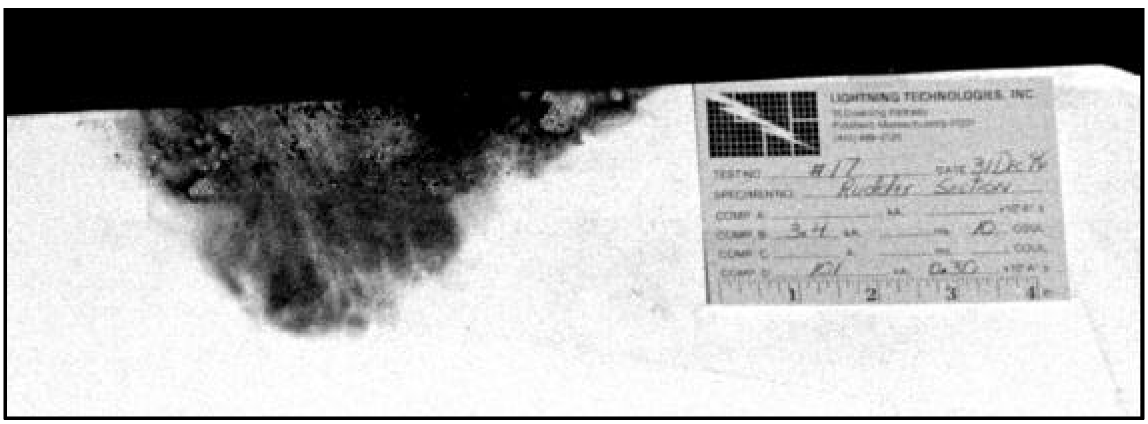


Figure 8.2.3-2 - Closeup photograph of trailing edge attachment

Damage to the trailing edge was limited to localized loss of expanded foil protection ply and minor loss of the resin at the area of the attachment. This loss of resin was localized in a region of less than 2 inches along the trailing edge. Damage to the trailing edge was minimal and would not affect flight safety.

Figure 8.2.3-3 shows the post test photograph of the attachment to the trim tab.

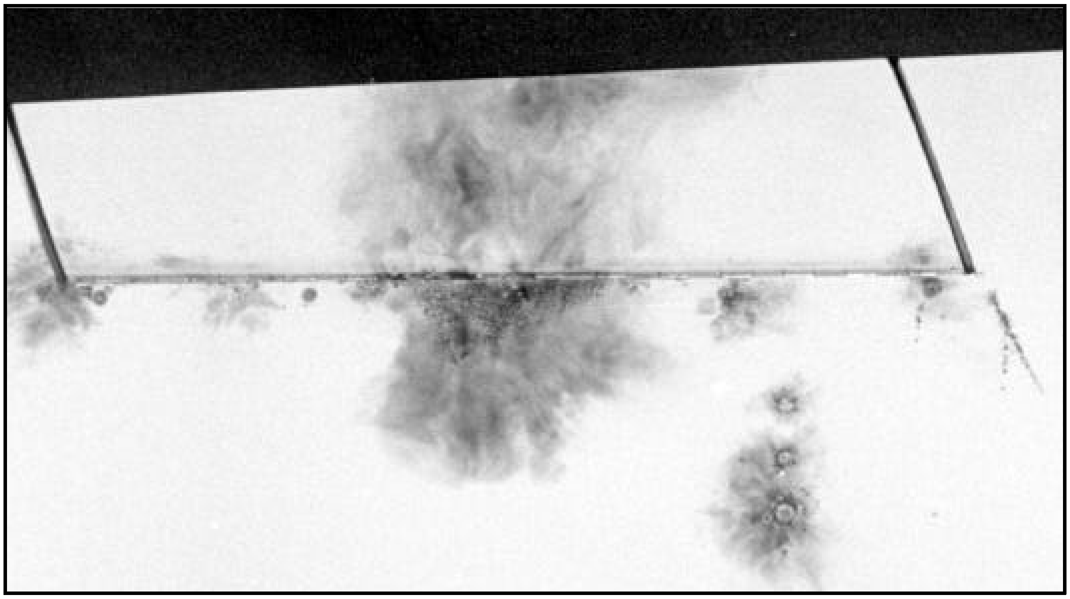


Figure 8.2.3-3 - Post test photograph of the attachment to the trim tab

The rudder data was derived from tests conducted for Pacific Aviation (Lightning Technologies, Inc., Report Entitled, “*Lightning Tests on the Model LC40 Aircraft Components”*, Report No. LT-97-1398, 1997).

9.0 Control Surface Hinges and Bearings

If hinges and bearings are located where lightning currents might pass through them, such as control surfaces in Zones 1B or 2B, they must be able to safely conduct currents without impairment of their function. Otherwise suitable means should be provided to carry the lightning currents around the rotating hinge points. Tests and experience are often the only real guides as to whether the hinge might be excessively damaged.

Slowly rotating joints often experience pitting and welding damage to the bearing surfaces. During laboratory testing, welding of bearings can occur, but the welding is seldom so severe that the joint cannot be broken apart by pilot induced forces on the control system. The welding induced by laboratory test techniques may represent somewhat of an overly severe condition, especially considering that control surfaces in flight may often be vibrating or moving during the lightning strike, which can help to minimize the welding effects and may prevent the formation of a stationary weld. Hinges with multiple points of contact, such as piano hinges, generally are capable of safely conducting lightning currents without endangering safe flight to landing. In most cases, all hinges and bearing should be checked in a timely manner after a lightning event to determine the necessity of replacement or repairs.

The hinges and bearing of most aircraft control surfaces have been able to tolerate the conduction of lightning currents without special protection techniques. The lightning currents can conceivably weld movable parts together, but generally the weld point would be small enough that the force of the actuator could free the joint.

If tests were to indicate that excessive damage might occur, additional conductivity should be provided. The most effective way of providing this additional conductivity is to provide additional areas of contact in the hinge itself, or else by additional hinges.

Bonding jumpers on hinges: Flexible bonding straps or jumpers are often installed across hinges. In many cases, however, the jumpers do not really reduce the hinge current. The reason for this is that the lightning tends to follow the path of least inductance, rather than the path of least resistance and the jumpers almost always involve longer and more inductive paths than do the paths through the hinges.

Bond straps are sometimes required to prevent the electromagnetic interference that arises when precipitation static charges must be conducted through hinges with loose or resistive contact.

The following paragraphs provide a summary of various tests that have been performed on hinges and bearings that are typically used on small aircraft installations.

9.1 Piano Hinge Installation

This example represents a typical piano hinge installation. The airframe structure was fabricated of fiberglass reinforced composite with an 0.016 lb/ft^2 expanded aluminum foil protection ply providing conductivity. The hinge length was 12 inches and had rivets installed every inch. Figure 9.1-1 shows a sketch of the test article.

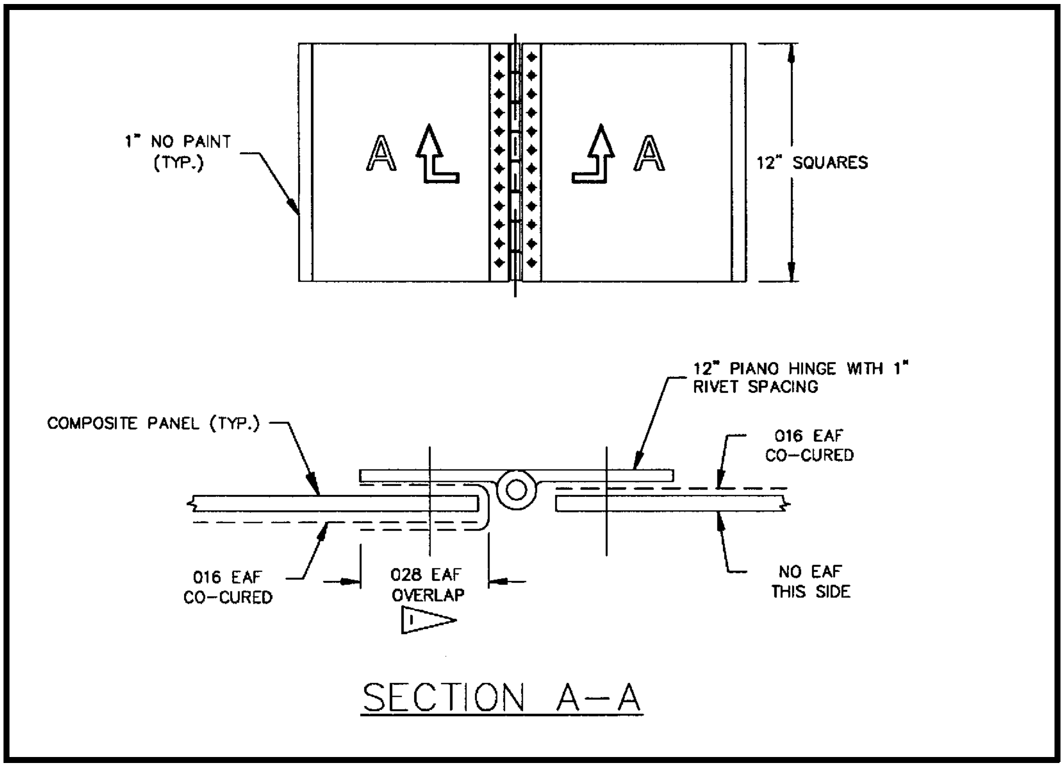


Figure 9.1-1 : Sketch of piano hinge test article

The test was performed to evaluate the conducted Zone 1A lightning currents across a typical piano hinge installation. The test current applied was approxiamately 133 kA of Component A and 10 coulombs of Component B

Test Results: The hinge remained functional with only the loss of expanded foil around fasteners of the hinge installation. The fiberglass structure was not damaged by the currents and the hinge remained rigidly attached. A small amount of additional frictional forces were observed during movement of the hinge. Figures 9.1-2 and 9.1-3 show photographs of the test article after the application of the test currents.

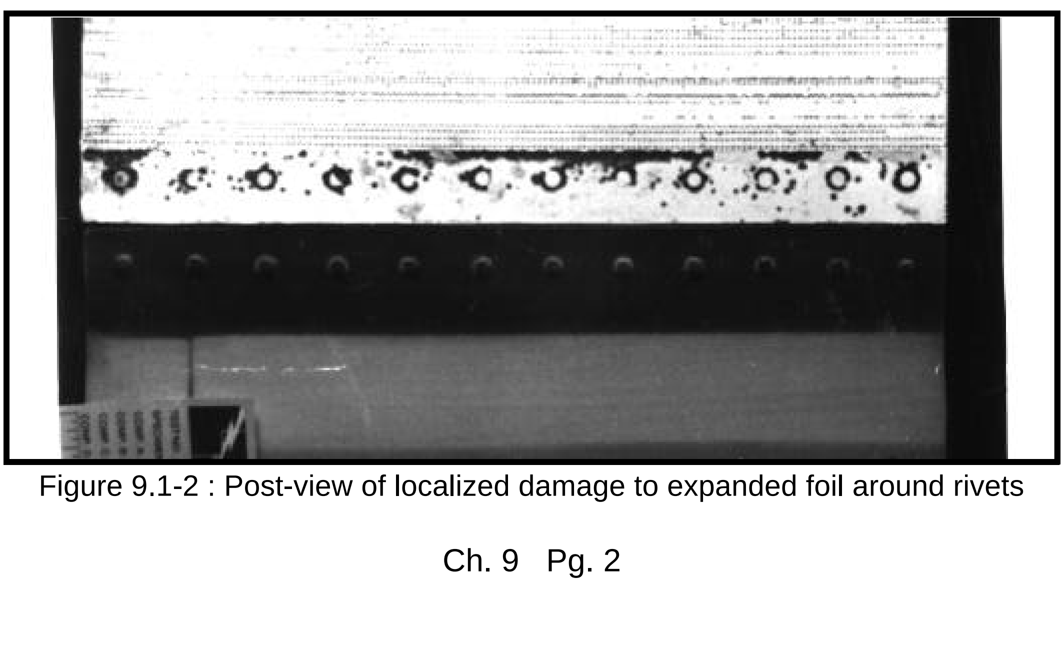


Figure 9.1-2 : Post-view of localized damage to expanded foil around rivets

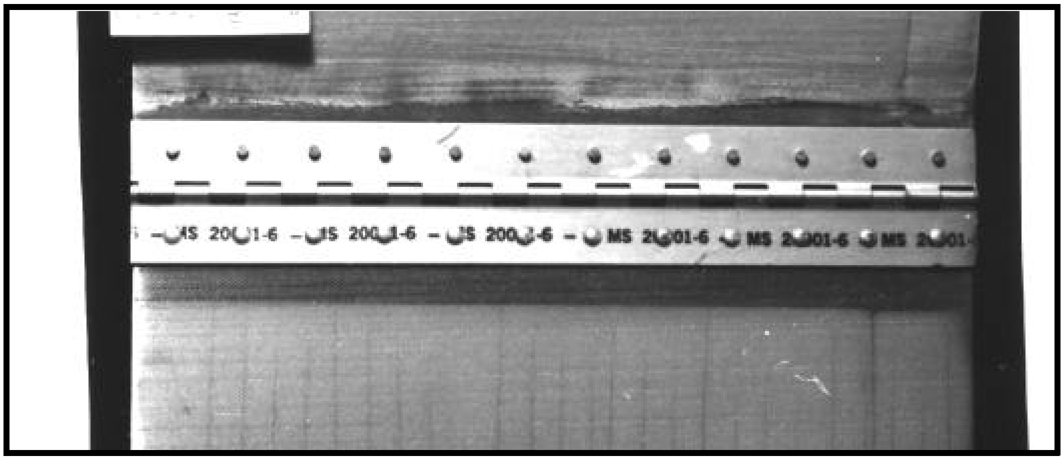


Figure 9.1-3 : View of lower side of hinge after test

9.2 Wing to Flap Hinge Interface

The test specimen simulated the flap to wing interface for the Glasair III-LP. The fiberglass wing and flap structure utilized expanded aluminum foil to provided a conductive path. Figure 9.2-1 provides a sketch of the test specimen. The test specimen was subjected to a Zone 2B lightning currents during the tests. The tests resulted in some loss of the expanded foil in the region near the hinge locations due to localized high current densities. A second ply of expanded foil, or a thicker expanded foil would have reduced the loss of foil near the hinge attachment points. Photographs of the post-test condition of the test specimen are provided in Figure 9.2-2.

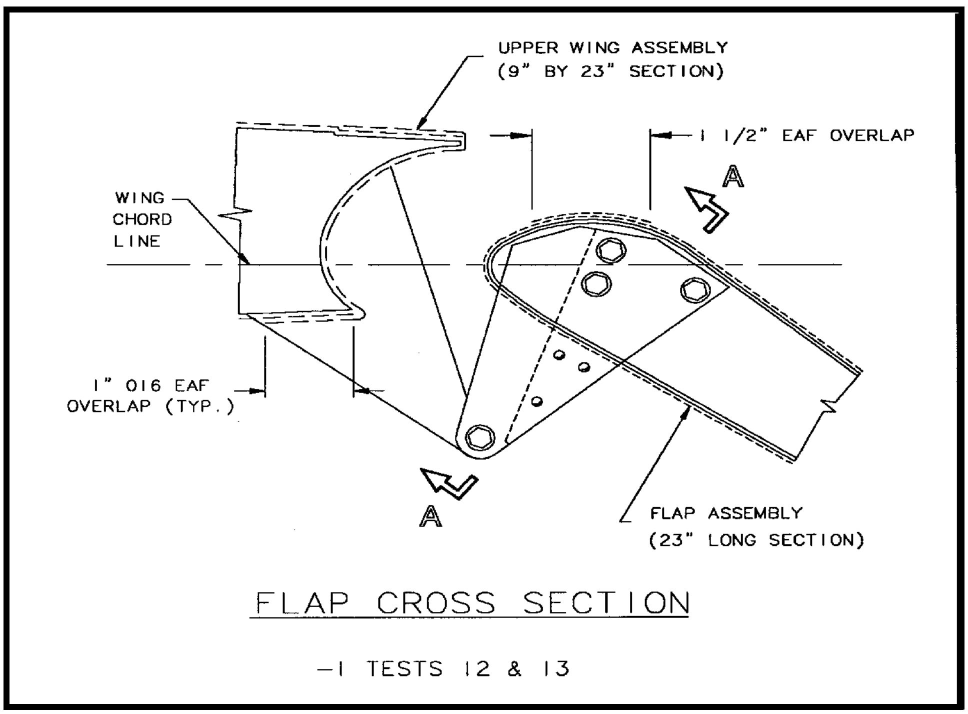
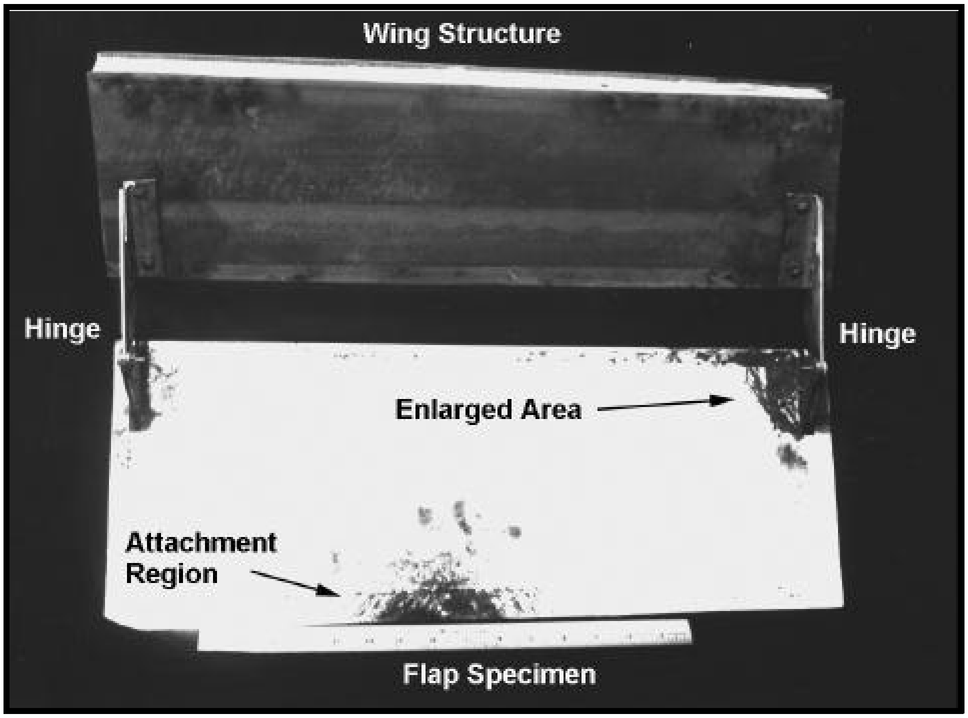
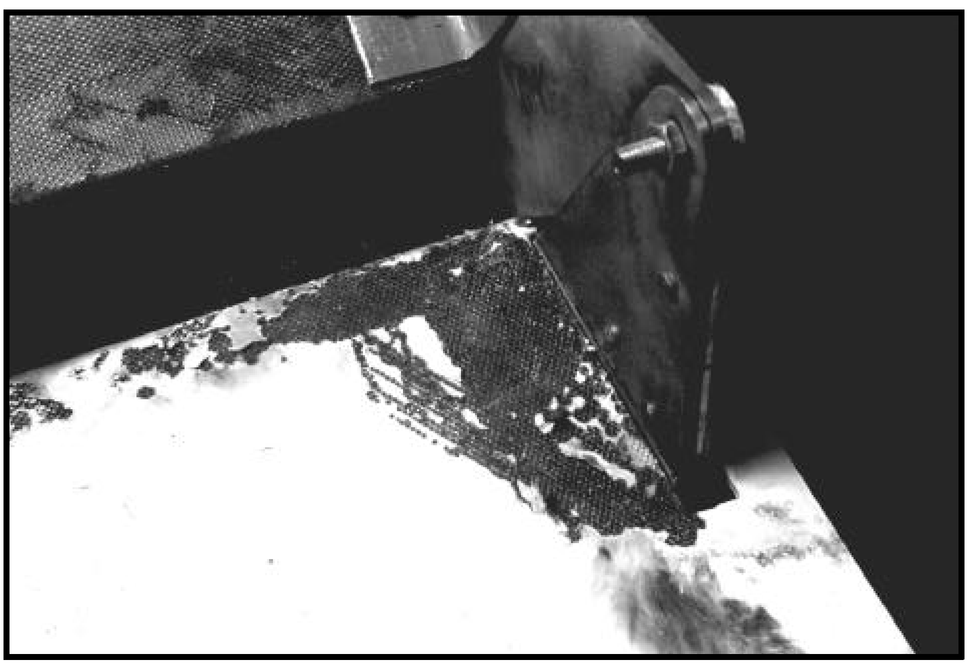


Figure 9.2-1: Sketch of flap test specimen



a) flap hinge specimen



b) close-up of hinge damage area

Figure 9.2-2 : Flap hinge post test photographs

9.3 Canopy Hinge

This test specimen evaluated a lightning strike to a typical canopy door hinge. Zone 1A lightning currents were conducted through the door hinge assembly. On the aircraft, two hinges share the lightning currents, therefore the test configuration anticipated a worst case currents of 133 kA which considers a maximum of 2/3 of the total current will pass through any single hinge assembly.

The canopy and adjacent fuselage structure was fabricated of fiberglass composites with expanded aluminum foil on the exterior surface. Figure 9.3-1 provides a sketch of the test specimen.

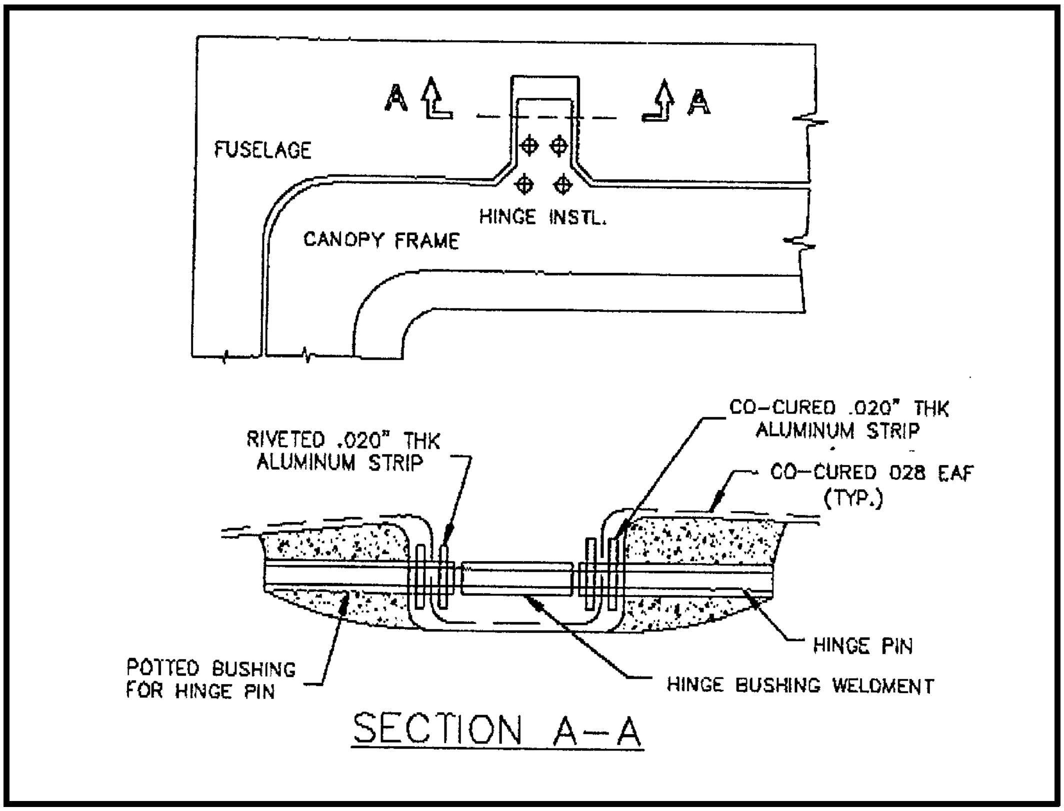


Figure 9.3-1 : Sketch of flap to wing hinge interface.

The tests were performed with no apparent damage to the fiberglass structure. Evidence of arcing at the hinge was observed, however the hinge continued to function normally. Figures 9.3-2 and 9.3-3 provide photographs of the canopy specimen after application of the lightning currents.

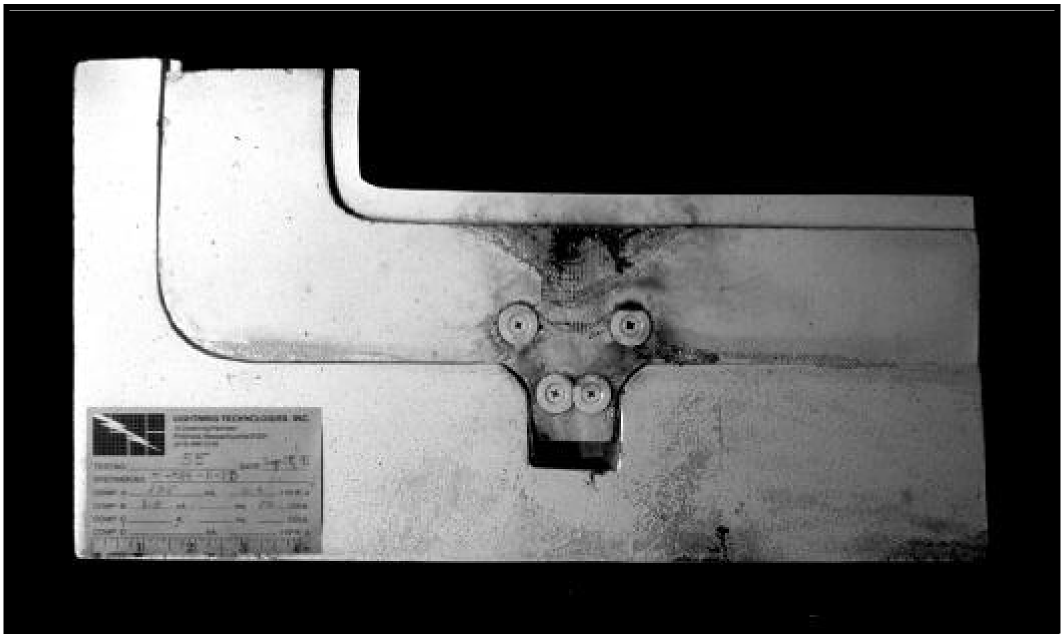


Figure 9.3-2 : Photograph of canopy hinge test article after the test

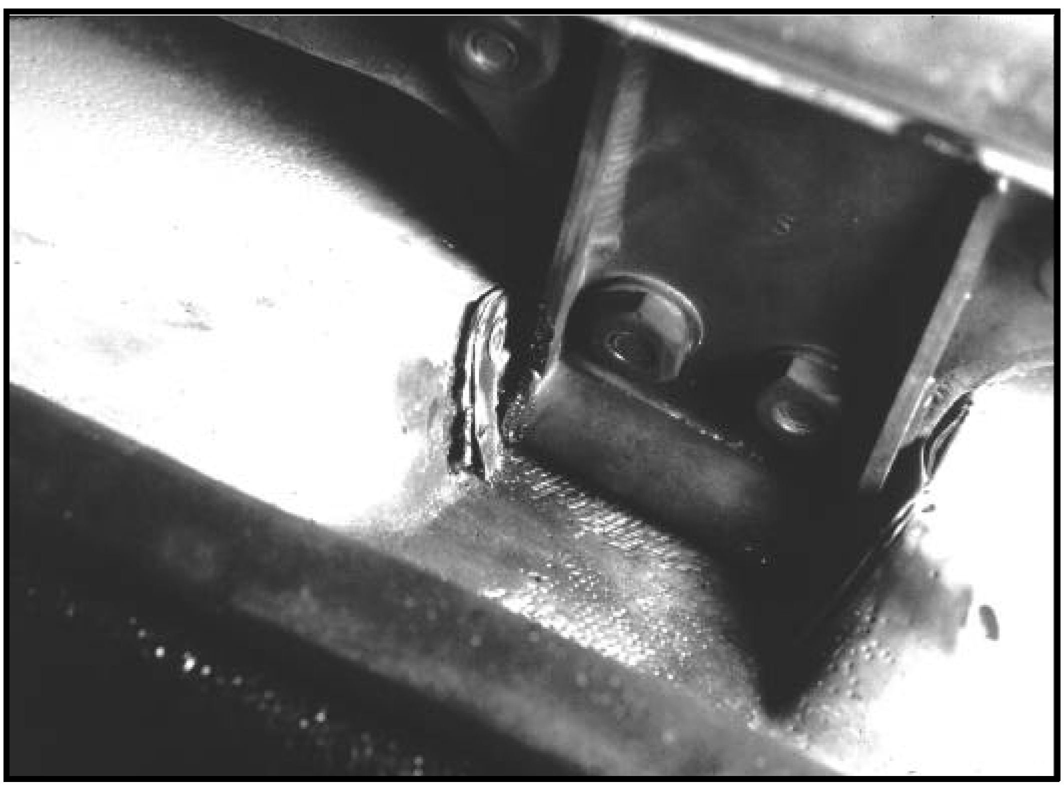


Figure 9.3-2 : Closeup photograph of canopy hinge after the test

10.0 Composite Fuel Cells

As we have seen, the principal challenge of designing fuel cells for air vehicles lies in protecting the fuel system from ignition by lightning. We will discuss in this chapter appropriate methods of protecting composite fuel cells from ignition by lightning strikes.

Protection of fuel systems will involve one or more of the approaches:

1) **Containment:** Designing the structure to be capable of containing the resulting over-pressure without rupture.

2) **Inerting:** Controlling the atmosphere in the fuel system to ensure that it cannot support combustion.

3) **Foaming:** Filling the fuel systems with a material that prevents a flame from propagating.

These approaches involve selection of basic structural materials, modifications in the airframe structural design and perhaps methods to prevent contact between any remaining ignition sources and fuel vapors. Successful implementation of these measures will require the designer to work closely with airframe and structures designers and manufacturing technologists from a very early point in the design process. Structural design modifications to minimize lightning protection problems can result in substantial savings in weight and cost, but these benefits will not be obtained unless such concerns are incorporated early in the design cycle. Structure design must satisfy many requirements and some lightning protection features may not be compatible with other requirements.

The following design approaches should be utilized to the extent practical to minimize potential ignition sources within aircraft fuel tanks.

1) Design the fuel tank structure to minimize the number of joints, fasteners and other potential arc and spark sources in fuel vapor areas.

2) Provide adequate electrical conductivity between adjacent parts of structures.

3) Provide a barrier to separate remaining arc or spark products from the fuel vapor.

4) Design fuel system components to interrupt potential current.

10.1 Tank Structures Design

As illustrated in the foregoing sections, most ignition sources are associated with structural joints and fasteners of various kinds. As much as possible, joints and fasteners should be eliminated in fuel vapor areas. If they cannot be eliminated, they should be designed so that they do not spark. If sparks cannot be completely eliminated, the fastener must be sealed so that the sparks do not contact the vapor. Several design approaches are possible.

Eliminating penetrating fasteners: Figures 10.1-1 through 10.1-3, show how wing spars and ribs can be rearranged to eliminate penetrations of fasteners into the fuel tank. This approach may eliminate possible fuel leaks at the fasteners as well as eliminating ignition sources, though the possibility of leaks due to bowing of the closeout rib would have to be considered.

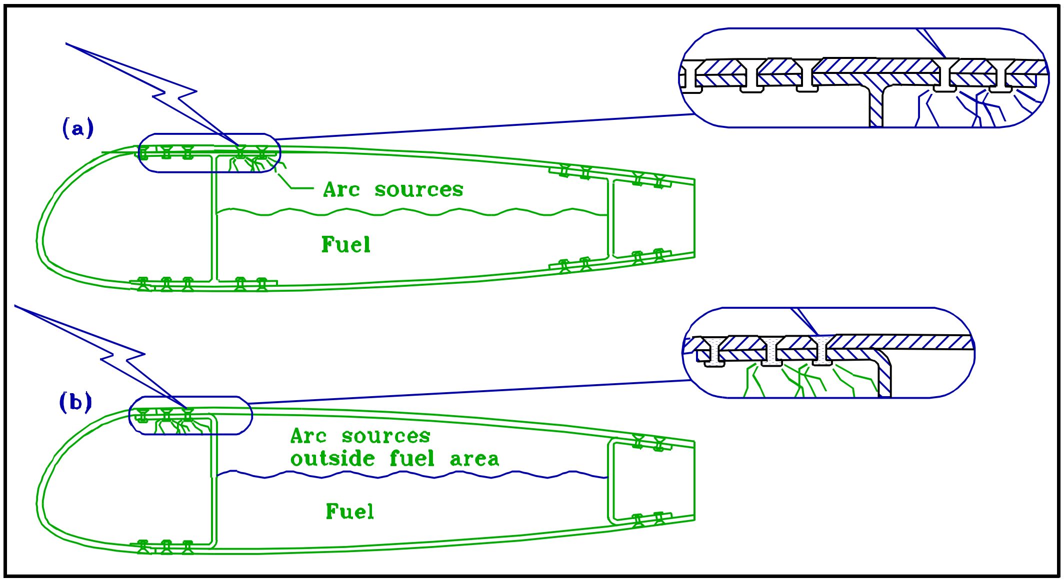


Fig. 10.1-1: Spar-skin interface design to reduce ignition hazards
a) Conventional - fasteners in fuel area
b) Improved - fasteners outside fuel area

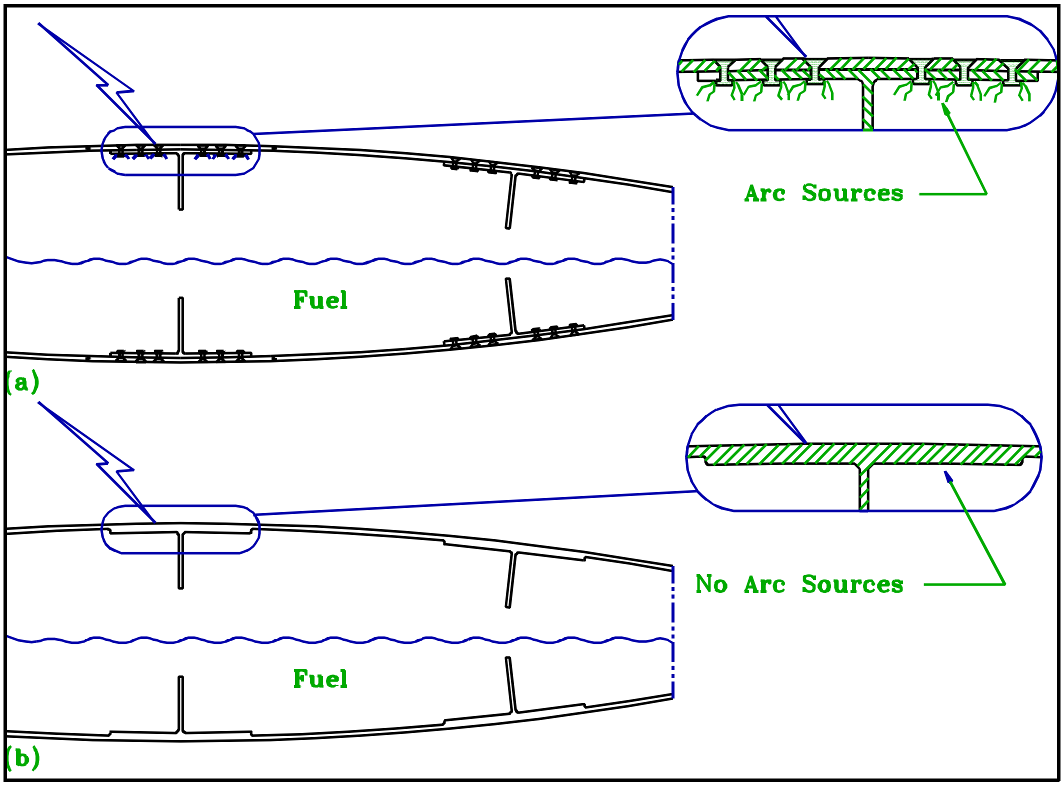


Figure 10.1-2: Wing stiffener design to eliminate ignition sources
a) Conventional - penetrating fasteners
b) Improved - integral stiffeners

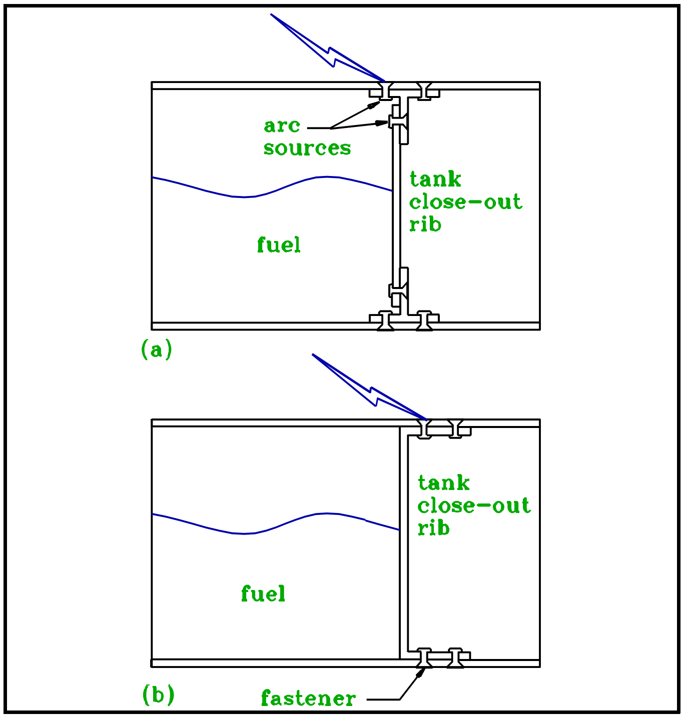


Fig. 10.1-3: Fuel cell closeout rib-skin interface
a) Conventional
b) Improved

Care must be given to ensuring that the edges of spars and the rib-to-skin interfaces do not present arc or spark sources themselves. This is usually done by use of electrically insulating, corrosion resistant finishes, as well as sealant materials between parts. Also, polysulfide type sealant is sometimes necessary at fillets and fasteners .

The approaches illustrated in Figures. 10.1-1 through 10.1-3 are applicable to CFC as well as to metal structures. Lightning currents in fasteners in CFC structures may be higher than those in aluminum structures because diffusion times in CFC are much shorter than in aluminum and more current will seek to flow in interior structural elements such as ribs and spars. Also, it is usually more difficult to make arc free electrical contact between CFC parts. These design approaches may be more necessary in CFC airframes than for aluminum airframes.

Likewise, the lightning current densities in airframes of small size, general aviation aircraft and small rotorcraft, will be proportionally higher than the current densities in larger transport category vehicles exposed to the same total amount of lightning current. Design approaches can be followed to eliminate potential ignition sources in small integral tank structures.

Co-curing of CFC tanks: The most radical way of eliminating fasteners and their associated problems is to build the tank as a single monolithic structure which is electrically conductive throughout. While this is not done at present, it is a technique that could be used to build CFC tanks.

In Fig. 10.1-4(a) fasteners penetrate the tank. In Fig. 10.1-4(b) filament winding is used to achieve an entirely co-cured structure. Practical limitations may prevent this method from being utilized to build complete wings of large aircraft, but similar approaches may be useful for construction of various substructures.

Co-cured joints in CFC structures will eliminate potential arc and spark sources and provide the best possible electrical conductivity among structural sections. In these joints, the pre-impregnated resin is used to bond yarns and plies together without the need for additional adhesives. Practical difficulties arise in co-curing large structures, but great improvements in lightning protection of CFC structures can be achieved by co-curing of simple interfaces, such as between stiffeners and skins.

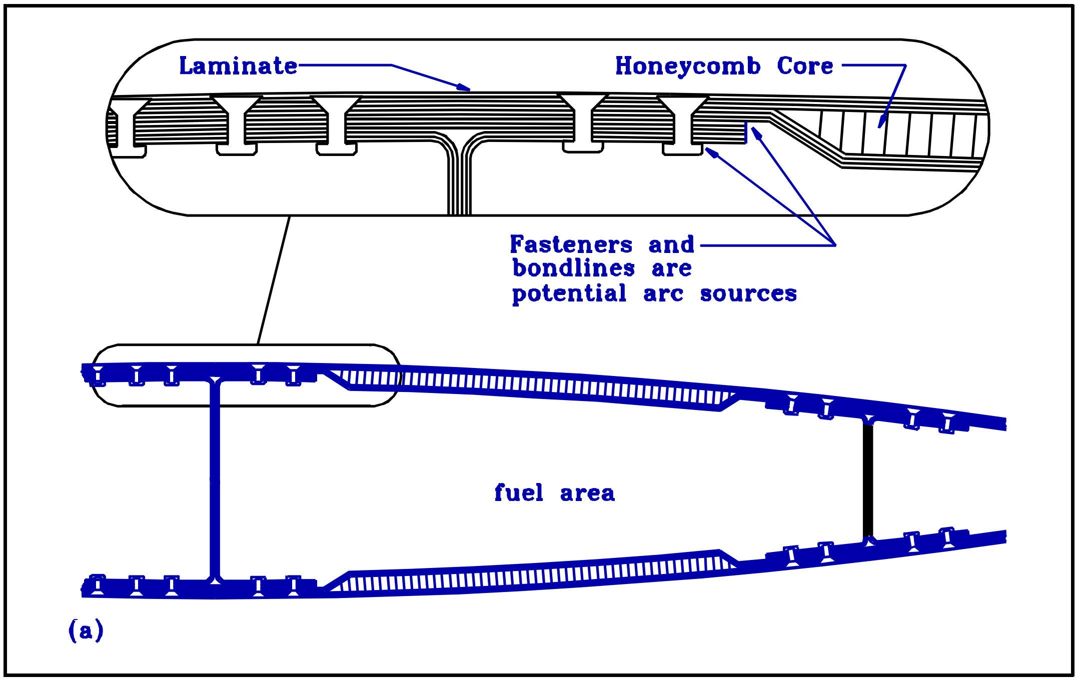


Fig. 10.1-4(a): Fasteners penetrate tank.

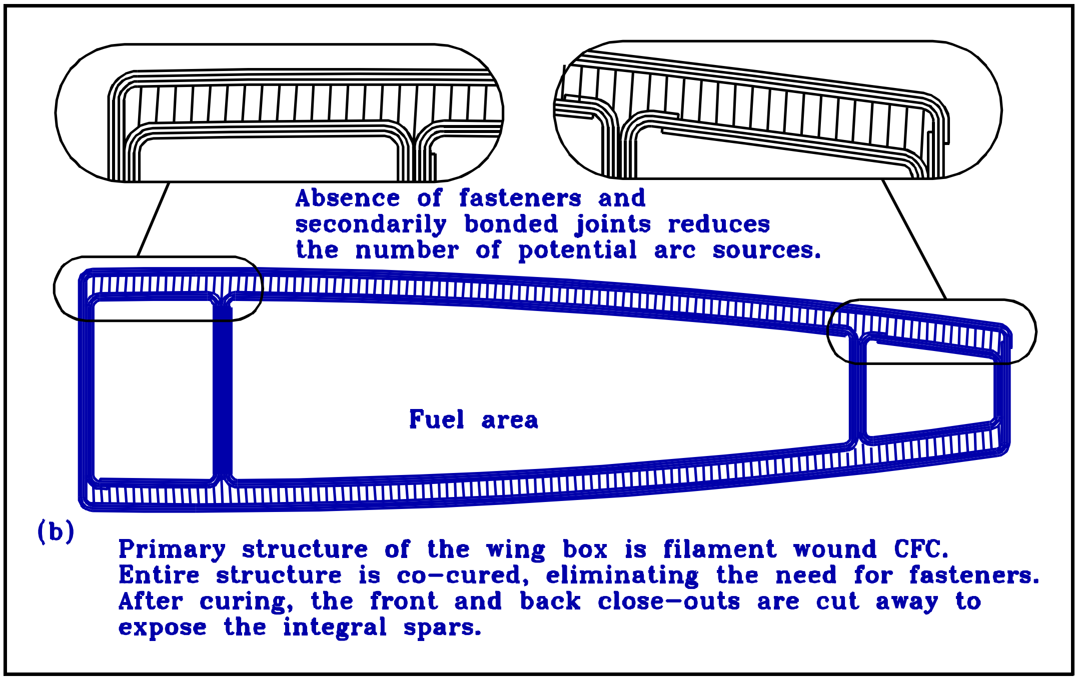


Fig. 10.1-4(b): Advanced manufacturing used to eliminate fasteners

Non-conductive ribs: Another method, shown in Fig. 10.1-5 illustrates the use of fiberglass or aramid fiber reinforced composites to fabricate ribs within a wing fuel tank. In this case, lightning currents tend not to flow into fasteners because these bear against non-conducting interior surfaces and do not constitute current paths. Mechanical strength considerations may preclude use of other than CFC material for spars and ribs. If so, several other approaches can be used to interrupt current through fasteners.

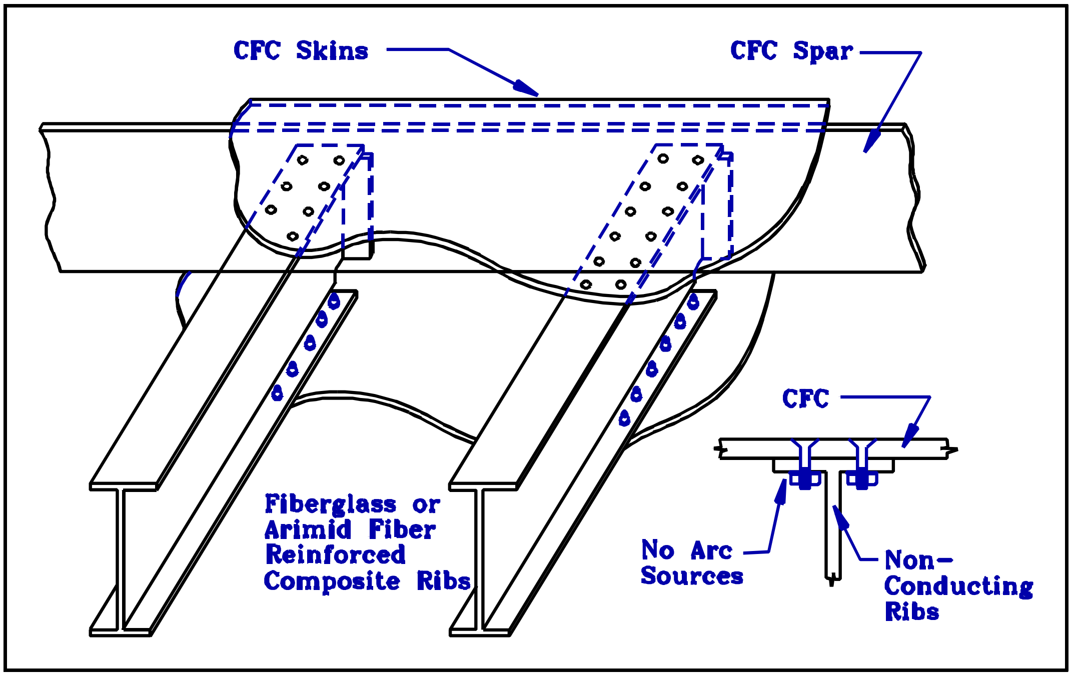


Fig. 10.1-5: Non-conducting ribs

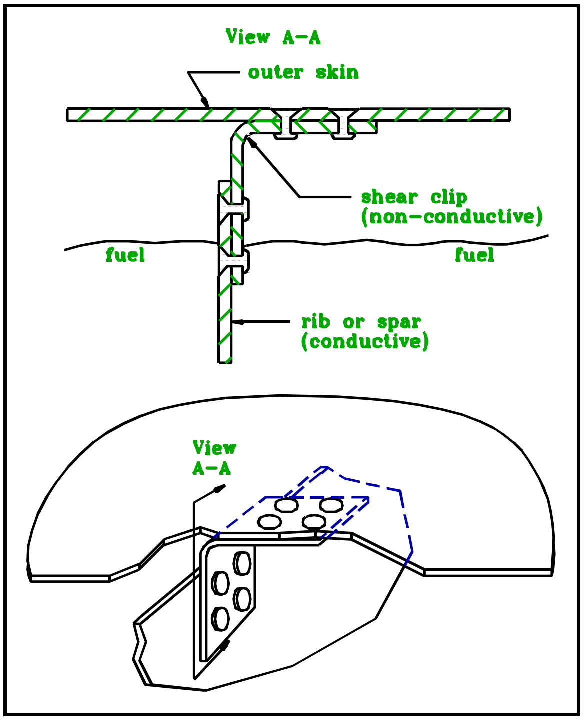


Figure 10.1-6: Non-conducting shear clips

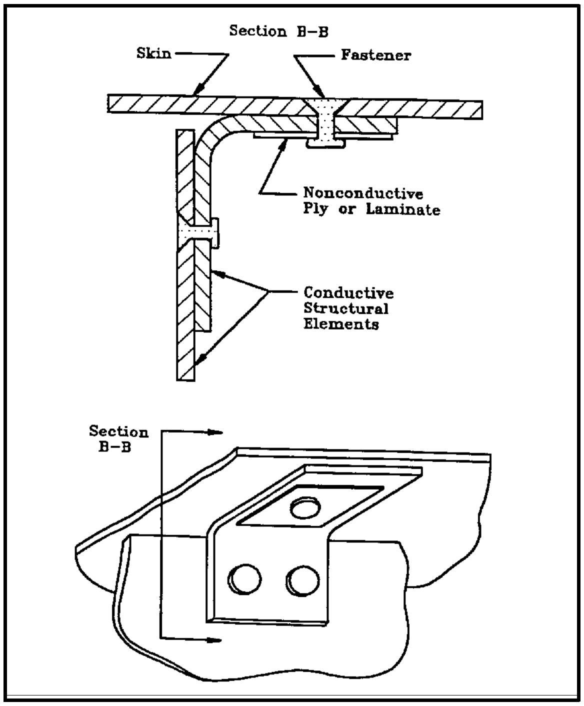


Fig. 10.1-7: Non-conducting ply or laminate

Non-conductive shear ties: Fig. 10.1-6 illustrates the use of a non-conductive shear tie, sometimes called a clip or shear clip, to interrupt electric current paths between skin and interior structures which are conductive. This allows these elements to remain conductive, yet ensures that lightning currents remain in the tank skin and eliminates potential arc sources at fasteners.

Prevention of fastener sparks: If it is not possible to use a non-conducting shear tie, Fig.10.1-7 illustrates a method of controlling internal sparking at the fastener. A non-conductive ply or multi-ply laminate is bonded to the interior surface of the clip. This prevents current from arcing from the fastener to the back of the shear tie at the surface.

The designs illustrated in figures 10.1-1 through 10.1-7 are examples of the kinds of approach that can be followed to eliminate the source of potential fuel vapor ignition. These concepts avoid the method of extensive sealant overcoat that impose cost and weight penalties and concerns regarding the durability of such coatings. Designers are encouraged to develop other approaches to solving these problems.

Since success is dependent on many factors such as dimensions, clearances and fit, the performance of any given design cannot readily be predicted. Any new design must be evaluated through testing.

When employing electrically insulating structural materials to interrupt lightning current, it must be remembered that current paths must be provided between extremities, such as nose, tail, wing and empennage tips and control surfaces. Thus, non-conductive elements may be utilized within a CFC tank, but the tank skins, and often the main spars, must be fabricated of conductive materials capable of conducting lightning currents.

10.1.1 Provision of Adequate Electrical Contact

A primary means of current transfer between fuel tank structural elements is often through fasteners. When current is conducted through them, arc products may be produced. These consist of plasmas of ionized air, vaporized and melted metals, and/or composite fiber-epoxy materials. Any of these arc products can be hot enough to ignite fuel vapors.

The basic mechanism is shown in Fig. 10.1-8. The lightning current is conducted from one part to another through the fastener, threaded nut, and washer. With lightning densities of hundreds or thousands of amperes per fastener, arcing will occur at the points of contact between fastener and fastened parts. If the fastener could bear directly against bare metal, the arc threshold (amperes per fastener) could be increased. However, bare uncoated parts are almost never tolerated within aircraft structures due to the possibility of corrosion.

Keeping current densities low: One method to minimize arcing at a fastener is to keep the current density in the fastener low. This may be accomplished by using fasteners as large as possible to maximize the contact area between the fastener and the joined surfaces.

The intensity of arcs may also be reduced by allowing or encouraging the current to be shared among several fasteners. With a large number of fasteners in a current path, the current in any one fastener will be lower. Lightning currents do not divide evenly among all fasteners in most designs, since overall current densities diminish with distance away from lightning entry and exit points. Reliable analysis methods are not readily available to calculate the current distribution among fasteners. Gross estimates can be made by intuition, sufficient to design test specimens and establish appropriate current levels.

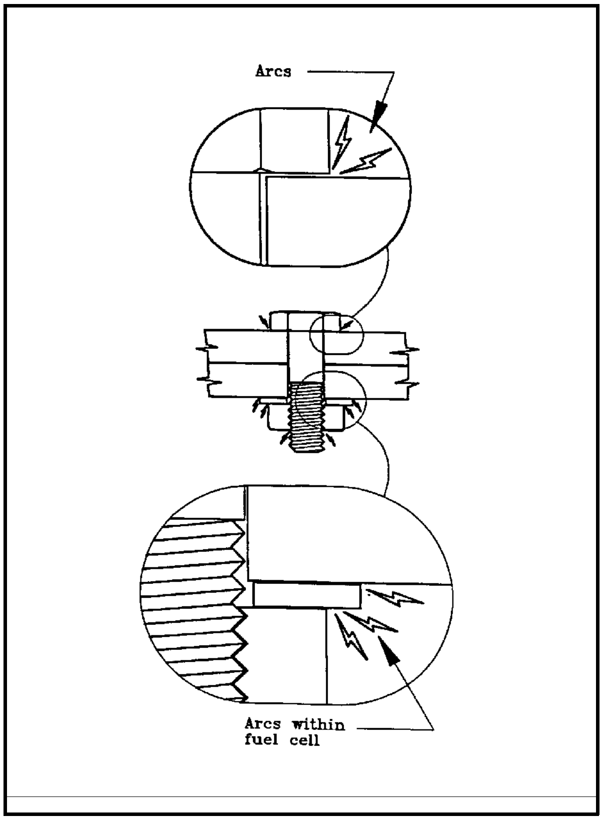


Figure 10.1-8: Arcing at fastener interfaces

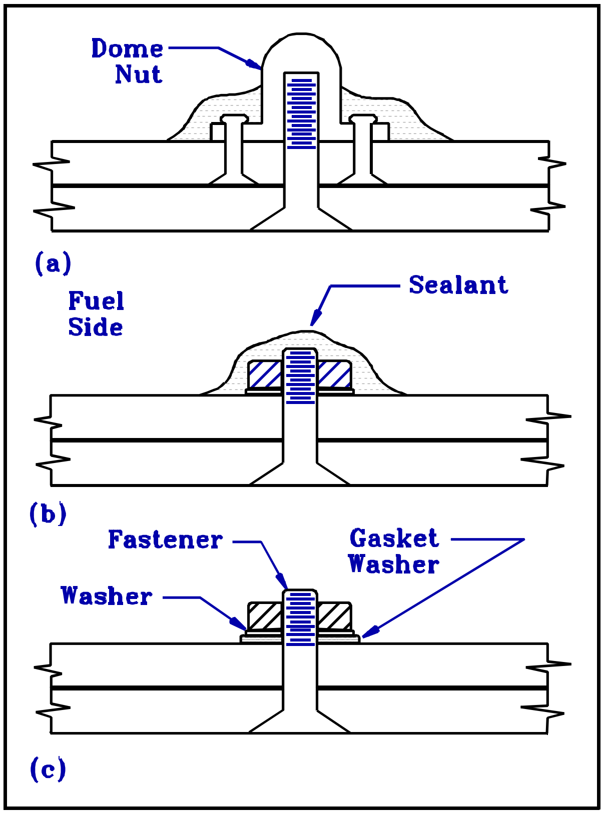


Figure 10.1-9: Fastener sealing concepts

Arc Containment: As noted earlier, certain design methods can be employed to reduce the intensity of arcs at conductive interfaces. These methods may prevent ignitions at low to moderate current levels, but at higher levels the arc pressure buildup may be sufficient to blow arc products into the fuel vapor space. For this reason, it is generally necessary to employ a barrier between arc sources and fuel vapor areas.

Containment with tank sealant: The most common method of containment is the addition of a fuel tank sealant coating over the surface of the fasteners. The basic principle is shown in Figure 10.1-9. It must be emphasized that sealant does not eliminate the arcs which occur, but merely contains the resulting products so that they do not contact the flammable vapor space.

Protection increases as the thickness of the applied sealant is increased, though there is a practical limit to the amount of sealant which may be applied because of the weight which it adds to the aircraft and the cost of labor and material. The effectiveness of overcoating depends upon the skill of the operator. The fastener must be thoroughly coated and there must be no voids or thinly coated areas.

Examples of acceptable and unacceptable sealant coverage for fasteners are shown in Figure 10.1-10. Figure 10.1-10(a) shows sealant applied at the sides of the fastener, but not of sufficient quantity to prevent arc pressure blowby through the sealant or at the interfaces between the sealant and the fastener. This is remedied, as shown in Fig. 10.1-10(b), by applying a coating thick enough to prevent arc product breakthrough. In addition, the sealant has been extended over the fastener head, thus eliminating the possibility of arc product blowby through the sealant at this location.

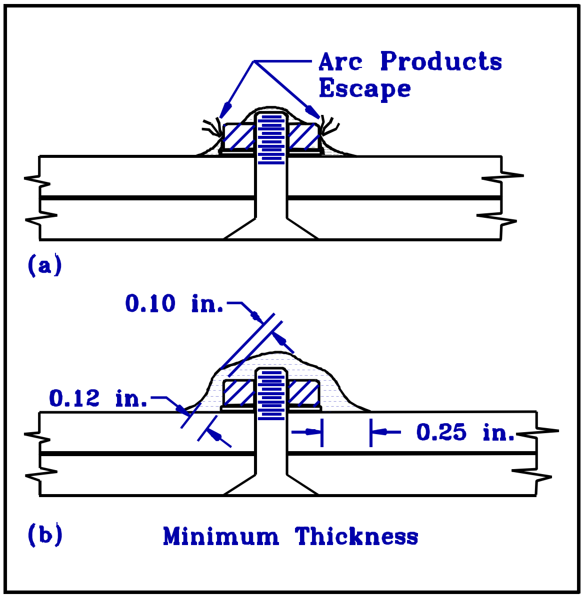


Fig. 10.1-10: Guidelines for overcoating fasteners

The advantages of sealant are:

1) Sealants may already be applied to prevent leaks. Containment of arcs and sparks may only require that the sealant be applied more thickly, or over a wider area.

2) They are easily applied.

3) They can be applied to existing designs; they can be retro-fitted to problem areas.

Disadvantages of sealant are:

1) Application is operator dependent.

2) Sealant exacts a weight and cost penalty.

3) Protection may deteriorate with age and flexing of the airframe.

Containment with fasteners: Although arcing can take place at any point of contact between the fastener and the CFC structure, the most significant arcing takes place between the shaft of the fastener and the hole surface. Pressure will then build up in this area and can vent under the fastener nut or washer into the fuel tank vapor space.

A method of containing these products is to use fasteners which provide a mechanical seal. These fasteners are fabricated with a gasket to contain the arc products which result from contact between the fastener and the structure. Arcing may occur between surfaces in close proximity, such as between the fastener housing and the skin surface as shown in the sketches, but electrically non-conductive primers or finishes on the skin surface may help prevent this problem. Typical installations should be tested for certainty.

Arcing threshold levels of self-sealing rivetless nutplates are generally higher than similar nutplate fasteners with rivets. This is due to the combination of the rubber seal, which prevents blowby of arc products into the fuel vapor space, and the elimination of rivets which are generally the source of arcing when currents of any appreciable amplitude are conducted through the nutplate fastener. While arcing threshold levels of typical fasteners have been shown to be approximately 5 kA, the levels achieved by rivetless nutplate fasteners have been three to four times this level.

Structural interfaces: Sealant coatings must also be applied to structural interfaces, at least in exterior skins where current densities are highest. In tanks fabricated of aluminum, coatings of electrically non-conductive corrosion finishes on interfacing parts can result in arcing between the parts due to the poor electrical contact. For CFC tanks, arcing can be caused by the non-conductive resins and adhesives used in the fabrication of structures. Arcing may occur due to insufficient electrical contact between elements and sparking may occur due to voltage potential differences between elements.

Recommended fillet sealing dimensions for sealants are provided in Figure 10.1-11.

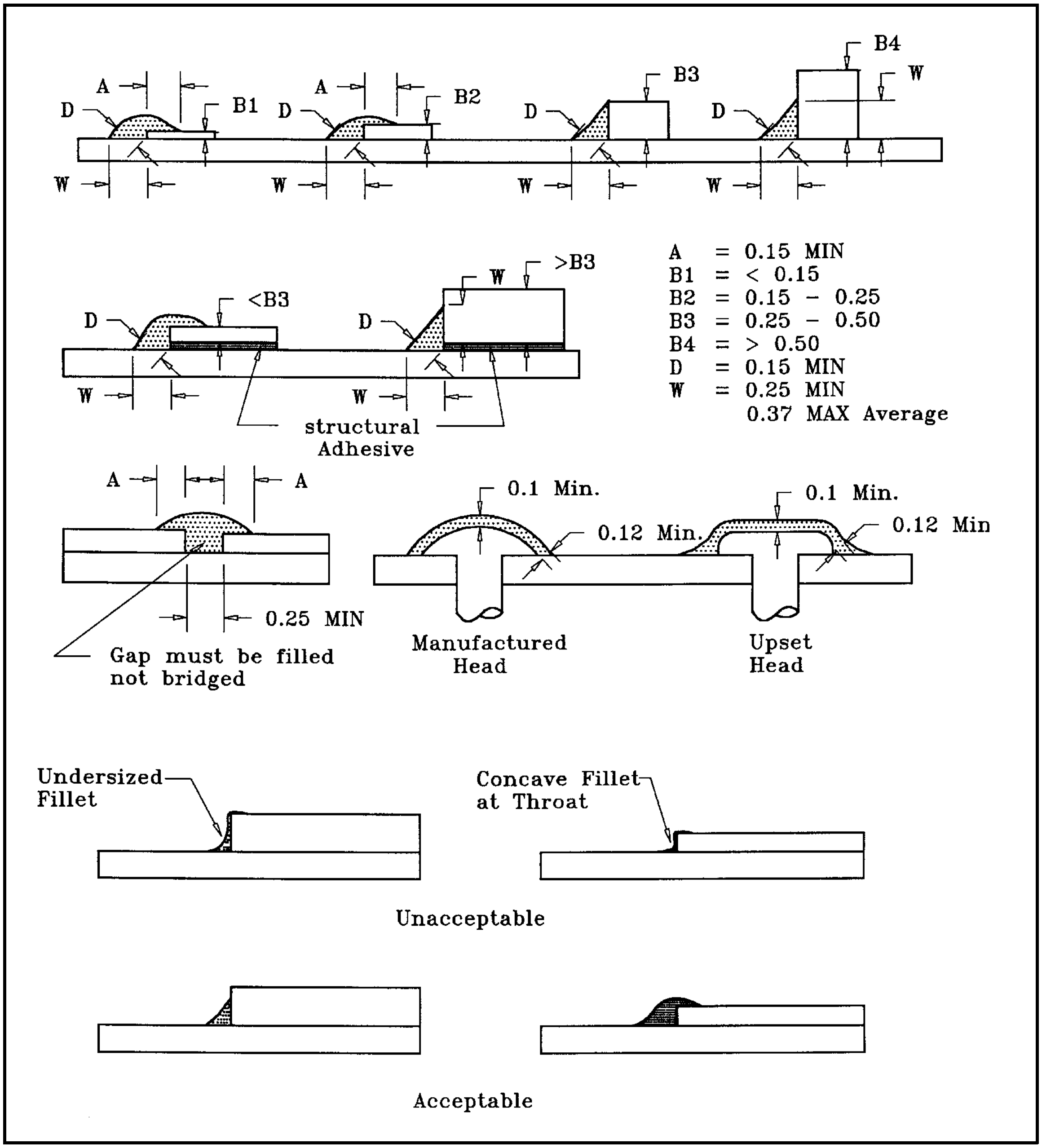


Figure 10.1-11: Recommended Sealant Application Notes

<u>Spark and arc thresholds</u>: The arc and spark threshold level of a particular aircraft design depends on several factors which include the following:

1. Type of skin material.

2. Skin thickness.

3. Thickness of primer and surface finishes.

4. Arc entry vs. conducted current entry.

5. Current amplitude.

6. Current division among structural elements.

7. Thoroughness of fuel tank sealant coverage.

The threshold levels at which arcs and sparks occur in a new aircraft design may be estimated by similarity with other designs for which a data base exists. However, the fuel tank designer should be careful when assuming that a new design is similar to a previous one. Any differences in materials, thicknesses, coatings, or number of fasteners will change the impedances and current paths within the tank, which can alter the threshold levels.

The current density in a particular set of fasteners can be estimated by mathematical techniques, but determination of structural current is impossible due to the complexity of current paths and the difficulty of describing them in electrical terms. Since there is uncertainty about the reliability of these calculations, it is best that designs be based on similarity or upon analysis supported by test data.

10.1.2 Filler Caps

Filler caps present a special series of problems when lightning protection is concerned. In an effort to maintain a liquid-secure fitting, the cap must be fitted with gaskets or seals between the cap and its tank adapter. If lightning contacts the filler cap (typically composed of an attractive conductor) the potential exists for sparking across or through the seals.

In addition, a filler cap lanyard has traditionally been used to retain the filler cap against loss. Usually made of light gauge chain or ball and wire chain, the lanyard produced an attractive environment for sparking in the case of lightning attachment.

There are a variety of design modifications which can be employed to remediate such difficulties.

A lightning protected filler cap most often uses a plastic insert so that there are no metallic faying surfaces across which sparking can occur. If a lanyard is required to retain filler cap to plane, it must be made of plastic.

In the case of the cap itself, a lightning protected cap can be installed in conjunction with mating adapters. Electrically non-conductive O-ring adapters provide a seal between plastic insert and mating adapter to prevent fuel leakage. If a strike occurs to the cap, the resulting currents arc from cap to the adjacent adapter, since the O-ring seal prevents direct electrical contact between the two parts.

Alternatively, an all-plastic cap can be installed, preventing any arc attachment.

Lightning protected caps must be used if there is any possibility that the cap can receive a lightning strike. This is the case if the cap is located in *Zones 1A, 1B*, *2A* or *2B*.

10.1.3 Access Doors

Like filler caps, access doors present a conflicting set need for the aircraft designer. Access doors must be found in all, or nearly all, aircraft designs to permit installation and maintenance of fuel system hardware. Such doors are normally located in exterior skins in areas subject to direct or swept stroke lightning strikes. Without protection, such access doors are likely to spark across the gap between door and jamb. Given the potential for ignition of fuel or fuel vapor, it is essential that access doors be given protection.

The following modifications have been used:

1) Metal to metal contact should be avoided in areas that may be exposed to fuel vapors.

2) Provision of adequate current conduction paths between door and adapter and and between adapter and surrounding skin, away from fuel vapors. This usually occurs via the fasteners, which are separated from vapor areas by O-rings, gaskets or sealants.

3) Application of sealant to other potential arc or spark sources so as to prevent contact with fuel vapors. The advantages and disadvantages of sealants have been discussed.

Design guideline for access doors: The following guidelines are intended to assist in designing access doors.

1) Provide as much electrical contact via screws or fasteners as possible while making the current paths through these fasteners as short as possible.

2) Fasteners should be isolated from vapors areas with non-conductive gaskets or O-ring seals.

3) All fasteners should be coated with tank sealant.

Verification

The nearly infinite number of variables involved in access door design mandates that lightning tests should be performed on all such installations.

A typical door should be fabricated into a panel specimen and tested by high current arc attachment to determine if arcing or sparking occurs on the interior of the door. Arc entry tests should be applied to the center of the door as well as to door fasteners. This is intended to show the adequacy of the access door-to adapter gasket seal, as well as the seals of the door fasteners/dome nuts. The door/frame samples can be tested in a flammable gas chamber environment, but if ignition occurs, it will be difficult to locate the source.

10.2 Fuel Tank Joints: Special Problems

High-density patterns of rivets or fasteners, as commonly used to join fuel tank skins to stiffeners, ribs, and spars, should be capable of conducting 200 kA stroke currents even when nonconductive primers and sealants are present between the surfaces, as in Fig. 10.2-1.

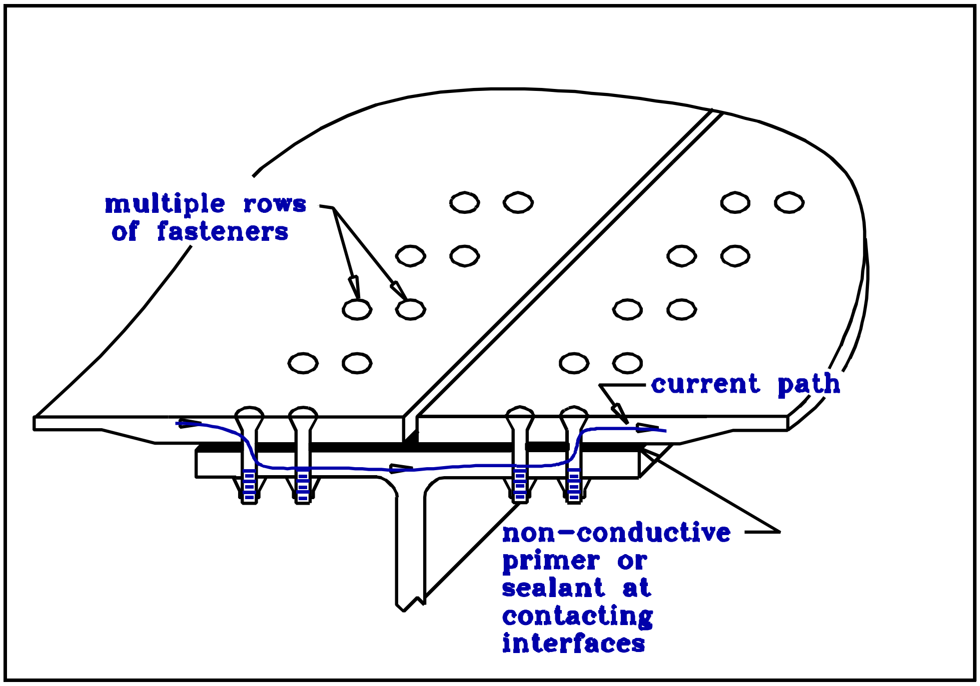


Fig. 10.2-1: Bonding through mechanical fasteners

There is no hard-and-fast rule for the number of fasteners per joint which are necessary to avoid arcing, but a rough guideline of 2-5 kA per fastener, as discussed below, can give some indication of the number of fasteners which may be required to transfer lightning currents among structural elements without arcing. In general, it has been found that structural fastener configurations inside tanks and not exposed to direct strikes can tolerate (Zone 3) current densities without visible arcing and the need for overcoating with sealant. Fasteners exposed to exterior surfaces in (*Zones 1* or *2*), however, must usually be protected and verified by testing.

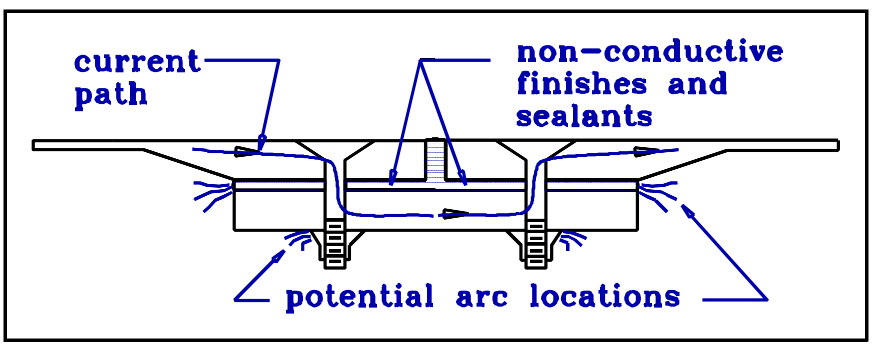


Fig.10.2-3: Potential arc sources at structural interfaces

At areas of high current density, arcing usually occurs at the interfaces between the fastener and surrounding structure, as shown in Fig. 10.2-2 and the occurrence of such arcing depends on other physical characteristics, such as skin material, skin thickness, surface coatings, and fastener tightness. Tests in which simulated lightning currents are conducted through the joint should always be made on samples of joints involving new materials or designs to confirm protection adequacy.

Arc thresholds of fasteners in Zone 3 areas: Under a program sponsored by NASA (NASA Contractor Report 3762, pp. 33-35, January 1984) tests were performed to determine the spark threshold level of typical fasteners used in aircraft installations. For those tests, aluminum lap joint specimens were bonded with electrically non-conductive fuel tank sealant and were also fastened with a single rivet which had been "wet" installed with the same sealant. Currents were conducted directly into one end of the specimen and removed from the other end. All current was forced through the single fastener since the non-conductive sealant eliminated any direct electrical contact between the mating surfaces. No coatings of any kind were applied to the head of the fastener.

The tests indicated that the spark threshold current level of the fasteners was 5 kA. Thus, a door containing 40 fasteners could conduct nearly 200 kA without sparking if the current were distributed evenly among the fasteners. In most cases, however, the current will not divide uniformly, but will be concentrated in those fasteners closest to the point of attachment or exit.

Direct attachments: The preceding discussion relates to joints located in *Zone 3* which must conduct only a portion of the lightning current. Joints located in other zones can be struck directly by the lightning arc. It is possible for the lightning arc to remain attached to a single fastener or rivet. If that happens, the arc can melt or otherwise damage the rivet and surrounding skin. If ignitable fuel vapors exist beneath such a joint, the joint may have to be larger than would be otherwise required.

Guidelines for joints: Some other guidelines which should be noted in designing integral tank joints are as follows:

1. Provide electrically conducting paths among the structural elements so that lightning currents can be conducted among elements without excessive arcing, and without having to spark across non-conducting adhesives or sealants. Often this will be via rivets or removable fasteners, which make metal to metal contact with joined parts. There must be sufficient areas of contact among all of the fasteners in the current path to avoid excessive arcing, damage to the fasteners or surrounding structural material.

2. Put no insulating materials in places that would divert lightning current from direct paths between entry and exit points on the aircraft. Voltages which may cause sparking will build up wherever diversions in these paths exist. The diversions through the fasteners and stringer of Fig. 10.2-1 are acceptable. More extended paths may not be.

3. Account for aging and mechanical stress which may cause reduced electrical conductivity. Continued flexing of structures under flight load conditions may eventually loosen a joint to the point where arcing could occur. To evaluate this possibility, perform simulated lightning tests on joint samples which have been previously subjected to fatigue or environmental tests.

4. Coat all joints thoroughly with fuel tank sealant to contain any arcs or sparks which may occur.

5. Do not depend on resistance measurements to confirm the adequacy of lightning current conductivity in a joint. The inductance of the path plays an equally important part. Resistance measurements (ac or dc) may be useful as a production quality control tool, but they are not useful for establishing the adequacy of the lightning current path through the joint.

10.3 Connectors and Interfaces in Pipes and Couplings

Electrical plumbing lines within a fuel tank will usually conduct some of the aircraft lightning currents since they provide conducting paths in contact with conducting structures. The amount of current in plumbing depends on the resistance and inductance of current paths in plumbing as compared with surrounding structural paths. Currents in plumbing within metal aircraft may be small, a few tens or hundreds of amperes, but current in metal pipes inside non-conducting or CFC structures may be very high.

Problems: The current in these lines may cause sparking at pipe couplings where there is intermittent or poor electrical contact. Some pipe couplings, for example, are designed to permit relative motion between the mating ends of a pipe to relieve mechanical stresses caused by wing flexure and vibration and this precludes the tight metal to metal contact needed to carry current. Also, electrically insulating coatings such as anodized finishes are often applied to the pipe ends and couplings to control corrosion. Relative motion and vibration may wear this insulation away, providing unintentional and intermittent conductive paths, situations that lead to sparking. Therefore, particular attention should be given to the design of fuel system plumbing.

Lightning currents in plumbing: The high amplitude return stroke currents will not spread very deeply into interior structural elements or other interior conductors because they are of short duration, but will instead tend to remain in the metal skins. Still, there will be some current. During a NASA sponsored program currents in the fuel lines within a fuel tank with adhesively bonded aluminum structural elements were measured. With a current of 88 kA injected into the wing, the current in a small diameter fuel line within the tank was 160 amperes.

The analytical procedures for determining how rapidly changing currents distribute, are complex, but intermediate and continuing currents persist for times long enough for the distribution to be calculated on the basis of the dc resistances involved.

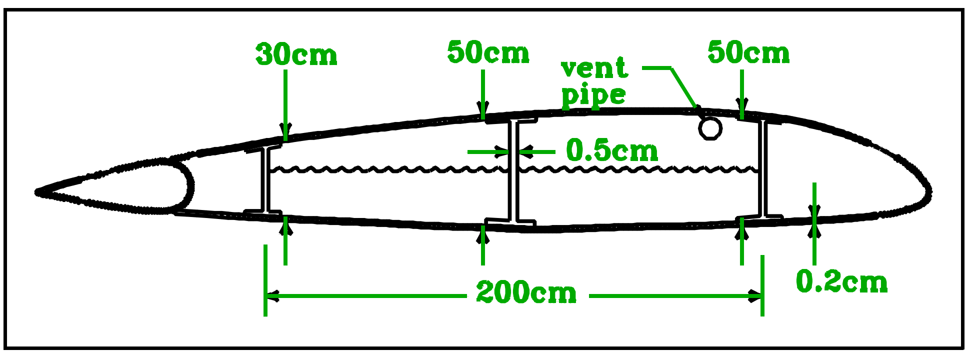


Fig. 10.3-1: Hypothetical wing box

Assume that the leading and trailing edge sections of a wing are nonconductive or sufficiently isolated as to be unavailable for conduction and that the remaining wing box is comprised of skins and spars having the dimensions as shown in Fig. 10.3-1. The cross sectional area of the spars and skins forming this box is 135 cm^2. The tank also contains an aluminum vent pipe electrically bonded to the structure at each end of the tank. This tube has an outside diameter of 10 cm, a wall thickness of 0.5 mm, and a cross sectional area of 1.56 cm^2.

Assume an intermediate strike with an average amplitude of 2000 A for 5 ms, in accordance with Component B of AC-20-53A. The current in the pipe can be calculated as follows:

$$I_{pipe} \approx [\frac{1.56 cm^2}{135 cm^2}] \times 2000 A = 21.3 A$$

Currents of this order of magnitude have produced arcs at movable, poorly conducting, interfaces in some couplings. More common examples of electric arc sources include motor commutators.

Bond straps: Electrical bond straps or jumpers are sometimes installed across poorly conducting pipe couplings, as shown in Fig. 10.3-2. These bond straps should not be relied upon to prevent sparking from lightning currents. Current is apt to divide in proportion to resistance which may be the result of a small contact area in the coupling. Some current in the coupling could lead to sparking even with the bond strap in place.

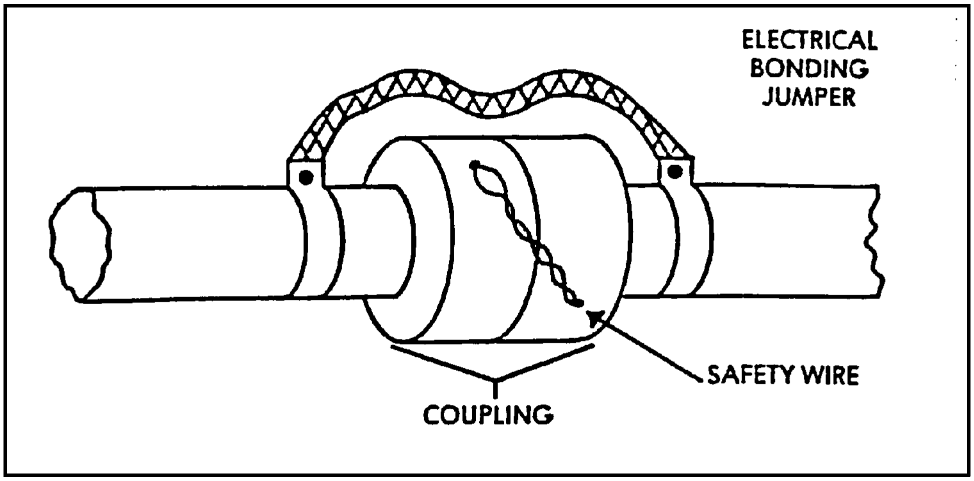


Fig.10.3-2: Bonding across couplers

Conduction through couplings and interfaces: The extensive use of anodized coatings to provide noncorrosive mating surfaces in pipe couplings would seem to preclude arcing across the pipe interface, but relative motion between these surfaces can wear through the anodized coating, forming a conductive path. If there happens to be a large, bare metal-to-metal contact within the coupling, this could provide a spark free path. However, a slight change in the relative position of the mating surfaces, or introduction of dirt or residue might drastically change the electrical capability of a coupling. It is probable that the electrical capability of a typical pipe coupling changes many times during a flight as a result of relative motion caused by structural vibrations and flexing.

Some of the commercially available couplings and bulkhead fittings have been designed to conduct impulse currents up to 2500 amperes without sparking. These couplings should be adequate for use in most metal tanks where currents are of the order of a few hundred amperes or less.

Fuel tanks fabricated of CFC materials, however, are more highly resistive than aluminum. Currents on the exterior skin surface of such tanks will diffuse more rapidly to internal conductive plumbing and currents might greatly exceed 2500 amperes.

Guidelines for protection: In the absence of definitive data on the electrical conductivity of pipe couplings under in-service conditions, it is advisable to take the following approach:

1. Determine, by analysis or test, the fraction of lightning current expected in a particular pipe.

2. Inject this current into a sample of the coupling under simulated in-flight vibration and contamination conditions.

3. Perform this test in a darkened enclosure and observe whether any arcs or sparks occur. Repeat the test until reliable and satisfactory results are obtained.

Non-conducting interfaces: One solution to the problem of arcs and sparks at couplings and plumbing interfaces with aircraft structure is to insert electrically non-conductive isolation links into these lines to eliminate them as current carrying paths. This solution, of course, requires additional couplings, which may add additional weight compared to the traditional all aluminum plumbing.

Another solution is to make the pipes of a non-conductive material. Various solid polymers or fiber reinforced resins may be used for this purpose. Some electrical conducting material must be provided in the interior linings of pipes transferring fuel however, to prevent frictional charge accumulation. The resistivity of these materials should be on the order of 10^6 to 10^8 ohm-cm. This is sufficiently high to prevent lightning currents, but still adequate to dissipate static charges. Lower values would make the lines too conductive. One such system presently under development is a reformable duct system of electrically non-conductive thermoplastic fluoropolymer, reinforced with aramid fibers.

10.4 Electrical Wiring in Fuel Tanks

Problems: Lightning current in an aircraft may induce voltages in electrical wiring. If this wiring enters a fuel tank, the induced voltages may be high enough to cause a spark.

Electrical wires found inside fuel tanks are typically those used for capacitance-type fuel quantity probes or electric motors used to operate pumps or valves. If these wires are totally enclosed by metal skins and ribs or spars, the internal magnetic fields and induced voltages will be relatively low. Electrical devices, such as fuel quantity probes, and their installation hardware, have been intentionally designed to withstand comparatively high voltages without sparking. The fuel system designer, however, must be continually alert for changes in material or structural design that might permit excessive induced voltages to appear in fuel tank electrical circuits.

Guidelines for design: In practice, design of small airgaps should incorporate a margin of 100% over anticipated actual voltage levels, to account for mechanical installation tolerances, the effects of contaminants, and the statistical variations in small gap sparkover voltages themselves. Thus, a particular gap should be sized to withstand, at altitude, twice the anticipated actual voltage.

In some cases, particularly installations within CFC tanks, this will require unacceptably large clearances between objects such as fuel quantity probes and adjacent structure. In such cases other means, such as coating adjacent surfaces with dielectric films, may be explored to enable smaller gaps to withstand twice the anticipated voltage. Designs like this must be given voltage withstand tests, as handbook type data does not exist to support specific designs.

It is particularly important that sufficient insulation be provided between the active elements and the airframe because the highest induced voltages usually appear between the wires and the airframe. These voltages may be IR voltages related to lightning currents in the structural resistance of the wing or they may magnetically induced voltages as illustrated in Fig. 10.4-1. Structural IR voltages may be only a few volts for a metal wing, but they may be several thousand volts in a composite wing.

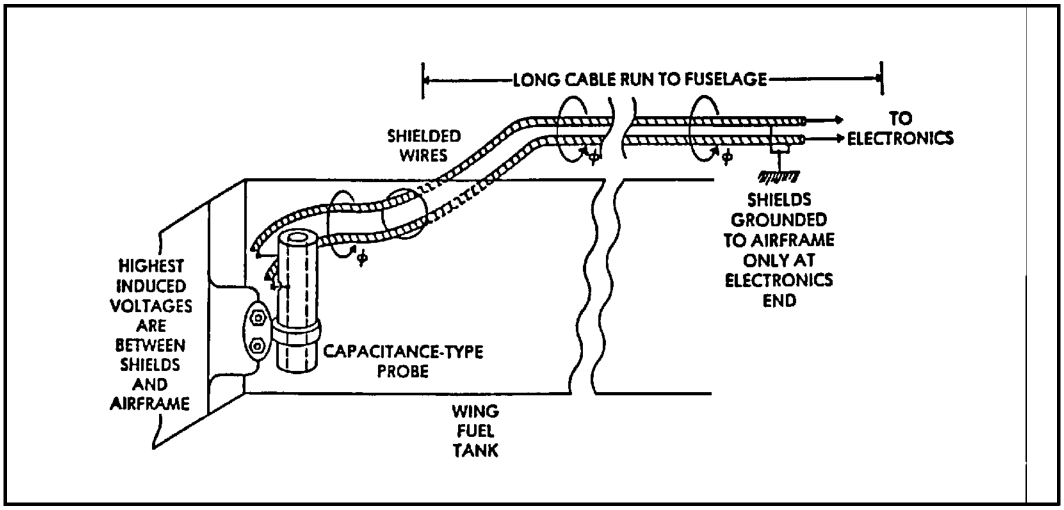


Fig. 10.4-1: Typical fuel probe wiring

Contaminants that accumulate with time on the probe surfaces may act to reduce the sparkover voltage; therefore, it is wise to incorporate a factor of two when designing clearances necessary to tolerate the anticipated induced voltages expected in fuel tank wiring harnesses.

Fig. 10.4-1 illustrates that the proximity of the probe to the airframe structure on which it is mounted is very important in determining breakdown voltages to the airframe. Because of this, design of adequate insulation between the active elements of the probe and the airframe may not be entirely within the probe designer's control.

<u>Shielding of fuel probe wires</u>: The fuel probe wires are most closely referenced to the airframe at the electronics end, which is usually in the fuselage. If one or more of the wires are shielded, there can be a conflict between the grounding practices that are best for control of lightning induced voltages and those considered best for control of steady state electromagnetic interference, EMI.

Usually, because of EMI considerations and concern for "ground loops", only one end of the shield is grounded; most commonly at the end remote from the fuel sensor. Grounding the shield at both ends permits stray ac fields to induce circulating currents in the shield, and such currents may interfere with the operation of the fuel quantity electronics.

The conflict arises because a shield grounded at only one end does not act to reduce magnetically induced voltage between conductors and ground, though it may reduce voltages between conductors in the shield. The gist of the matter is that a shield can reduce voltages between conductors and ground only if it is grounded at both ends and allowed to carry current. If a shield is ungrounded at one end, magnetically induced voltages can develop at that end between the conductors and ground. Thus, most shields found on fuel quantity probe wiring harnesses offer little or no protection from lightning induced effects.

Routing of wires: The routing of the fuel probe wires can have a lot to do with how much induced voltage appears at apparatus inside fuel tanks. Good practice dictates that wires should be routed in regions which are shielded from intense magnetic and electric fields.

10.5 Fuel Tank Access Door Example

An ignition source test was performed on a *fuel tank access door* as part of a series of tests (Lightning Technologies, LF 2100 Lightning Results - Wing, R43222, 1985) designed to certify an outboard access panel on a carbon fiber wing structure. The access door was a fabricated from kevlar, however potential sparking at around the fasteners had to be evaluated.

A 35 mm camera was positioned within the fuel tank area through the access door. Prior to the test, the tank interior was lit and a background photo recorded by the camera (Figure 10.5-1). These photos were used as an aid in pinpointing the position of any arcing or sparks which might occur during testing. After initial background photos were taken, the cameras were set to f 2.8 and shutters set for bulb exposure. The fuel tank was then made light tight. Exposures were made and developed to equivalent of ASA 3200 at f4.7.

Following the initial test, it was found that door sealant was too stiff to permit adequate contact between access door and the doubler. Figure 10.5-2 shows evidence of arcing at various locations around the door.

Prior to a second test on the door, the sealant was removed and replaced with a different grade. The second test showed that arc blowby was eliminated and the door installation passed with evidence of no light at the access door interfaces.

Analysis: Arcing between door fasteners and the mounting interface was solved with the application of a PROSEAL sealant, P/N PR703. The sealant provided an adequate barrier and prevented the arc products from entering the wet region of the fuel cell.

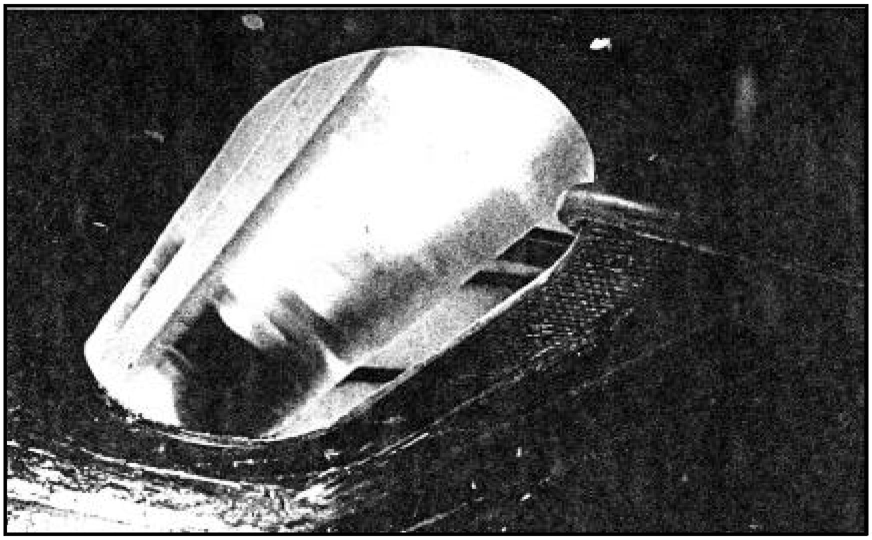


Figure 10.5-1: Background photo of access door opening provided for reference during the actual test.

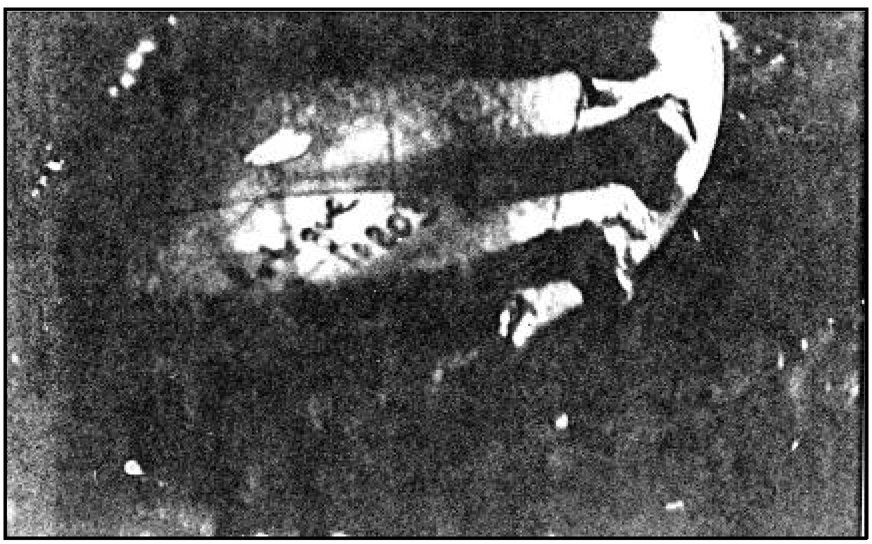


Figure 10.5-2: Photographic evidence of sparking in region of access door installation.

Note: Successful test should result in no visible light in the photograph.

11.0 Externally Mounted Hardware

11.1 Design Guidelines

Externally mounted hardware includes antenna and air data probes such as pitot probes, angle of attack sensors, temperature sensors, stall detectors, and any other device mounted on the external surface of the aircraft. Most of these devices protrude somewhat into the airstream and so may be a preferential attachment point for lightning strikes, especially if they are located in Zones 1 or 2. Experience shows that many off-the-shelf hardware design will remain functional following a lightning strike to aircraft as long as the lightning does not contact the external hardware. However, those with sensitive electronics and movable parts may especially be susceptible when the lightning channel attaches directly to the device.

Hardware such as angle of attack probes which have movable parts and antennas with dielectric covers may be damaged, especially when lightning is allowed to attach directly to the device or hardware. The likelihood of damage is often increased when external hardware is installed or mounted to non-conductive or poorly-conducting (i.e. CFC) airframe materials. When the hardware is installed on aluminum surfaces and the wire harnesses and other supporting systems are installed within an aluminum airframe (i.e. fuselage), additional lightning protection measures may not be necessary.

When external components are mounted on composite skins, the following protection guidelines should be followed.

a) Protect the surface on which the external component is to mounted with metallic coatings. Materials such as foils or meshes are excellent candidates for these coatings. The coating should be capable of conducting the lightning currents away from the component in cases when lightning attaches.

b) Attach the external component to the protected surface with a minimum of four (4) metal fasteners. Rivets, or preferable removable fasteners, of the largest size practical should be utilized. If necessary ply buildups in the fastener area is recommended to facilitate a secure attachment. It is best to allow metal-to-metal contact between the component body and the metalized surface treatment. A preferred method of accomplishing this is to co-cure a 0.016 in. (or thicker) aluminum plate to the metallized skin treatment. This process produces a smooth, hard metal surface that will allow a more consistent electrical bond than is usually available between the component and metallized composite skin.

c) Enclose the electrical component electrical wire harness in braided tinned copper shields, minimum shield cross-section should be equivalent to AWG No. 8. This should be securely attached to the device housing and the interfacing equipment case, or adjoining conductive structure such as an equipment rack, instrument panel, or metal airframe.

   The shields are necessary, even though exterior surface protection is present, since the metalized coating on composite skins does not provide as much conductivity as does a solid aluminum fuselage. The shield helps to prevent excessive currents from being conducted on wiring, which may include critical circuits or distribution buses. (Note that the application of wire harness shields should be coordinated with the overall lightning indirect effects and EME protection design, which is outside the scope of this handbook.

d) Utilize non-electrically conductive air tubes for the transfer of air data. This eliminates the possibility of lightning currents flowing in these tubes and damaging them or associated instruments.

e) Sensors which provide essential or critical data should be installed in a manner that should remain functional after a lightning strike, otherwise the sensor may provide erroneous data.

Examples of the external components and their installation which have successfully tolerated the zone 1A and 2A lightning environments are described in the following paragraphs. When installing sensors and antennas on a CFC skin, care must be exercised to assure that lightning currents flowing from the component into the composite skins do not cause excessive damage, including heating, arcing, delamination and vaporization of the resin in the adjacent area to fasteners. The possibility of debris entering fuselage-mounted engine inlets must also be considered. In a pressurized fuselage, explosive decompression is of concern.

The following paragraphs discuss several different external component installations on composite structures. The following examples are provided:

- Pitot Static installation on CFC laminate
- Antenna installation on protected fiberglass laminate

11.1 Air Data Probes (Pitot Tube)

The pitot probe installation is very similar to other air data probes (i.e. ice detection, static ports, etc.) located at various locations on an aircraft. Data described in this section is easily transferrable to other types of probes.

<u>Test Article Description:</u> The pitot tube probe was mounted on a CFC composite panel. The Nomex honeycomb core was removed locally which allowed for the inner and outer plies of carbon cloth to be closed out at the local area where the pitot probe was installed (See Figure 11.1-1). The probe was mounted to an aluminum plate and the aluminum plate was then riveted to the closed out carbon fiber laminate. Figure 11.1-2 and 11.1-3 show the pretest condition of the test specimen.

<u>Test Description</u>: The probe was subjected to a Zone 1A lightning strike, which forced the lightning current to be conducted from the pitot mast to the carbon fiber panel. The primary current path from the pitot to the CFC was via the 16 rivets because the aluminum plate was isolated from the carbon fiber laminate by a non-conductive liquid shim barrier. The high current density at fasteners caused overheating of the carbon fibers adjacent to the fasteners, resulting in localized damage around the fasteners. The pitot installation remained solid and probably functional, however if less fasteners had been used, loosening of the probe may have been a higher probability. Figure 11.1-4 provides a photograph of the post-test condition of the test specimen.

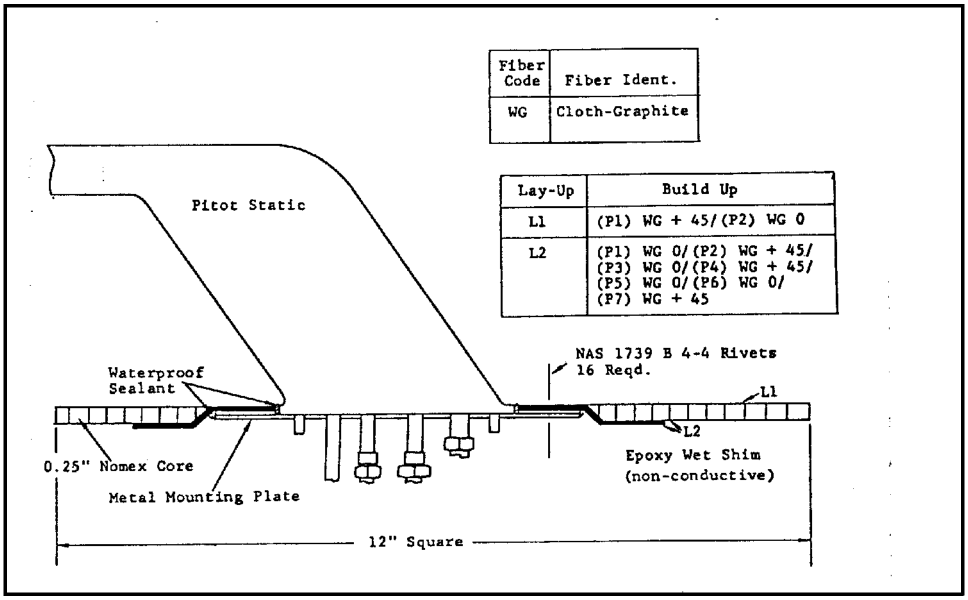


Figure 11.1-1: Description of Test Article

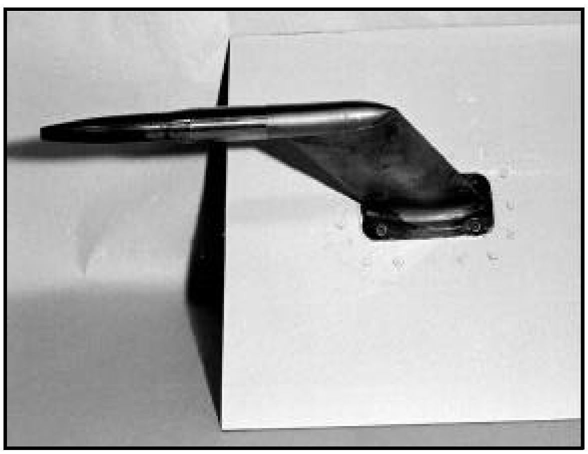


Fig. 11.1-2: Pitot probe before strike, exterior view.

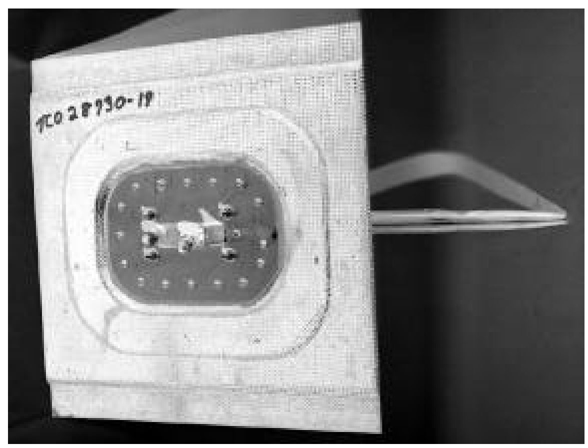


Figure 11.1-3: Pitot probe before strike, view of interior mount.

Design Guidance: The following design recommendations will help to minimize the effects of a lightning strike to external air data probes;

a) Rivets of the largest size practical should be used to install the probe

b) Additional plies of carbon cloth helps to minimize the damage around the fasteners.

c) If liquid shim material is used, a conductive, carbon-filled material will help to reduce current in the fasteners.

d) Ideally the aluminum mounting plates should make direct contact with the CFC laminate to help provide additional conductivity.

e) The mounting plate should be fabricated from a material that resists corrosion or has a semi-conductive finish, such as an Alodine 1200 coating.

f) The lightning threat can be minimized to probes by installing them in Zone 2 or 3 regions of the aircraft.

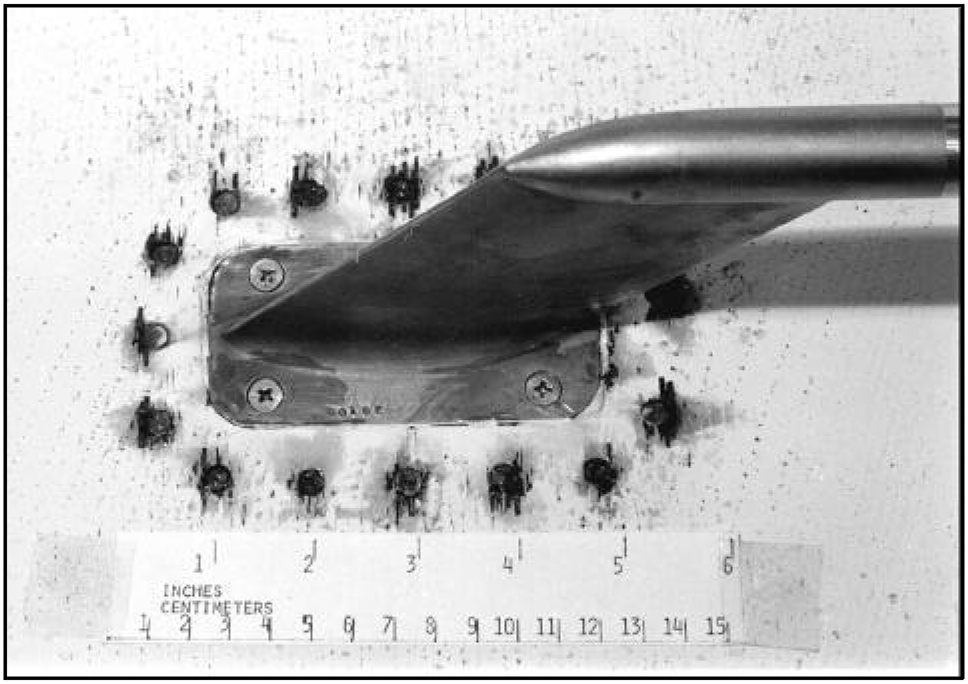


Figure 11.1-4 : Exterior view of pitot probe, post test results showing current concentration at fasteners.

11.2 Antennas (Simulated L-Band Installation)

Most antennas are fastened to the exterior surface of an aircraft. Generally, removable fasteners secure the antenna to the surface. The base of the antenna which interfaces with the skin, along with any fasteners, provides the primary path for conduction of lightning currents onto the airframe structure. The current densities can be very high in local areas, especially when the antenna is small. High amplitude lightning currents conducted into a very small region of composite structure can result in significant damage to a localized area of the structure. The examples discussed in this section illustrate effective designs which minimize the potential for damage.

11.2.1 L-Band Antenna Installation of FRC

The L-Band style of antennas have a relatively small footprint which can carry lightning currents into the airframe structure. Typically only four fasteners are installed and the antenna may only be about 4 in. long and 1 or 2 inches wide. Usually these antennas are installed in a Zone 1A or 2A region of the aircraft and may still result in current densities exceeding 50 kA per square inch. In the case of FRC, the lightning strike surface protection and the interfacing coax are the only conductive medium which can carry away the lightning currents.

<u>Test Article Description</u>: The antenna was simulated by a 0.25 in. thick aluminum plate that was approximately 2 in. wide and 4 in. long. The simulated antenna was fastened to the skin sample with 4 (ea.) No. 10 fasteners. The FRP test specimen was protected with an 0.016

lb/ft^2 expanded aluminum foil (EAF) co-cured on the outer surface of the skin specimen. A 0.020 in. thick aluminum plate was also co-cured on the outer surface of the expanded foil in the region where the antenna was installed. Figure 11.2.1-1 shows a sketch of the test specimen.

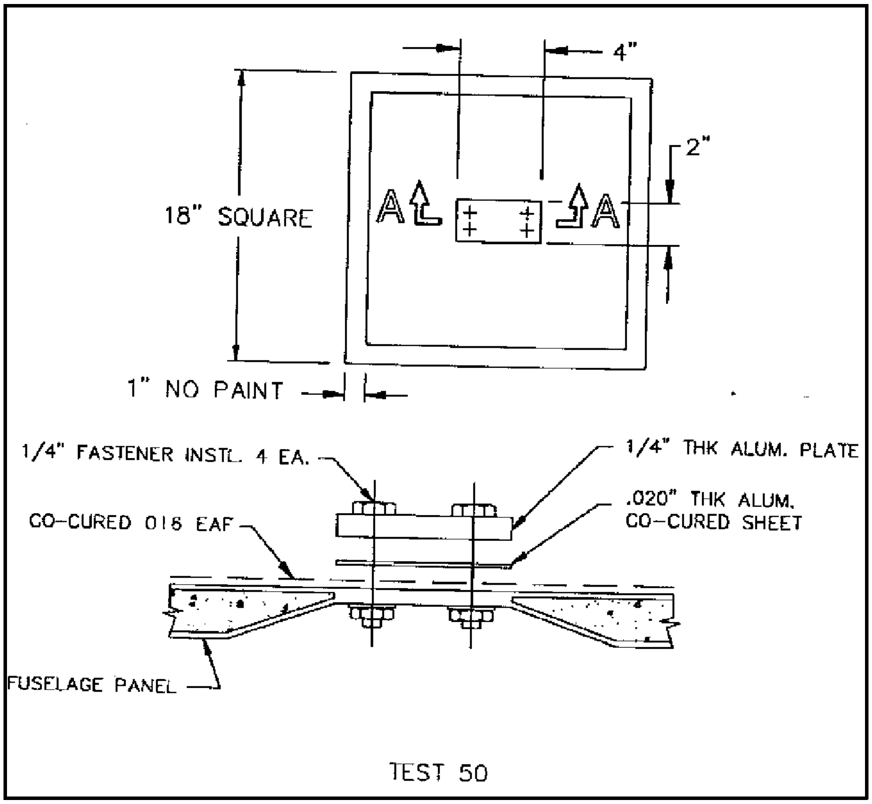


Fig. 11.2-1 : Installation details simulated antenna.

Test Description: The simulated antenna was subjected to a Zone 1A lightning strike. The FRC skin panel showed very little degradation to the laminate. The only apparent damage was the loss (vaporization) of expanded foil for a region of about 20 in. in circumference around the antenna. Figure 11.2-2 provides a photograph of test specimen after the test. The loss of EAF adjacent to the antenna has the potential to cause antenna performance degradation due to the loss of electrical conductivity to the surrounding EAF. It is also probable that antennas that have not been qualified to lightning test procedures similar to RTCA DO-160C, Section 23, may in themselves fail due to the lightning attachment.

Generally a second antenna with physical separation is installed on the aircraft to decrease the risk of total loss of reception or transmitting capabilities.

Fig. 11.2-2 : Antenna following test.

Design Guidance: The following guidelines provide methods that can minimize lightning effects or provide alternate means of meeting certification compliance.

a) Efforts should be taken to provide good conductivity between antenna and aircraft skin

b) Redundancy or multiple antenna installations can be considered a valid means of providing continued system operation if multiple radios or isolated antenna inputs are provided so that one interface can fail while the other remains operable. This concept is only acceptable if antennas are placed in a manner that minimizes the chance of a lightning flash attaching to both antennas.

c) In cases where antennas are allowed to be damaged by lightning, they should be installed in regions that prevent antenna debris from striking the propellers or entering engine intakes.

d) Spark-gap surge arresters can be installed between certain types of antennas and radio equipment to minimize transients that might normally damage the radio interface.

e) When non-conductive gaskets or sealants are used between the antenna base and airframe, adequate conductivity may need to be maintained by other means such as multiple rivets or bolts.

12.0 Radomes

These structures must remain electromagnetically transparent to permit radio and radar operation and are known as radio frequency (RF) transparencies. Therefore, in most cases, only diverter strips may be utilized for lightning protection if the transparent region is large enough to allow puncture by the lightning channel. Figures 12-1 and 12-2 show typical damage that might be expected from a radome puncture by lightning.

The methods of protecting radomes are included in Section 5.3, "Protection Methodology".

12.1 Radome Design

Radomes present a number of unique problems in terms of designing lightning protection. The radome by nature must be transparent to radar. What this means for the designer is that many of the standard protection methods are unworkable. In addition, radomes are usually constructed of non-conductive composites or dielectric resins. The most common means of protecting radomes is diverter strips which is discussed in Section 5.2 of this document.

The majority of radomes used by multi-engine aircraft will be located in the nose of the aircraft, an area usually considered to be *Zone 1.* Single engine aircraft may have small radomes located on the leading edges of wings or in the wingtip fairings. Often the radomes are utilized for weather radar. Recently however, composite aircraft have integrated radomes within the fuselage structure for other applications like GPS and emergency locator systems. Typically many of these locations place the radome in regions that have a high probability to be struck.

Most experience for general aviation and transport category aircraft has been with radomes located on the nose of the aircraft. Smaller single engine aircraft may have radomes located in different locations, but the protection methodologies will be similar. The designer will probably have to choose one of the following options when considering lightning interaction with his radome design:

a) Install diverters, either segmented or solid.
b) Increase the dielectric of the radome by the addition of various films or sheet plastics. Plastics, such as acrylics, polycarbonates, or urethanes, have been used to increase the dielectric of the radome.
c) Position the radome in a Zone 3 region where a lightning attachment is unlikely.
d) Minimize the radome regions to the extent that the surrounding structure is likely to intercept the lightning strike. This can often be done for small GPS antennas, where the RF window can be small and located on a fuselage Zone 2A region.

The verification process for radomes generally requires some experimental testing.

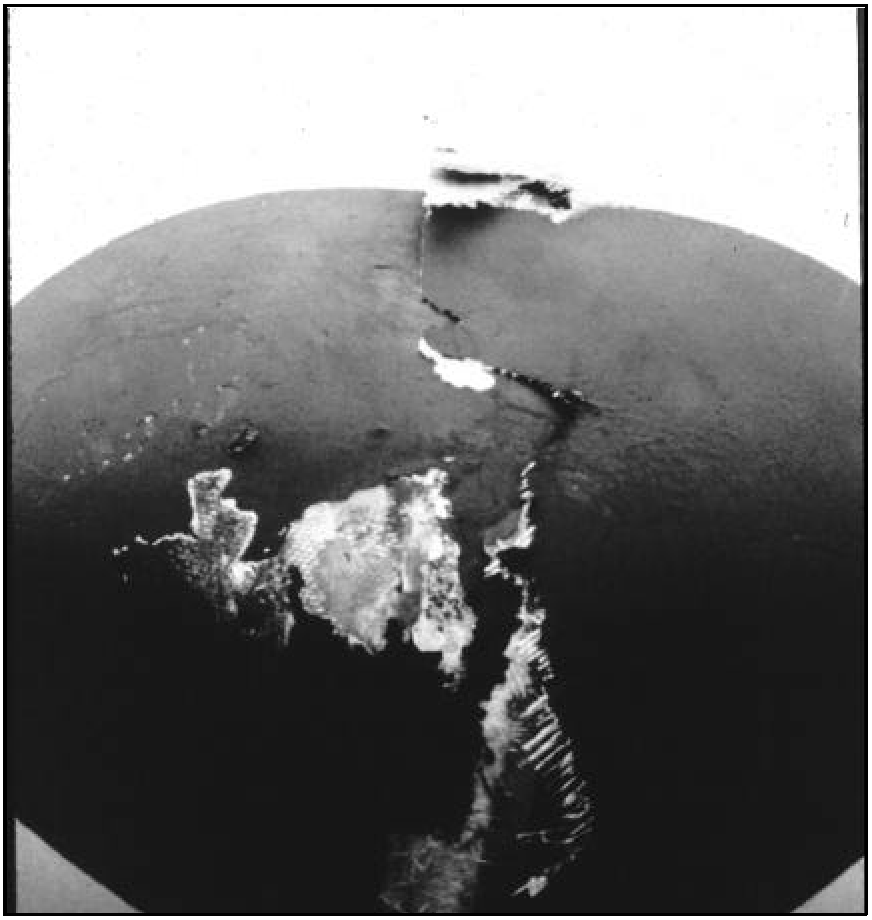


Figure 12-1 : Typical lightning damage to a radome

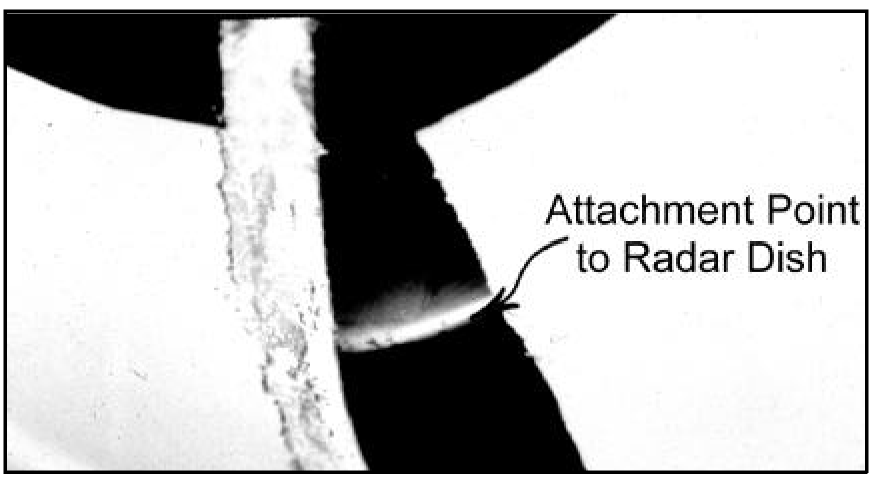


Figure 12-2 : Close-up showing attachment to internal hardware

12.2 Verification of Design

The adequacy of a design is often proven by a series of tests. These tests are usually broken down into a high voltage attachment test and then followed by a high current test. This two step process in the laboratory is required because of the limitations of test generators. In the test laboratory, this process of high voltage evaluation is separate from the high current evaluation.

Procedures for high voltage and high current testing can be found in several industry documents. The most prevalent document used by commercial companies is the SAE document, "Lightning Protection of Aerospace Vehicles and Hardware", Report of SAE Committee AE-4, Special Task F, 5 May 1976.

<u>Step 1 - High Voltage Testing</u>

Generally the high voltage test may produce up to several million volts of potential to simulate the high voltage attachment phenomena of lightning. However, these generators only produce several thousand amperes and do not simulate the damage mechanism of the high current components of lightning

Figure 12.2-1 provides a photograph of a typical high voltage test of a radome in the Laboratory. This photograph shows the verification of a segmented diverter system to prevent punctures to a nose radome. This test setup requires that conductive objects within the radome must be installed or simulated.

Figure 12.2-1 : Typical high voltage test

The high voltage test procedures have limitations that must be understood prior to testing.

a) High voltage testing can be used to determine the following;

- diverter spacing
- dielectric qualities of radome materials
- determine probable high voltage puncture locations

b) High voltage testing will not evaluate;
- damage
- inductive or magnetic effects

Step 2 - High Current Testing

The high current tests produce upwards of 200,000 amperes to simulate the high current damage capabilities of lightning. However, these generators typically only produce 50 - 100 thousand volts of electrical potential which limits their capability to produce long arcs that exceed several inches. This limits their ability to assess dielectric breakdown.

Figure 12.2-2 provides a photograph of a typical high current test of a radome in the Laboratory. This photograph shows the verification of a segmented diverter system to prevent punctures to a nose radome. This test setup requires that conductive objects within the radome must be installed or simulated.

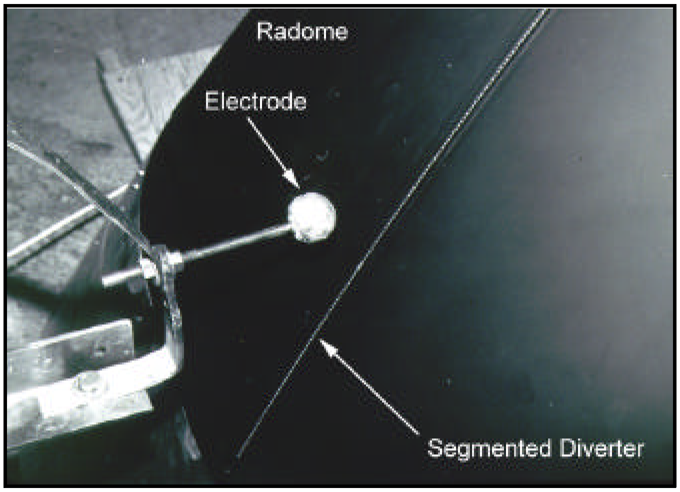


Figure 12.2-2 typical high current setup

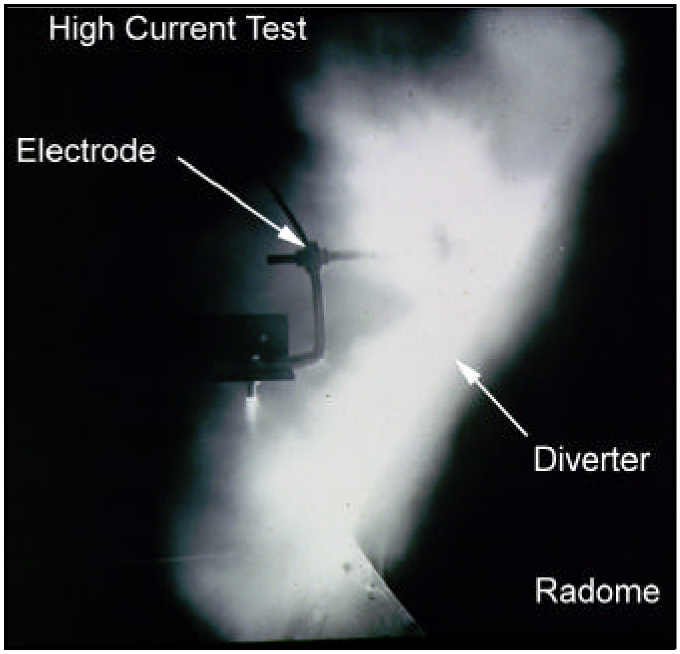


Figure 3.2-3 : Radome under test, high current

Step 2 - High Current Testing

a) High current testing will determine the following;
   - physical damage to radome
   - diverter termination
   - evaluate arc overpressure effects

b) High current testing will not determine the following;
   - Evaluate dielectric breakdown
   - Cannot produce long arc tests without incorporation of special techniques

Similarity: Similarity is sometimes used to qualify one radome with another style. For similarity to be acceptable a number of factors must be met such as;

a) layup design,
b) core type
c) geometry
d) location of internal metallic objects

Experience has shown that the difference between pass or fail may be caused by as little as a one-inch difference in gap between the inner radome wall and a radar dish, as might be the case with an updated radar installation in a previously certified installation.

12.3 Typical Nose Radome Test

Purpose: A full scale radome assembly was tested for lightning protection of the Lear Fan 2100 Program (1985). The radome was composed of six plies of Kevlar. The interfacing aft fuselage skin was fabricated of plies of graphite with an outer ply of interwoven aluminum wire. Four diverter strips were fastened to the forward radome skin. A glide slope antenna was installed within the radome, as was a mock-up of a radar antenna.

The first series of tests evaluated the high voltage attachment phenomena. The high voltage electrode was positioned 1 meter from the radome at various locations and discharged into the radome. In the first test, two strikes were applied between diverter strips. In the second test another two strikes were applied at another spot between a different pair of diverters. In the third test, the strike was positioned adjacent to the outboard end of two diverters. In the fourth test, negative polarity was applied to simulate differences between characteristics of positive and negative streamers. The internal simulated radar dish was positioned so the antenna was at its closest position to the inner radome skin, nearest to the attachment point. The segmented diverters intercepted the simulated lightning leader and conducted it without puncturing the radome to the diverter termination points.

The second series of tests used the high current generator, capable of producing a 200,000 ampere strike. The electrode was place along the length of the diverter to evaluate the ability of the design to transfer the high amplitude lightning currents from the diverter to the primary carbon fiber aircraft structure. The photograph in Figure 12.3-1 shows the transition from the non-conductive radome to the carbon fiber fuselage skins. The current density was sufficient to cause vaporization of the small interwoven wires that provide lightning protection for the carbon fiber fuselage skins, however the fastening hardware and structural integrity of the installation remained within acceptable design parameters.

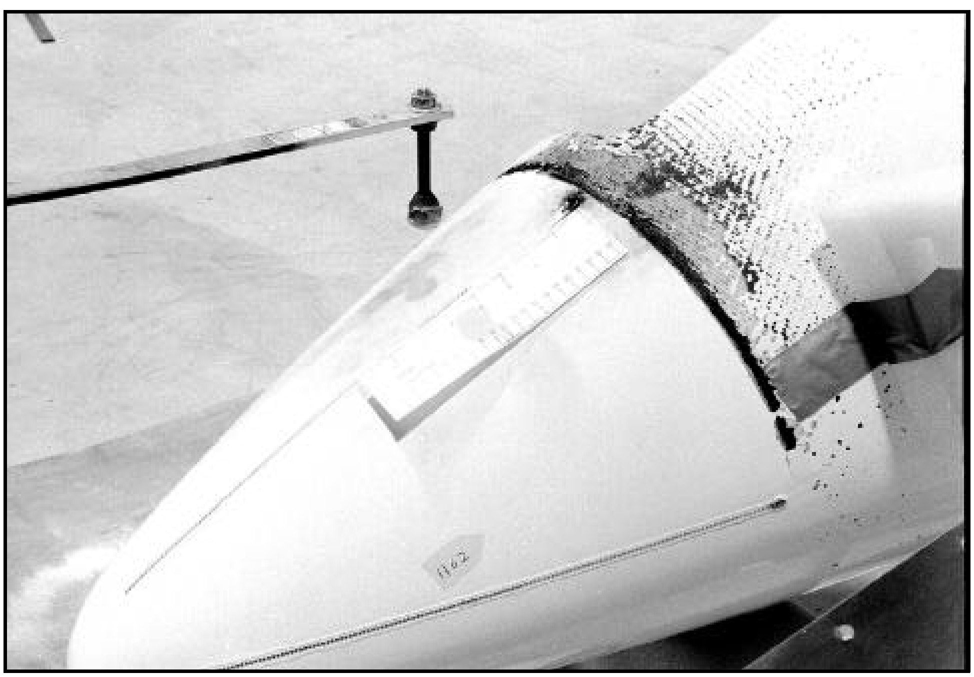


Fig. 12.3-1: Lear Fan Model 2100 results of simulated lightning strike showing minor scorching of paint, no structural damage.

13.0 Propulsion Systems

Propellers, engines, and nacelles will require protection if located in a lightning strike zone, as most are. The aircraft propulsion system may contain some electrical instruments or electronic controls which can be damaged by lightning direct effects if lightning is allowed to contact them. Therefore, nacelles should be provided with sufficient protection to prevent lightning strikes from contacting potentially vulnerable components. These and other indirect effects are not addressed in this handbook. The effects discussed here are those related to propellers and rotors, gear boxes, and stalls of turbofan engines.

Bond straps, typically flat, wired copper, maximum 1 inch wide and equivalent to AWG No. 4 wire cross-section should be installed across non-conductive shock mounts in engine trusses.

The same methods are describe for other airframe surfaces are available for protection of engine nacelles. Lightning currents will directly enter propeller drive shafts and transfer across bearings and gears to engine frames, and from these via mounting hardware to conducting airframe. There may be some damage to bearings and gears following a strike, though this has not been catastrophic. Engine manufacturers requirements regarding engine teardown and inspection should be followed after a lightning strike. Replacements of some parts may be necessary. There is no way to direct lightning currents around these interfaces, or prevent this damage.

13.1 Propellers

Aircraft propellers are frequent targets for lightning strikes. The general location of propellers, front for traction or rear or pusher, probably accounts for their susceptibility to lightning strike attachment. Tractor blades are usually in a *Zone 1A,* while pushers will be in *Zone 1B.* The stroke current component of lightning, due to its short duration, will affect only one blade. The intermediate current is also of a short enough duration that it too will also involve only one of the blades. However, the propeller does spin fast enough that the long duration continuing current will divide among all the blades, if they are in *Zone 1B*.

A lightning flash to a metal propeller does little damage. It may produce minor pitting and erosion of metal at trailing edges, but not enough damage to require special protection features.

Propellers of composites are potentially more vulnerable to lightning damage, if the protection techniques are the same as for other composite skins. Sometimes a metal leading edge rain erosion strip can be part of the protection design.

Verification is mandatory due to the critical function of the blade. If protection is required, methods discussed in sections can be applied. The **effectiveness of such protection must always be verified by tests**, since small variations in designs can have a significant effect on protection effectiveness.

13.2 Rotor Blades

Helicopter rotor blades are also susceptible to lightning strikes. The same protection methods as are available for composite propeller blades are also applicable to composite helicopter rotor blades. Most helicopter rotor blades are in Zone 1A, and, if protection against strikes to helicopters on the ground is desired, the rotor blade should be protected against the Zone 1B environment.

13.3 Gear Boxes

Lightning currents entering propellers or rotor blades will conduct to the aircraft through the gears and bearings supporting the propeller or rotor shaft. The conduction of these currents through the bearings, which are supported on insulating lubricant films, will result in some pitting of the bearing surfaces. This does not appear to be a major problem since there do not appear to be any records of any catastrophic failures of bearings associated with lightning strikes. Engine manufacturers, however, have always recommended that gear boxes and bearings be disassembled and inspected after a strike. This usually results in replacement of the bearing since arc pitting of critical parts may shorten their life expectancy wear.   There does not appear to be any way of avoiding such pitting since lightning current will always travel through the bearing.

There is currently no practical way of diverting current away from the bearings.

13.4 Turbojet Engines

Small turbojet engines, especially those mounted on or within the fuselage, may experience turbine stall or roll-back during a lightning strike to the aircraft, especially one that attaches to the nose. Present theory holds that this effect is caused by the lightning channel interrupting air flow at the engine air inlet. Numerous cases of temporary engine power loss have been reported and in one particular instance both engines flamed out. Physical damage to the engine or nacelle is seldom observed. There apparently is no protective way to prevent this. Therefore, pilots should be made aware of this possibility and provided with instruction in in-flight restart procedures.

13.5 Test of a Propulsion System

An entire turboshaft propulsion system was tested for lightning protection adequacy. The system (Lightning Technologies, Inc. LF 2100 Lightning Results - Propulsion System, R43225,) was designed for the Lear Fan 2100. The tests described here were performed in 1985.

The system consisted of a twining gearbox designed to combine the power of two Pratt and Whitney turboshaft engines to drive a single propeller. The propeller was located in Zone 1B, and therefore, the gearshaft was in Zone 3.

Purpose: Two kinds of tests were used to demonstrate the ability of the unit to withstand a *Zone 1B* and Zone 3 strike. First dynamic test was performed, with the drive shafts and gearbox to rotating at cruise speeds. The second test was conducted with drive shafts and gearbox in a stationary, non-rotating condition. After dynamic test, the gearbox was replaced to avoid lightning damage accumulation.

During each of these tests, the test setup was arranged in such a manner that the test currents entered the gearbox through the propeller shaft and exited from the gearbox via the gearbox/fuselage mounts and the engine drive shafts in a manner representative of the aircraft installation.

Result: Neither test showed any significant damage to the gearboxes, but some pitting occurred around mounting holes on the gearboxes and on the drive shaft attachment flanges. Following the second static test, the propellor shaft showed a temporary freeze, indicating some welding at roller bearings and associated races.

The minor pitting which occurred is consistent with similar tests and with the analysis of strikes which have occurred in flight. It is sometimes difficult to determine if the wear or pitting on bearings is due to a lightning strike or to ordinary wear.

These tests indicated that conventional turbomachinery can withstand the effects of Zones 1A/1B/3 lightning currents without an immediate hazard to continued safe flight and landing, although the engine is often disassembled and inspected following a lightning strike.