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STATUS OF RESEARCH INTO LIGHTNING EFFECTS ON AIRCRAFT

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SUMMARY

Developments in aircraft lightning protection since 1938 are briefly noted. Potential lightning problems resulting from present trends toward the use of electronic controls and composite structures are discussed, along with presently available lightning test procedures for problem assessment. The validity of some procedures is being questioned because of pessimistic results and design implications. An in-flight measurement program is needed to provide statistics on lightning severity at flight altitudes and to enable more realistic tests, and operators are urged to supply researchers with more details on electronic components damaged by lightning strikes. A need for review of certain aspects of fuel system vulnerability is indicated by several recent accidents, and specific areas for examination are identified. New educational materials and standardization activities are also noted.

INTRODUCTION

The widespread concern about the effects of lightning on transport aircraft was perhaps first evidenced by the formation in 1938 of the subcommittee on lightning hazards to aircraft of the National Advisory Committee for Aeronautics (NACA). This committee numbered among its members some of the most prominent flight safety, weather, and lightning experts of the day. Among the latter was Dr. Karl B. McEachron, then director of research at the General Electric High Voltage Laboratory, who performed for the committee the first man-made lightning tests on aircraft parts and structures. During the later part of this committee's 12-year existence other organizations such as the U.S. National Bureau of Standards, the University of Minnesota, and the Lightning and Transients Research Institute (LTRI) also begain to conduct research into lightning effects on aircraft. Much of this research was sponsored by the NACA and its successor the National Aeronautics and Space Administration (NASA), along with the Federal Aviation Administration, the U.S. Air Force and Navy, and aircraft manufacturers and operators.

For a long time the physical damage at the point of flash attachment to the aircraft was of primary concern. Typical of the damage were holes burned in metallic skins, puncture or splintering of nonmetallic structures, and welding or roughening of movable

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hinges and bearings. The ignition of the fuel was of particular concern, as was the problem of conduction of lightning current directly inside the aircraft via long-wire antennas. A considerable amount of research was also directed toward its effects on people, such as flash blindness and electric shock.

The early research led to the development of protective devices, including fuel filler caps, which will not spark when struck by lightning; lightning arresters, which safely conduct lightning currents from antennas to the airframe; diverter bars and tapes, which minimize punctures of radomes; and static dischargers, which reduce electromagnetic interference in communications systems.

In 1963 the fuel tanks of a Pan American Boeing 707 aircraft exploded in-flight near Elkton, Maryland, after a lightning strike. The exact source of the ignition has never been established, but the explosion stimulated further research into the effects of lightning on fuel systems and fuel tank inerting systems. This research has been instrumental in the development of active surge tank protection (STP) systems for extinguishing flames ignited at vent outlets. The incorporation of much of this protection technology into the design of modern transport aircraft is a principal reason for their present excellent safety record in the lightning environment.

The lightning-safety record is not quite as good for U.S. military aircraft, several of which have been lost in recent years due to lightning strikes. The military have been a traditional proving ground for new technology, and there are several concepts reaching the application stage which may increase potential lightning hazards still further. Fortunately, most of these possibilities have been recognized and efforts are underway to develop effective protection. Since some of this new technology will eventually be used in commercial aircraft, it is appropriate to review recent developments and identify the directions in which aircraft-lightning research should proceed in the future.

SYMBOLS

C capacitance of aircraft or lightning flash to its surroundings, F/m

e_1 induced voltage between wires, V

e_2 induced voltage between wire and airframe, V

f frequency of traveling wave reflections at either end of aircraft, Hz

i_L lightning stroke current, A

L inductance of the lightning current flow path in aircraft, H/m

ℓ aircraft length, m

R radius of electrostatic field, m

R_s resistance of an airframe, Ω

r radius of lightning channel, m

T time for a traveling wave to travel the aircraft length and back, s

t time, s

v velocity of traveling wave propagation, m/s

Z surge impedance, Ω

φ_i internal magnetic flux produced by lightning current, A/m

φ_o external magnetic flux produced by lightning current, A/m

ELECTRICAL AND ELECTRONICS SYSTEMS

In recent years it has become apparent that lightning strikes may indirectly affect electronic equipment located elsewhere in the aircraft from the point of lightning attachment. Examples of this are the interference or damage to instruments and power distribution systems summarized from a sampling of 214 airline lightning strike reports in table I. Another example which caused more alarm among safety experts was the lightning strike to the Apollo 12 vehicle which disrupted the command module power system after lift-off.

The cause of these indirect effects was thought to be the electromagnetic fields associated with lightning currents flowing through the aircraft. Research (ref. 1) began in 1967 to determine the coupling mechanisms involved and the potential impact that these indirect effects might have on equipment operation and flight safety. Briefly, it has been confirmed that, when lightning currents flow through an aircraft, magnetic fields are produced and structural voltage rises occur which couple transient voltages into the vehicle's electrical wiring (as shown in fig. 1). In some cases these voltages are high enough to damage solid-state electronic equipment to which the wiring is connected. Unlike other aspects of aircraft design, there are no specifications or standards which say what level of transient voltage a piece of apparatus must withstand or conversely, what levels the transient voltages must not be allowed to exceed in vehicle wiring. This incompatibility between the transient withstand capability of electronic devices and the transients to which they are exposed is not limited to the aerospace industry but is one which is appearing to some degree wherever solid-state electronics are used, with a wide range of unfortunate consequences.

Some idea of the actual transient voltages that lightning may produce in an aircraft's electrical circuit might be obtained by passing simulated lightning currents through an aircraft and measuring the voltages induced. Existing generators, however, are incapable of forcing the high currents (up to 200 000 A) associated with a severe lightning strike through a test circuit as large as a complete aircraft. Even if it were possible, most owners would, understandably, hesitate to allow this much current to be passed through their aircraft. Therefore, under sponsorship of the NASA Aerospace Safety Research and Data Institute a nondestructive test called the lighting transient analysis (LTA) (ref. 2) was developed. In LTA impulse currents as low as 1/1000 of that expected in an actual lightning strike are passed through the aircraft between typical lightning attachment points. Voltages induced by these currents are then linearly extrapolated to full-scale levels. Comparison of voltages induced by LTA and full-scale test currents have confirmed that linear extrapolation is valid in most situations.

Typical wire-to-wire and wire-to-airframe voltages induced by LTA test currents in a fighter aircraft (ref. 3) wire bundle are shown in figure 2. When 300 amperes was impressed upon the airplane, the peak voltage measured between either wire and the airframe was 2.4 volts (left oscillogram). A linear extrapolation to a severe lightning stroke of 200 000 ampers would induce

$$(2.4\ \text{V})\ \frac{200\ 000\ \text{A}}{300\ \text{A}} = 1600\ \text{V}$$

between these wires and airframe ground at plug P22. The measured voltage between the two wires (right oscillogram), however, extrapolates to only about 350 volts. This result illustrates the benefit of two-wire (independent return) circuits over single-wire and airframe return. The benefit comes from the smaller circuit loop through which magnetic flux may pass as compared with the single wire and airframe return. On the other hand, the two-wire method requires more wire and this may be undesirable from weight and cost standpoints.

Whether the two-wire or any other protective scheme (with other penalties) provides sufficient protection or is even necessary at all depends on the actual transient voltage levels that may be induced and the upset or damage levels of the associated electronics. Because tools to calculate expected voltage levels by analysis alone are not yet available, the LTA test has been used to tell designers what to expect in such aircraft as the NASA Flight Research Center F-8 digital-fly-by-wire airplane, the Navy - Lockheed S-3A antisubmarine warfare aircraft, and the USAF - General Dynamics F-16 Air Combat Fighter. Lightning transient analysis techniques are also beginning to be used to certify new systems being installed on present transport aircraft.

A large amount of induced voltage data has been obtained from these LTA tests. Perhaps because direct effects tests on sections of an aircraft (for which a few government specifications are available) are usually performed at the 200-kiloampere level, the LTA data have been extrapolated to this level for design purposes. This has resulted in alarmingly high voltages being predicted for some critical circuits. As might be expected, the validity of these predictions is being questioned by aircraft designers who continually ask for proof that such voltages in fact occur in flight and whether 200-kiloampere strikes really occur often enough to be the design level. The increasing reliance on electronics to perform flight critical functions, as in fly-by-wire flight controls without mechanical backup, means that reliable values must be available for design purposes, since indiscriminate application of protective shielding and surge suppression devices would impose unacceptable size, weight, and cost penalties.

There are other aspects of the induced voltage problem which also are not well understood. For example, certain of the induced voltages bear a clear mathematical relationship to the lightning current which causes them. But other voltages, sometimes superimposed on the familiar ones (as shown in fig. 3), seem to bear none. While of short duration, they are often among the highest voltages measured and thus the determining factor in protection decisions. It has been suggested by Fisher (ref. 4) that these voltages are induced by traveling current wave reflections excited in the airframe when the lightning flash first strikes the aircraft. These reflections would arise because of the probable differences in the surge impedance Z of the lightning flash channel and the aircraft (fig. 4). The velocity v of the traveling waves in the aircraft would be that of light, 3×10^8 meters per second, and the period of oscillation would be proportional to the length of the aircraft.

The voltage of figure 3(c) was induced in an aircraft whose length ℓ is 13 meters, for which the period T of one complete down-and-back cycle would be

$$T = \frac{2\ell}{v} = \frac{26\ \text{m}}{3\times10^8\ \text{m/s}} = 8.67\times10^{-8}\ \text{s}$$

and the frequency f of repeated cycles would be

$$f = \frac{1}{T} = 11.53\ \text{MHz}$$

If a current of this frequency had been in the airframe, it could have induced a voltage of the same frequency in the aircraft's electrical circuits. A frequency of this order is indeed evident in the induced voltage oscillogram of figure 3(c). The question is, Do these oscillations actually occur in aircraft struck in flight or are they caused only by the LTA test? The explanation of figure 4 depends on an inequality between the surge impedance of the lightning channel and that of the aircraft. Bewley (ref. 5) defines the surge impedance of a lightning stroke in terms of the radius r of the lightning channel and the radius R of the electrostatic field due to the volume of the cloud that participated in the discharge, as follows.

$$Z = 60\left(\log \frac{R}{r} - \frac{1}{2}\right)$$

And Bewley calculates values of between 100 and 600 ohms for typical strokes. The surge impedance of the aircraft is determined from its lengthwise distributed inductance L and capacitance to its surroundings C by the relation:

$$Z = \sqrt{\frac{L}{C}}$$

A conductor as large as an aircraft would have a low inductance and relatively high capacitance. Assuming the inductance to be 0.1 microhenry per meter and the capacitance to be 50 picofarads per meter, then the surge impedance of the aircraft would be

$$Z = \sqrt{\frac{0.1\times10^{-6}\ \mathrm{H/m}}{50\times10^{-12}\ \mathrm{F/m}}} = 44.7\ \Omega$$

which is considerably less than that of the lightning stroke. The reflection and refraction coefficients defined by Bewley (ref. 6) for an aircraft of this impedance are calculated in figure 4, where the surge impedance of the lightning channel is taken for convenience to be 450 ohms. These calculations show that the initial peak of traveling wave current in the airframe could be 1.8 times the amplitude of the incident lightning current. A current of this magnitude and frequency might well induce the kind of voltage shown in figure 3(b).

There could be no better way of confirming the existence and severity of these voltages than by an in-flight data gathering program. Instrumentation technology has advanced to the point where it should now be possible to develop small instrument packages capable of measuring and recording the magnitudes and waveforms of actual lightning currents and the voltages they induce in aircraft circuits. Such instruments might be installed in commercial transport aircraft and monitored for several years to obtain a good sampling of data on the real life environment they experience.

FUEL SYSTEMS

Stimulated in part by the Elkton accident and also by the SST development program, a large amount of research was conducted during the 1960's to determine mechanisms by which lightning strikes might ignite flammable vapors in aircraft fuel tanks and to develop protective measures. Emphasis was placed on integral wing tanks and associated vent systems. The research led to the development of methods to extinguish fires that originated at vent outlets or to prevent their ignition in the first place. Successful test techniques have also been developed (refs. 7 and 8) to enable the definition of safe thickness for integral tank skins of various metals. A large amount of data such as that shown in figure 5 is on hand relating skin materials and thicknesses to the lightning environment. These protective measures and test techniques are in use today by the major airplane manufacturers and have contributed to greater flight safety.

Since 1971, however, at least three accidents involving in-flight explosion of fuel tanks and suspected lightning strikes have occurred. These accidents again bring up the issue of fuel system vulnerability. The earlier focal points of vent systems and skin punctures appear not to have been involved in these accidents (a USAF KC-135, a USAF F-4, and an Iranian Air Force B-747), yet there is evidence that lightning could have struck these aircraft at or about the time the explosions occurred. The exact mechanism of fuel ignition has not been found in any of these cases. The accidents therefore indicate a need for a reexamination of fuel system vulnerability to lightning. Whereas most earlier research dealt with ignition sources originating at the arc attachment point, less is known or documented about the effects of lightning current conduction through typical fuel tank structures and associated plumbing. Airworthiness Standards such as the U.S. Federal Aviation Regulations Part 25 (ref. 9) pertaining to fuel systems specify that the ignition of fuel vapors by stroke attachment or steaming shall be prevented, but do not appear to place equal stress on the effects of current conduction through the airframe. The lightning tests that are suggested in an associated document (ref. 10) relate primarily to proof against sparking from stroke attachment to access doors, filler caps, and the like. The emphasis in existing military standards is the same (ref. 11).

With reference to figure 6, some aspects of fuel systems that might bear further examination are

(1) Mechanical bonding - Does the bonding together of integral tank walls, ribs, spars, and skins provide adequate electrical bonding for lightning currents? Are there any conditions in present constructions that may result in an electrical spark? If not, how much margin of safety exists?

(2) Fuel system lines and fittings - How much lightning current may actually flow in the vent lines, fuel lines, hydraulic lines, etc., present in typical fuel tanks? How

does the current get into and out of this plumbing? Can sparks occur across joints and couplings? To what extent, if any, do procedures to prevent excessive vibration of lines and fittings (per FAR pt. 25, par. 25.993) degrade electrical bonding among sections of lines and between lines and structures?

(3) Electrical sparks - If electric current is flowing from one metallic element to another, what conditions of current amplitude, waveshape, contact resistance, relative motion, and corrosion must exist to cause a spark? Much is known about how much electrical energy must be discharged through a spark to cause ignition, but this parameter is hard to equate in terms of lightning current. How much electric current does it take to cause a spark sufficient to ignite fuel?

(4) Electrical apparatus inside fuel tanks - Are fuel tank electrical parts, such as pump motors, valves, and fuel quantity probes, really as immune to sparking as their manufacturers say they are? What about lightning-induced voltages brought to these items from electrical circuits that run outside of the fuel tanks, and which may therefore be outside of the fuel system designer's control?

(5) Fuel - The three aircraft mentioned above carried JP-4 fuel which has a wider flammability envelope than the aviation kerosenes commonly used by U.S. commercial airlines. How much safer is Jet A than JP-4 under the conditions in items (1) to (4) which may cause sparking?

(6) Design guidelines - What, if any, new design guidelines should be followed to overcome the situations in items (1) to (4) which may result in sparking?

Answers to these questions could probably be obtained from a combination of basic research into sparking mechanisms of metals in various types of contact with one another and an extensive series of carefully instrumented laboratory tests of typical aircraft fuel tanks, including, especially, integral tanks in wings. Included in these tests would be full-scale simulated lightning currents conducted through the tanks with ignitable hydrocarbon-air mixtures inside.

STRUCTURES

Recent emphasis in lightning protection of structures has been placed on the fiberglass, boron, and graphite reinforced composites which are beginning to replace conventional aluminum in some applications. Much is now known (refs. 12 to 14) about the electrical conduction properties of these materials and the degree of damage that specific amounts of lightning currents can cause. Protective coatings have been developed to minimize this damage, and work is now underway to develop mechanical bonding and fastening techniques which can safely conduct lightning currents without sparking or loss of strength. In some applications, such as engine fan blades, wing leading edges, and fuselage skins, composites will not be exposed to direct lightning strike effects, but in other cases these materials are being used where lightning strikes frequently attach. Initial experience has been with fiberglass and, though protected in many cases by metallic diverter bars, fiberglass wing tips, radomes, and fairings have been extensively damaged by lightning strikes as shown for example in figure 7. To date, none of this damage has caused a fatal accident, but there have been some close calls. The protective devices designed for these structures have performed well under laboratory tests, but their performance on an aircraft in flight has not been as good.

There appear to be several reasons for this poor performance. (See fig. 8.) One is the presence of anti-erosion paints which are often applied over a protective diverter on the real aircraft. Another is the way the nonmetallic part is attached to metallic substructural elements, which are outside the control of the protection designer. Still another is the continued use of the same type of electrical wiring inside the nonmetallic structure as was used satisfactorily within the metallic structure it replaced, and yet another - and possibly the most important reason - is a lack of knowledge of the basic relation between the lightning flash and the aircraft during the formative stages of the strike. This deficiency has limited our ability to simulate the real world in the laboratory and properly test protective diverters.

Improvements in understanding this situation can probably be obtained by in-flight evaluations of the performance of protective devices against laboratory predictions, and by use of more thorough instrumentation in the laboratory to obtain a better understanding of dielectric breakdown processes in typical aircraft structures.

In addition to the direct effects considered above, the potential impact on electrical and electronic systems of replacement of the aluminum skin with a composite skin remains to be learned. Whereas aluminum skins provide sufficient shielding of many of today's aircraft electronic systems, the absence of this property in a composite skin (fig. 9), will expose internal wiring to much more intense electromagnetic fields and require marked changes in electrical system design.

EDUCATION AND STANDARDIZATION

Since lightning may have some affect on nearly every system in an aircraft, successful protection depends on many designers being aware of potential lightning problems. To improve this awareness, some educational materials are available which are worthy of note.

Educational Films

The U.S. Navy Air Systems Command has prepared four educational films (ref. 15) on the protection of aircraft against lightning. These are available from the Navy for loan to anyone desiring to introduce the subject to aircraft designers or operators.

In response to inquiries for more detailed information on protection of fuel and electrical systems, the Navy is preparing two more films, which treat these subjects in greater detail.

Lightning and Static Electricity Conferences

The Society of Automotive Engineers (SAE) Committee AE-4 on Electromagnetic Compatibility together with (at various times) the U.S. Air Force, U.S. Navy, Royal Aeronautical Society, and Institution of Electrical Engineers has conducted international conferences on lightning and static electricity as applied to aircraft. These conferences have provided a forum for researchers to review advancements in the state of the art every 2 years since 1968. Proceedings of each conference have been published (refs. 16 to 19).

Aircraft Lightning Protection Handbook

The Aerospace Safety Research and Data Institute of NASA Lewis Research Center has sponsored a handbook on Lightning Protection of Aircraft by Fisher and Plumer of General Electric, in which the results of many research programs are digested and presented in a manner useful to aircraft designers and operators. This book is to be published as a NASA Special Publication in 1976.

Test Standards

Lightning protection has suffered in the past from a lack of lightning qualification test standards which reflect the state of the art. Those that do exist (e.g., refs. 10 and 11) apply only to a few systems or components or are impossible to perform as written and therefore are subject to individual interpretations and deviations. Accordingly, a subcommittee composed of experts in lightning laboratories, industry, and government has been formed under SAE Committee AE-4 to draft lightning test waveforms and techniques that would form the basis of new or updated government specifications. This committee has completed its work on this task with the publication of a report defining lightning test waveforms and techniques for aerospace vehicles and hardware (ref. 20). The Committee is now embarked on an additional task of recommending transient test levels for aerospace electronics equipment.

CONCLUDING REMARKS

One of the keys to answering the lightning effects questions raised in the preceding paragraphs is a more thorough understanding of the interaction between the lightning flash and the aircraft in flight. The instrument development work and in-flight measurement program needed for this will require the efforts of several researchers, designers, and operators of aircraft and will take a number of years to accomplish.

In the meantime, it is important that details of lightning strike incidents to aircraft flying today are recorded by the operators and made available to researchers, especially when there is interference or the malfunction of electronic equipment aboard the aircraft. For example, if an instrument is believed to be damaged by a strike, a description of any parts burned out and replaced by the repair shop would enable researchers to get some idea of the magnitude of the induced voltage surge involved and the location of the aircraft wiring in which it originated. Methods to provide protection against similar incidents could also be developed from these data. Admittedly, it is difficult to track component failure information in the midst of the other requirements imposed on operations personnel, yet these data are available now and would be extremely valuable in achieving a better understanding of the indirect effects problem and designing protection for future aircraft.

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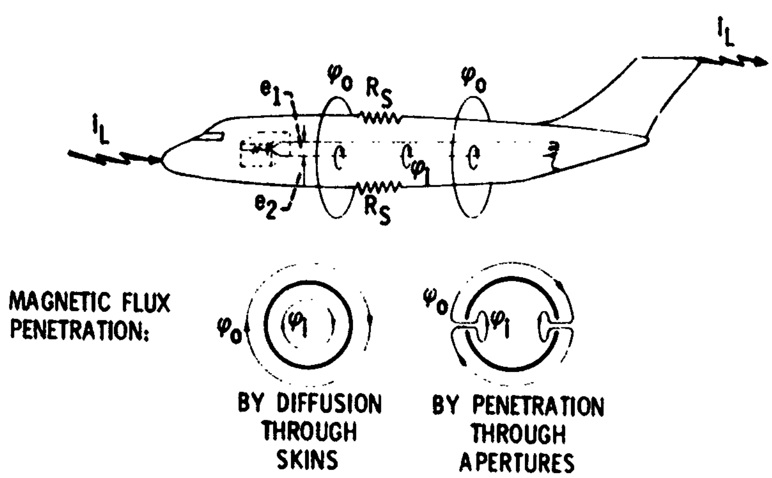
TABLE I. - EXAMPLES OF INDIRECT EFFECTS IN COMMERCIAL TRANSPORT AIRCRAFT

[214 lightning strike reports.]

System	Interference	Outage
HF Comm	--	5
VHF Comm	27	3
VOR receiver	5	2
Compass (all types)	22	9
Marker beacon	--	2
Weather radar	3	2
ILS	6	---
ADF	6	7
Radar altimeter	6	---
Fuel flow gage	2	---
Fuel quantity gage	--	1
Engine rpm gages	--	4
Engine EGT gages	--	2
Static air temperature gage	1	---
Windshield heater	--	2
Flight director computer	1	---
Navigation light	--	1
AC generator tripoff	(6 instances of tripoff)	
Autopilot	1	---



$$e_1 = \frac{d\varphi_i}{d\tau}$$

$$e_2 = \frac{d\varphi_i}{d\tau} + i_L R_S$$

Figure 1.- Induced voltage mechanisms.

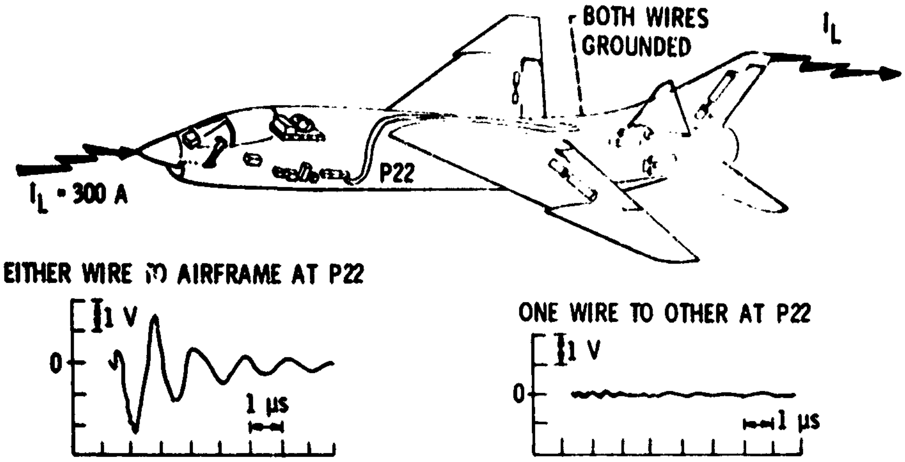


Figure 2.- Typical induced voltages: wire-to-wire and wire-to-airframe.

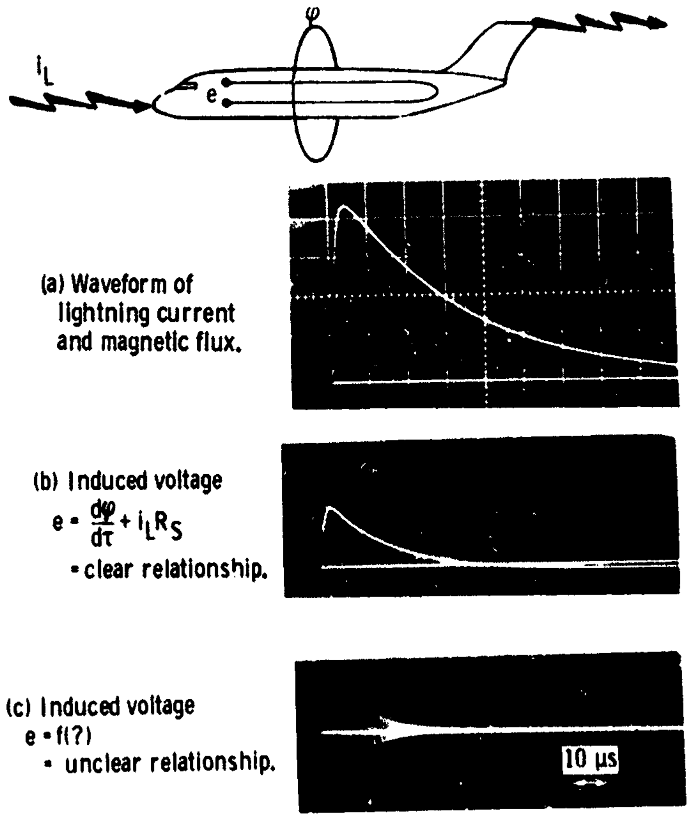


Figure 3.- Relationship between lightning current and induced voltages.

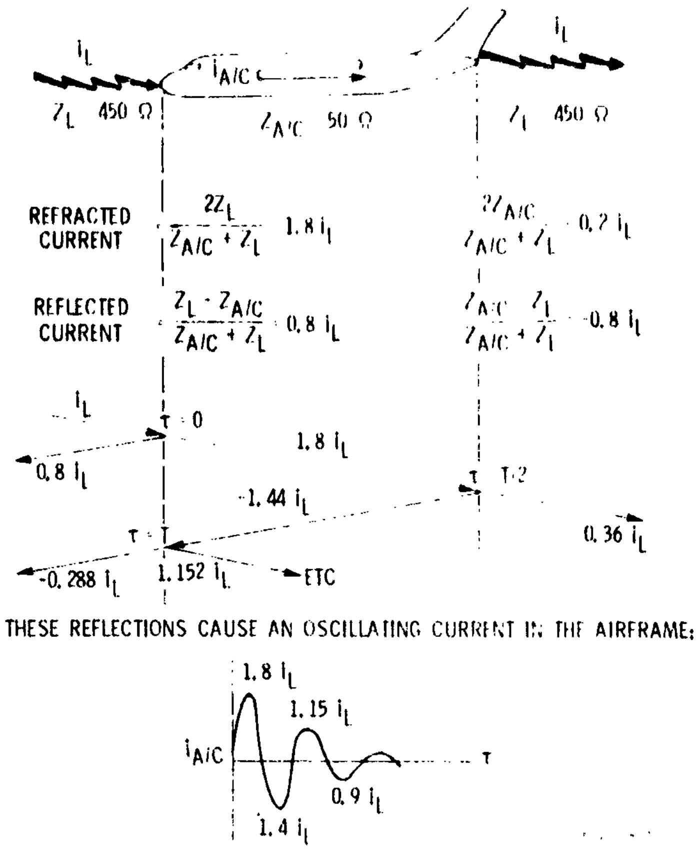


Figure 4.- Traveling wave reflected in aircraft.

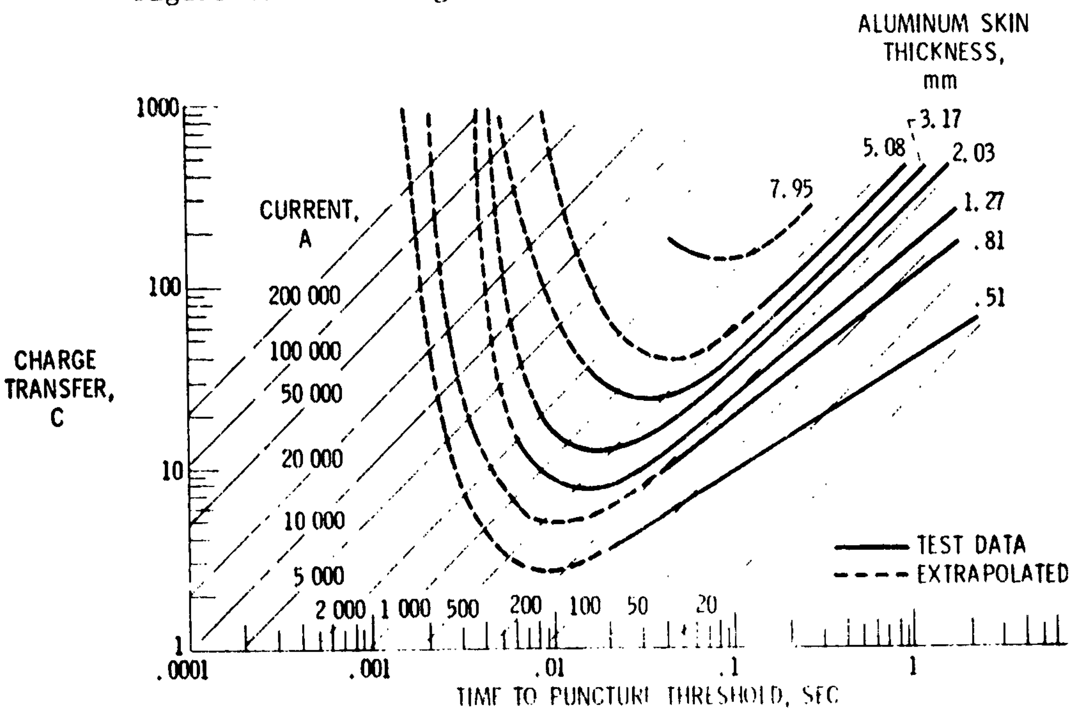


Figure 5.- Lightning charge required to puncture fuel tank skins of various thicknesses (from ref. 8).

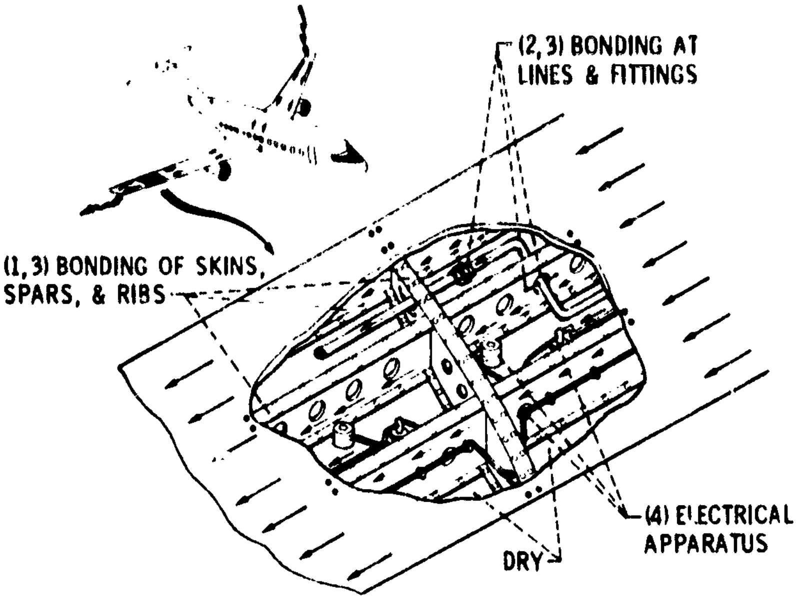


Figure 6.- Areas for reexamination for lightning effects in fuel systems.

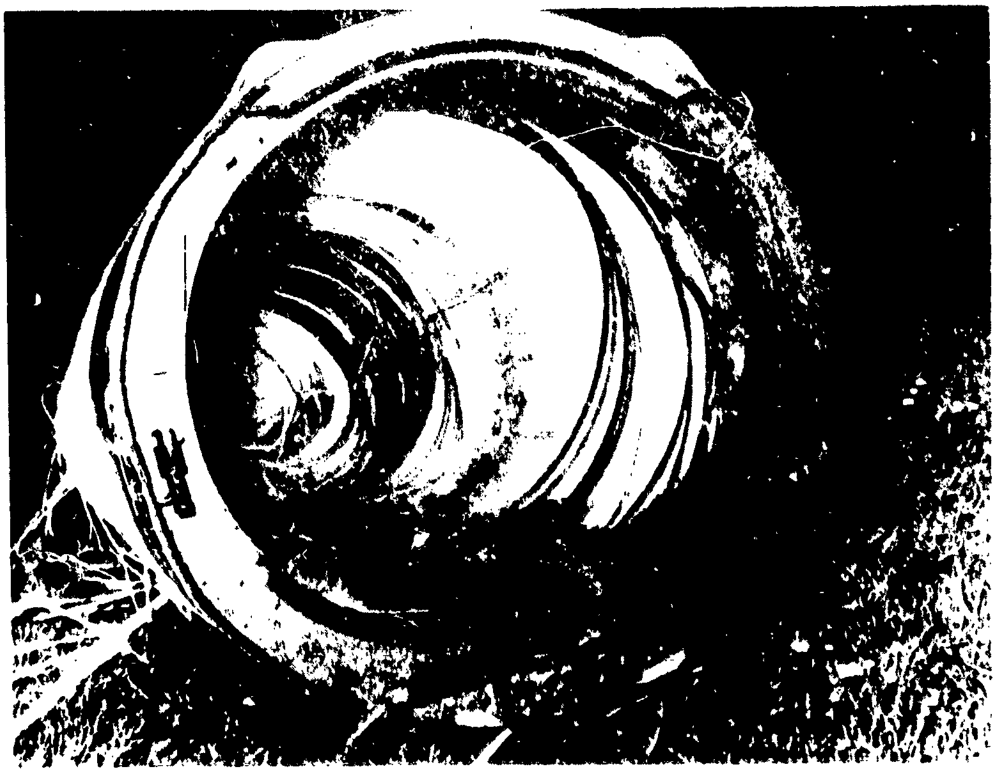


Figure 7.- Fiberglass structure damage by lightning.

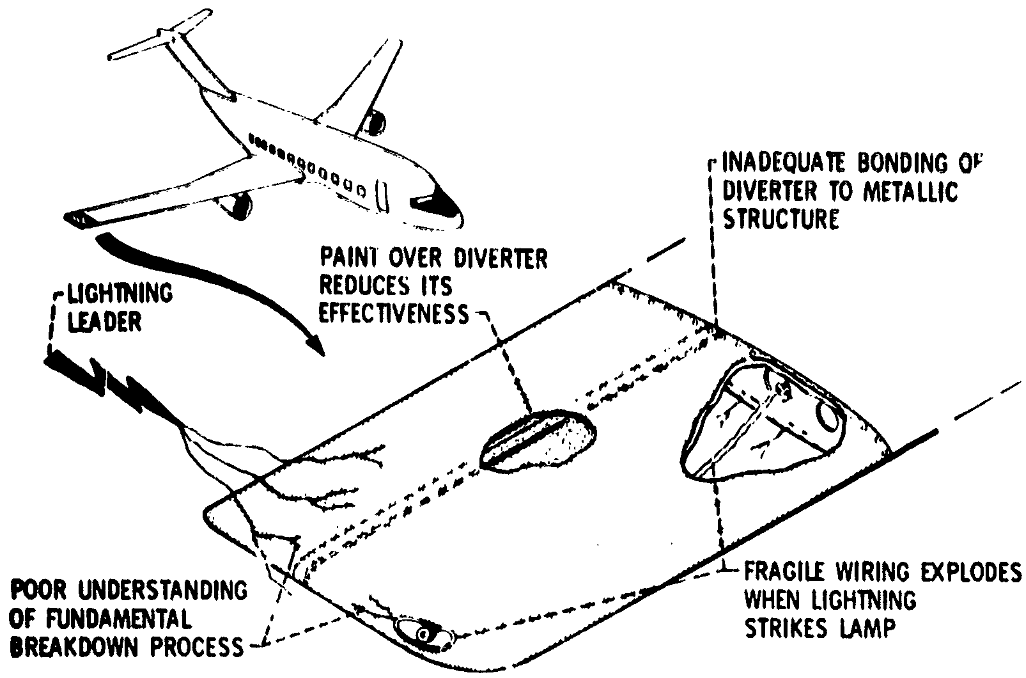


Figure 8.- Problems in protection of composite structures.

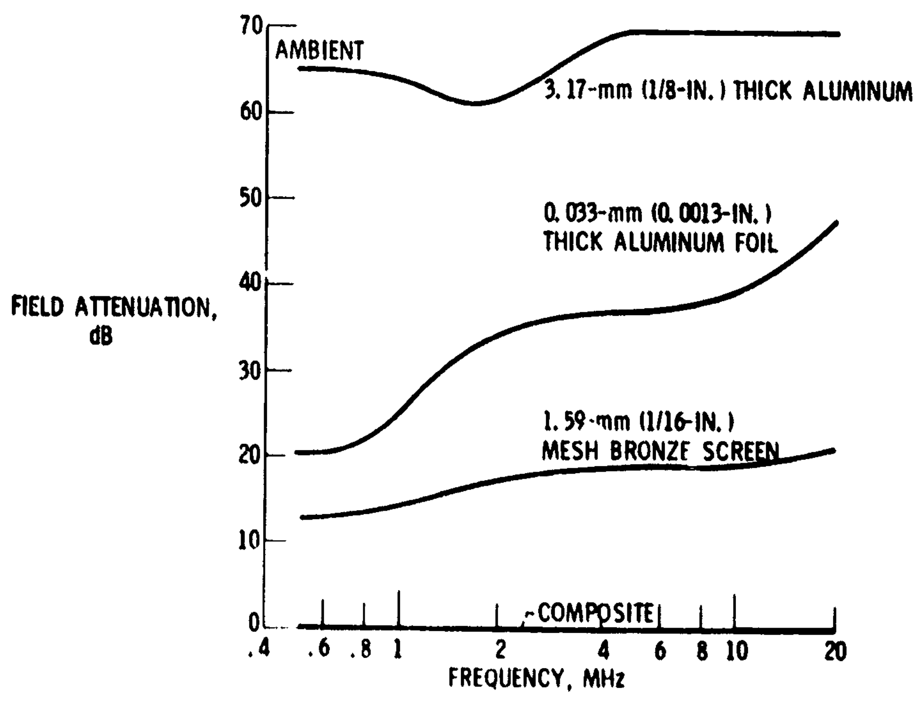


Figure 9.- Magnetic shielding property of composites.