



AEROSPACE INFORMATION REPORT

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Superseding AIR6185

Lightning Effects on Hydraulic Transport Elements on Aircraft

RATIONALE

This document has been revised in response to a Five-Year Review.

FOREWORD

Throughout this document, the term “Hydraulic Transport Elements” is used. This refers to all the hydraulic parts that are installed in an aircraft including valves, actuators, pumps, manifolds, and tubing.

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1. SCOPE

This SAE Aerospace Information Report (AIR) describes the aspects of hydraulic system design and installation to minimize the effects of lightning. Techniques for effective electrical bonding, hydraulic system lightning protection, and lightning protection verification techniques are discussed.

1.1 Purpose

The purpose of this document is to provide lightning effects consideration in the design and installation of the hydraulic systems and components on aircraft.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AMS4946	Titanium Alloy Tubing, Seamless, Hydraulic 3Al - 2.5V, Texture Controlled Cold Worked, Stress Relieved
AMS5561	Steel, Corrosion and Heat-Resistant, Welded and Drawn or Seamless and Drawn Tubing, 9.0Mn - 20Cr - 6.5Ni - 0.28N High-Pressure Hydraulic
ARP1870	Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety
ARP5412	Aircraft Lightning Environment and Related Test Waveforms
ARP5414	Aircraft Lightning Zone
ARP5415	User's Manual for Certification of Aircraft Electrical/Electronic Systems for the Indirect Effects of Lightning
ARP5416	Aircraft Lightning Test Methods
ARP5577	Aircraft Lightning Direct Effects Certification

2.1.2 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

AC 20-53	Protection of Aircraft Fuel Systems Against Vapor Ignition Caused by Lightning
AC 20-136B	Aircraft Electrical and Electronic System Lightning Protection

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

AC 20-155 Industry Documents To Support Aircraft Lightning Protection Certification

AC 25-27 Development of Transport Category Airplane Electrical Wiring Interconnection Systems Instructions for Continued Airworthiness Using and Enhanced Zonal Analysis Procedure

AC 25-981-1 Fuel Tank Ignition Source Prevention Guidelines

2.2.2 Other Publications

NASA-STD-4003 Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment

Goodloe, C.C. (1999). *Lightning protection guidelines for aerospace vehicles* (Report no. NASA/TM-1999-209734). Marshall Space Flight Center.

Gabrielson, B.C. (1988). *The aerospace engineer's handbook of lightning protection*. Interface Control Technologies.

Fisher, F.A. and Plumer, J.A. (1977). *Lightning protection of aircraft* (Report no. NASA-RP-1008). National Aeronautics and Space Administration.

3. INTRODUCTION

Aircraft are routinely struck by lightning, especially when aircraft are flying in precipitation. Lightning attaches to two or more points on the aircraft, typically at extremities such as the nose, wingtips, engine inlets, stabilizer tips, and blade antennas. When lightning strikes an aircraft, the aircraft structure and skin conduct the lightning current between the lightning attachment points. Other equipment such as metal fuel and hydraulic tubes, control cables, pushrods, and wires within the aircraft can also conduct a portion of the lightning current. Even where this equipment is not directly conducting the lightning current, the magnetic fields produced by the lightning current can induce current in this equipment.

For aircraft that use aluminum for their skin and structure, most of the lightning current is conducted through the skin and structure since aluminum is a very good electrical conductor. This current is conducted with very low voltage potential developed and dissipates very little energy into the aircraft as it passes through. Other metals used for aircraft structures, such as titanium and steel, are an order of magnitude less electrically conductive than aluminum and result in a higher voltage potential with the conduction of lightning current. Carbon fiber composite aircraft skin and structure have electrical conductivity a few orders of magnitude lower than aluminum, which results in even higher voltage potential from the conducted current.

The lightning current conducted through the aircraft skin and structure will create a voltage difference between points on the aircraft, due to the resistance of the material. Joints between these materials can also result in high voltage if the materials are not electrically bonded to one another. As the resistance of the material or joint increases, the voltage difference due to lightning currents will also increase. The voltage difference determines how much energy is released from the passing current and can result in various deleterious effects for the aircraft. For example, when a lightning current is conducted through an aircraft wing with aluminum skin and structure with good electrical bonds between materials, the lightning-induced voltage difference between the wing tip and root can be on the order of tens of volts. A similar wing with carbon fiber composite skin or aluminum skin with poor conducting joints between panels can have a lightning-induced voltage difference between the wing tip and root on the order of several thousand volts. Electrical conductors such as fuel and hydraulic tubes, control cables, pushrods, and wires within the aircraft that are routed between these points on the aircraft can be exposed to this current through direct conduction or induced current conduction.

When hydraulic tubes or components bridge gear doors, control surfaces, or other moveable aircraft parts, high voltages can develop between these parts and the aircraft structure, regardless of the structural materials used. These voltages can cause arcing at the hydraulic tubes or components and high currents through those hydraulic tubes and components, resulting in damage and leakage.

4. ANALYSIS OF LIGHTNING EFFECTS ON HYDRAULIC TUBES AND COMPONENTS

The lightning environment in aircraft areas where the tubes and components are installed should be determined to evaluate lightning effects on hydraulic tubes and components. The aircraft geometry, structure, and materials all affect the lightning currents and voltages on hydraulic tubes and components. Electromagnetic simulation and analysis may be used to determine the lightning currents and voltages on the hydraulic tubes and components. For aircraft with conventional aluminum skin and structure, simple resistance calculations might be used to estimate the lightning current and voltage on hydraulic transport elements. Aircraft with unconventional configurations or aircraft that use significant carbon fiber composite skin and structure may require more detailed electromagnetic analysis to predict the lightning current and voltage on hydraulic transport elements.

A simplified process flow required for the current and voltage effects analysis on hydraulic tubes and components is shown in Figure 1.

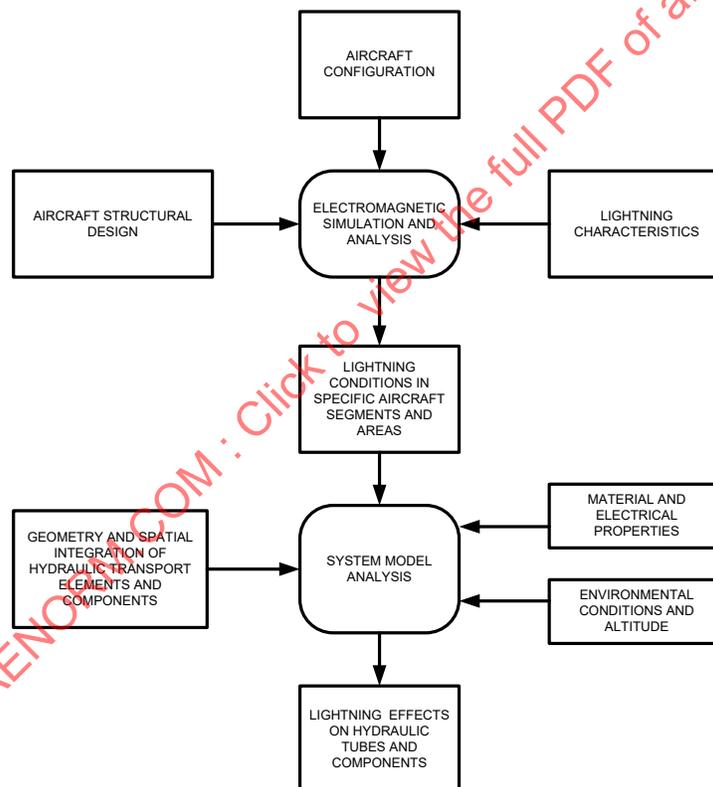


Figure 1 - Process flow for current and voltage effects analysis on hydraulic tubes and components

5. AIRCRAFT HYDRAULIC TRANSPORT ELEMENTS AS LIGHTNING CURRENT CONDUCTORS

Hydraulic transport elements are part of the aircraft flight control and landing gear systems. Hydraulic tubes and hydromechanical components can be located in the fuselage, on the landing gear, in the horizontal and vertical stabilizers, in the engines and pylons, in electrical and electronic bays, in fuel tanks, in flammable areas, and throughout the wing, as shown in Figure 2. The hydraulic transport elements can go across moving parts of the aircraft, such as across the horizontal stabilizer trim hinges and across the landing gear mechanisms. The hydraulic transport elements connect to hydraulic actuators that can be located near the extremities of the aircraft, where a lightning attachment is the most likely.

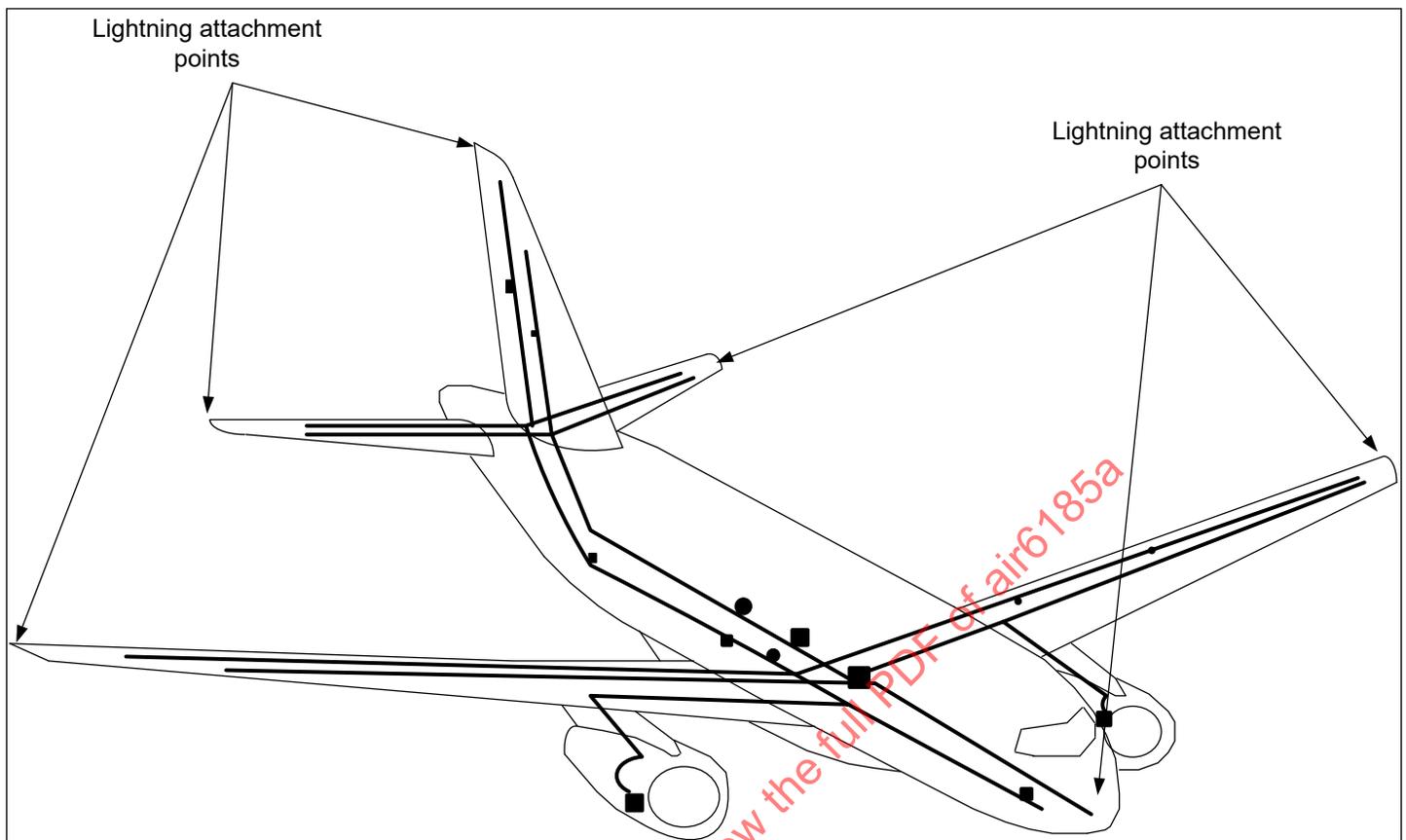


Figure 2 - Simplified architecture of aircraft single hydraulic system

The hydraulic transport elements are typically made of electrically conducting aluminum, titanium, and corrosion-resistant steel (CRES). Since the hydraulic transport elements are routed to the aircraft extremities, they can conduct significant lightning current and can be exposed to significant voltage along their span. The lightning current can create resistive heating, magnetic deformation, and high-energy arcs. These lightning effects can result in high-pressure hydraulic leaks and damage to hydraulic components. The lightning voltage can create arcs across air gaps and insulating materials and coatings. Explanations of these effects are described in ARP5416, 3.1.

The hydraulic transport element and the installation design should consider the following issues related to lightning:

- a. High voltage breakdown through insulating materials used in hydraulic transport elements.
- b. Electrical flashover from hydraulic transport elements to adjacent aircraft structure or parts.
- c. Magnetic deflection or deformation due to high lightning currents on hydraulic transport elements.
- d. Resistive heating due to high lightning currents on hydraulic transport elements.

5.1 High Voltage Breakdown Through Insulating Materials Used in Hydraulic Transport Elements

Lightning can result in high voltage breakdown on hydraulic couplings with an electrically insulating coating. In many cases, the fittings used to join hydraulic tubes use an anodized coating, particularly on aluminum fittings. The anodized coating is an electrical insulator but is typically not controlled to prevent high voltage puncture. The induced voltage along hydraulic tubes can break down and puncture the thin anodized coating. Once the anodized coating is punctured, the lightning current moving through the anodized fitting is concentrated at the puncture location. The resulting high-current arc can burn a hole in aluminum hydraulic tubes or can cause pitting across the fitting mating surfaces. Both can result in hydraulic leaks.

For hydraulic equipment exposed to direct lightning attachment (landing gear, ram air turbines, certain flight control actuators), consideration should be given to the conduction of the lightning current in the attached tubes.

Where induced current can occur, such as tubing inside of structure such as inside the fuel tanks, the design should prevent lightning-related arcing that could result in fuel ignition. Refer to AC 20-53 for further information on fuel system lightning protection.

Wherever material changes occur, a potential for a resistive joint is present. Where these joints are protected with anodize coatings or other protective finishes, or where the joints' material is thinnest, will have the highest potential for arcing and subsequent damage. Figure 3 shows the potential tube puncture and pitting locations between hydraulic tube and swaged fitting with B-nut shown.

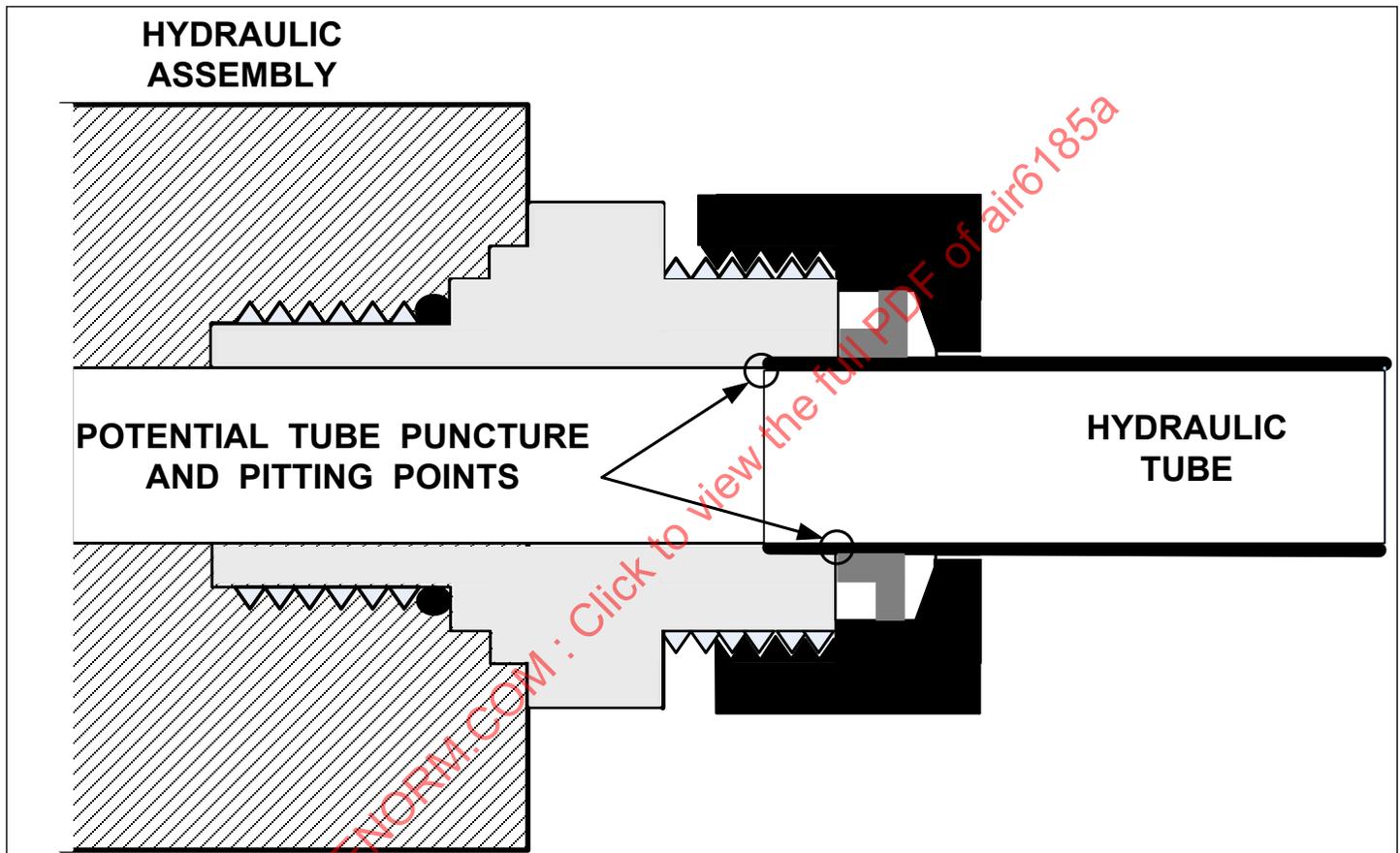


Figure 3 - Potential tube puncture and pitting locations for swaged fitting

A swivel valve is a typical component in a hydraulic system, which can cause arcing and sparking when it is directly exposed to the high lightning current. The hydraulic swivel valves allow relative rotation between two segments with hydraulic ports to accommodate the movement of hydraulic lines that occurs during actuation. An insulating polytetrafluoroethylene (PTFE) coating around the pivoting shaft electrically isolates the two hydraulic segments from each other. A lightning strike can cause high voltage breakdown across small air gaps.

Areas of possible material erosion and deposit, as a result of arcing and sparking across the swivel valve, are shown in Figure 4.

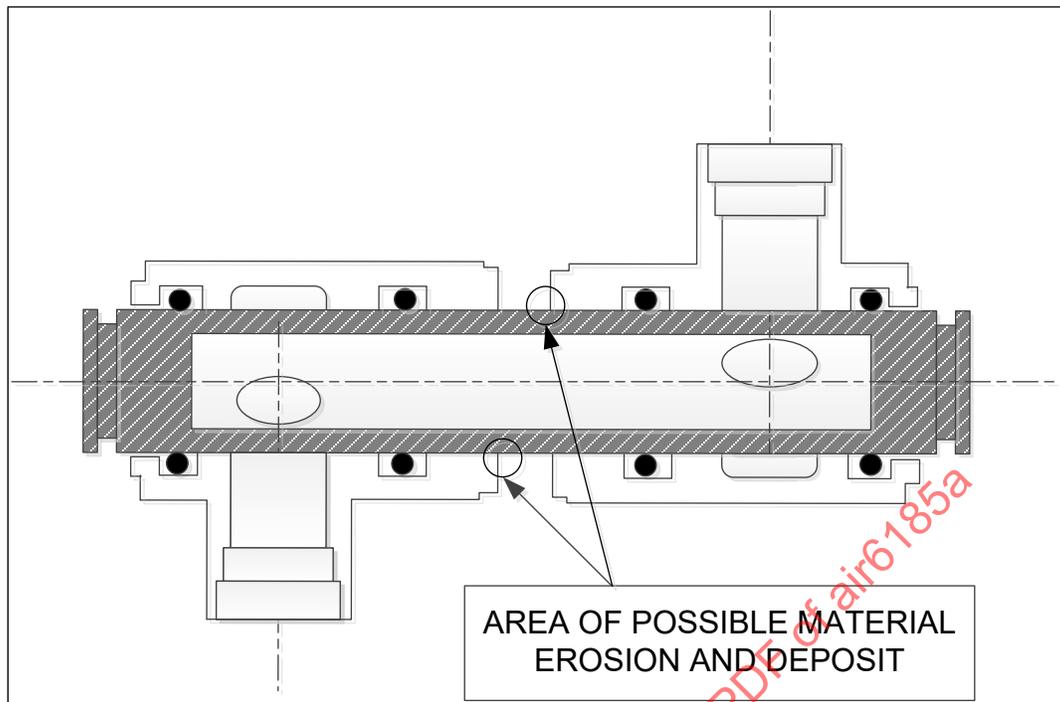


Figure 4 - Areas of possible potential material erosion and deposit on a typical swivel valve

Internal arcing and sparking can also occur on hydraulic actuators, as shown in Figure 5, when it is directly exposed to the lightning. Internal pitting and melting are possible on the piston and the inner surfaces of the cylinder. The piston may be isolated from the cylinder with seals, so arcing can occur between the piston or shaft and the cylinder. Internal damage caused by arcing between the actuator cylinder and piston may cause internal leakage when the actuator is pressurized.

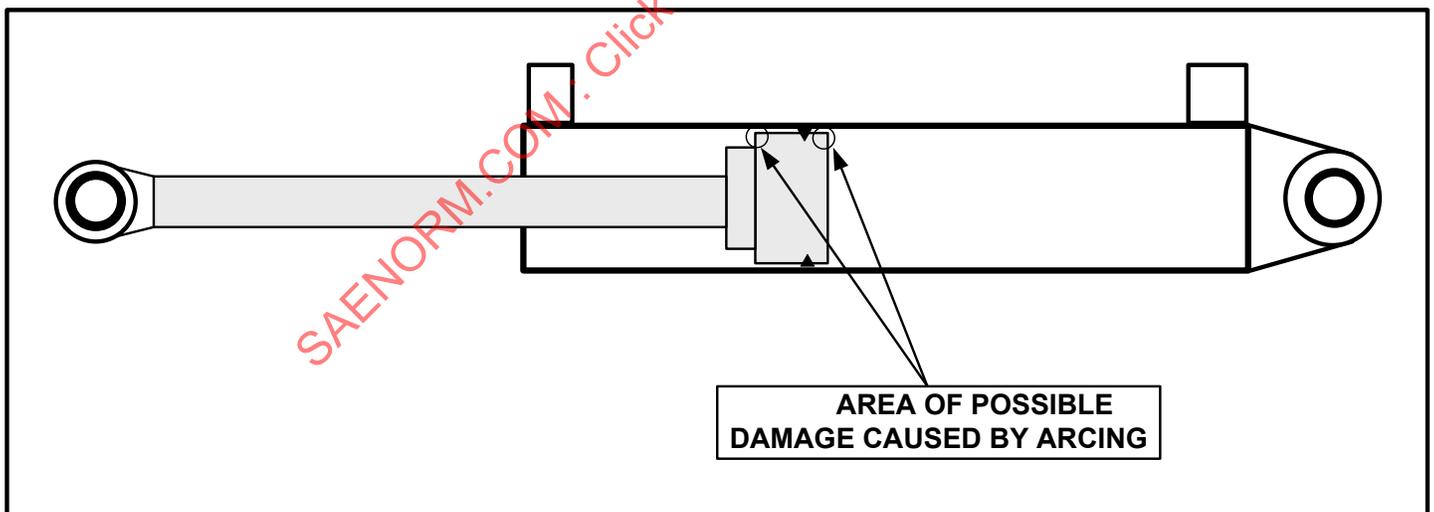


Figure 5 - Possible hydraulic actuator internal damage caused by arcing

Also, electrically insulating coatings and anodized finishes are often applied to the pipe ends and couplings to control corrosion. Over some time, relative displacements due to the air load on the wings and vibrations may wear this insulation away, providing unintentional and intermittent conductive paths, where lightning conditions can lead to arcing and sparking.

5.2 Electrical Arcing From Hydraulic Transport Elements

Lightning can cause arcing and sparking on hydraulic actuators with hydraulic ports and insulated spherical bearings located at the rod end and head end. Lightning current can pass through the actuator body and the metallic conductive surface of the spherical bearing. Arcing can occur between the outer side of the spherical bearing and the mounting pin, as shown in Figure 6. The intensity of the arc depends on the lightning current amplitude, duration, and air gap between two conductive elements.

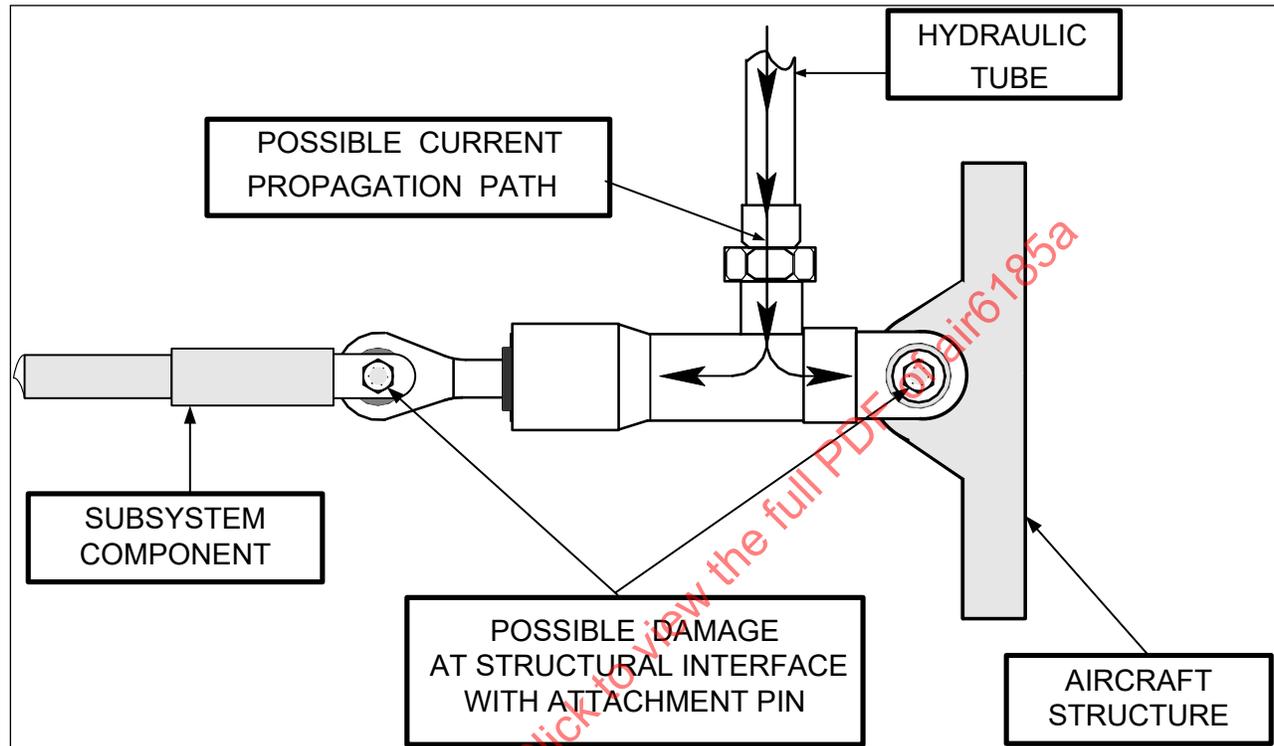


Figure 6 - Possible component damage caused by arcing between two conductive elements which are separated by an air gap

Electrical arcing can also occur between parallel hydraulic tubes. In many installations, steel or titanium is used for high-pressure hydraulic supply tubes, while aluminum is used for the lower-pressure hydraulic return lines. If the supply and return lines are routed in parallel, and significant lightning current flows on the tubes, a significant voltage difference between the lines can result due to the difference in tube resistances. For closely spaced lines, this voltage difference can cause an electrical arc between the tubes, which can melt through the tubes and cause significant leaks. There can be a similar voltage difference between the tubes and structure, with the potential for electrical arcing between the tubes and structure.

This electrical arcing can be minimized by electrically bonding the tubes to the structure at multiple points along the hydraulic tube route. This reduces the voltage from point to point along the hydraulic tubes. Effective high-current electrical bonding straps should be installed across any hinge point where hydraulic tubes also cross.

The breakdown voltage of insulation such as hydraulic actuator bushings or lubricating sleeves surrounding the hinge pin is typically in the 3000- to 5000-V range; these values could change after time in service.

A low impedance path should be provided between hydraulic equipment and aircraft structure or current return network (CRN). Bonding jumpers can provide electrical bonding across insulating support clamps or other nonconductive mounts. The impedance of a bonding jumper increases as the jumper length increases. Very low-impedance bonding jumpers typically have lengths on the order of 5X the jumper width. If the bonding jumper length exceeds tens of centimeters, consider the effects of the higher bonding jumper impedance for the expected lightning currents. It is critical that the bonding jumper can handle the current that might be conducted in that location. Bonding jumpers should also be routed as straight as possible, with shallow bends.

Equipment on the aircraft may have several possible electrical paths to structure, including the mounting hardware and bonding straps. Metal fasteners into either a metallic structure or a designated grounded conductor can provide adequate electrical bonding. The surface of the carbon fiber composite or metal structure may not be conducting due to resin or paint so may need to be prepared by removing these finishes to ensure an effective electrical connection.

Examples of good low-impedance electrical bonds are:

- Electrical faying surface bond to metal structure (metal to metal surface in contact).
- If the metal structure has primer or another nonconducting coating, mounting bolts in good electrical contact with the equipment and with the metal structure.

Specific electrical bonds should be provided across insulating seals, nonconductive bearings, rubber isolators, surfaces, and fasteners with insulating corrosion protection.

5.3 Magnetic Deflection or Deformation Due to High Lightning Currents on Hydraulic Transport Elements

Lightning current on hydraulic transport elements can result in large magnetic forces, which can damage these elements. When electrically conducting hydraulic tubes are routed in parallel, lightning currents on these parallel tubes will result in magnetic force $F(t)$ on the tubes, which can be approximated and calculated as:

$$F(t) = \frac{\mu_o * I_1(t) * I_2(t)}{2\pi} \times \frac{Z}{D} \quad (\text{Eq. 1})$$

where:

$F(t)$ = magnetic force (N)

D = distance between hydraulic tube centerlines (m)

Z = length of the parallel hydraulic tubes (m)

$I_1(t)$ = pulse current in the first conductor (A)

$I_2(t)$ = pulse current in the second conductor (A)

μ_o = magnetic constant in air, $4\pi \cdot 10^{-7}$ (H/m)

The force between two hydraulic tubes is attractive if the two currents flow in the same direction, and repulsive if the currents flow in opposite directions. The amount of force is proportional to the square of the induced lightning stroke current amplitude. How long the magnetic force will be present depends on the time duration of lightning-induced currents.

The amplitude of the lightning current determines the magnetic force which can cause a reversible or irreversible deformation on hydraulic tubes. Special attention should be given to the long parallel hydraulic tubes traveling exposed to high lightning currents. An example is shown in Figure 7, where hydraulic tubes are installed in parallel from the bulkhead through the nose landing gear bay.

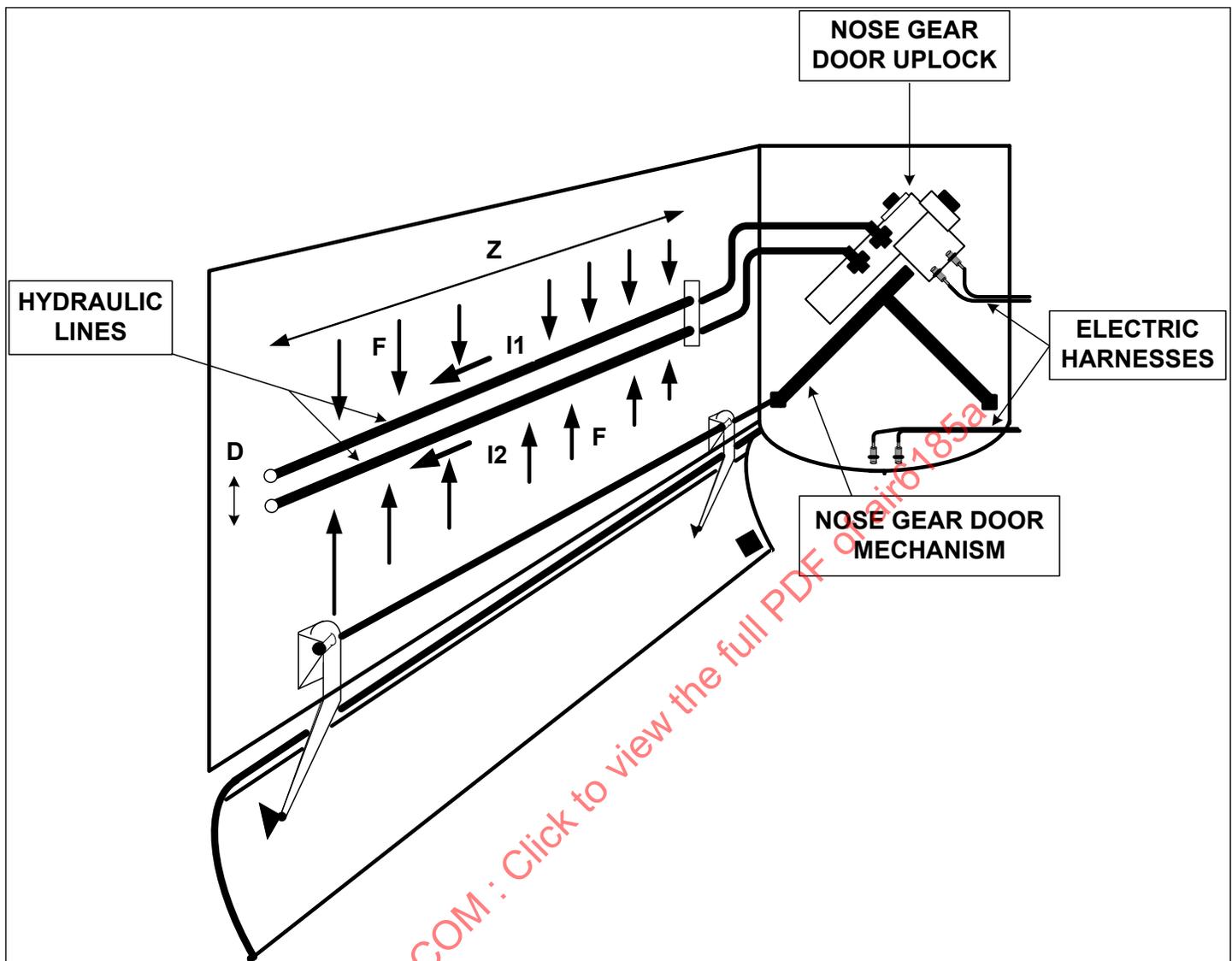


Figure 7 - Example of the parallel hydraulic tubes located in the nose landing gear bay with lightning-induced currents flowing in the same direction

The amount of deformation depends on the stiffness of the hydraulic tubes, material properties (aluminum, titanium, or CRES), and the duration of exposure to the magnetic force. Hydraulic tubes exposed to the dynamic force caused by induced current pulse will have a different reaction depending on whether it is pressurized or not. For that reason, the most vulnerable parts of the hydraulic transport elements are joints between tubes and hydraulic fittings. The magnetic force depends on the peak current, but not the rate of change of current. However, the effect of this force on hydraulic tubes and joints would certainly be influenced by the time duration and intensity of a given lightning strike.

Appropriate electrical bonding between the hydraulic tubes and structure can reduce magnetic forces resulting from lightning current present on parallel hydraulic tubes. There should be a short electrical bonding path between the hydraulic tubes and the structure. In carbon fiber composite structures, the distance between electrical bonding points on the hydraulic tubes (distance Z) should be reduced. Another option to prevent lightning currents on hydraulic tubes is the installation of in-line isolators or nonconductive hoses. Such in-line isolators break the conducting path and reduce the induced lightning current from several thousand amperes to a very low current.

5.4 Resistive Heating Due to High Lightning Currents on Hydraulic Transport Elements

Lightning current conducted on hydraulic transport elements and system components will cause resistive heating. When the resistivity of a conducting element is high or when the cross-section area is low, lightning currents can cause a temperature rise in the conducting element.

The temperature rise due to lightning currents in conductive elements of the hydraulic system can be calculated based on the material properties, conductive cross-section, and specific energy.

In Figures 8A and 8B, a quantitative temperature increase of hydraulic tubes is shown as a function of the lightning peak pulse current. The lightning current signal corresponds to Waveform 1 defined per ARP5412, followed by 10 A constant current for 250 ms for titanium, CRES, and aluminum tubes.

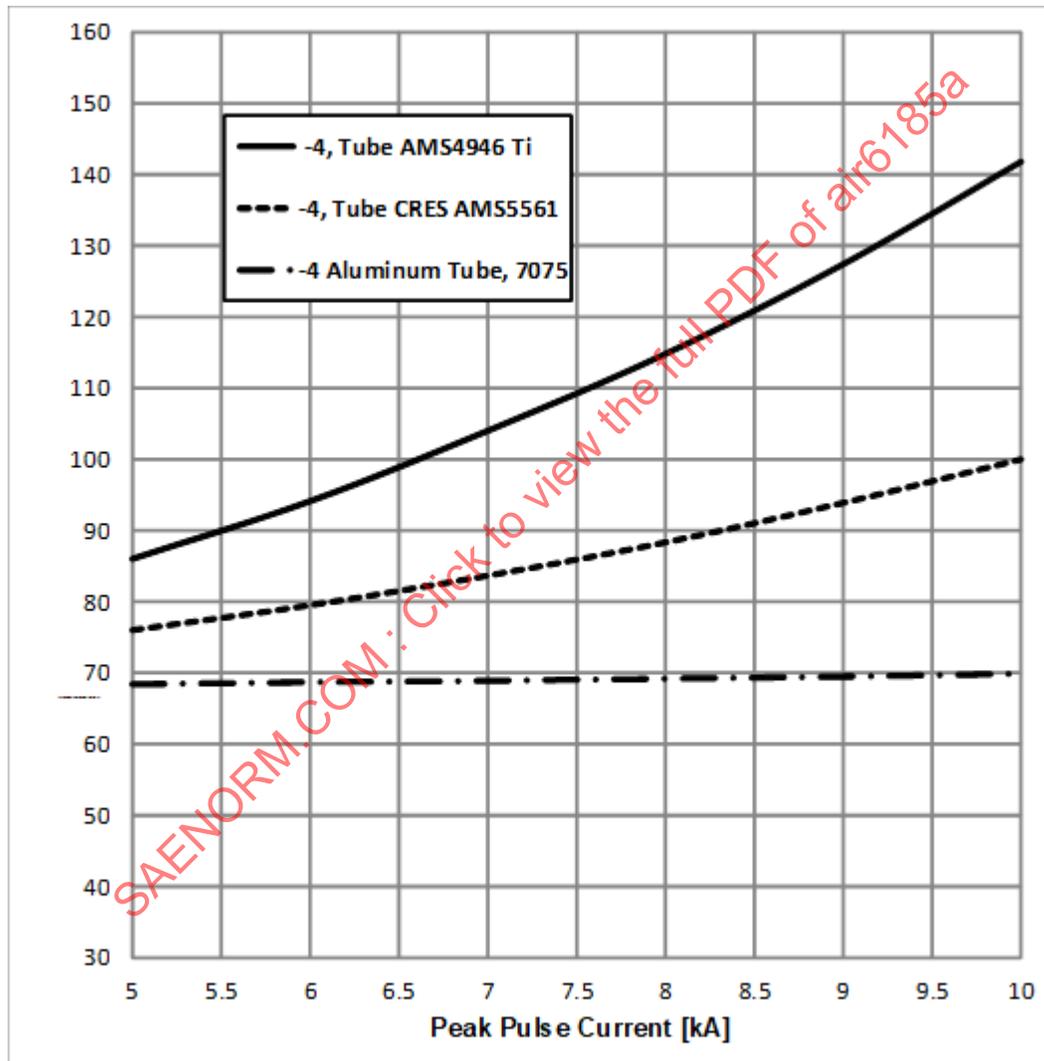


Figure 8A - Hydraulic tube temperature increase from an ambient temperature $T_1 = 68^\circ\text{F}$ as a function of the peak pulse current