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Lightning Strikes on Commercial Aircraft: How the Airlines Are Coping

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ABSTRACT

The hazard posed by lightning strikes is an important issue in commercial aviation. Extensive research into methods for coping with lightning strikes has been continuing for many years. This paper addresses the issues pertaining to lightning strikes, impact on commercial aviation, and initiatives undertaken to prevent lightning strike mishaps. This paper concludes that commercial airliners are generally quite safe during electrical storms. The metal skin of the plane conducts the current on the outside around the passengers. Fuel tanks are now designed to prevent entry of electrical charges.

INTRODUCTION

In a typical year, 2,000 commercial airliners around the world are hit by lightning, according to Aviation Week and Space Technology magazine. Fortunately, planes are designed to take a hit and disperse the jolt through tassel-like "static discharge wicks" on their wings and tail fins (Howe, 1998).

In what may be a first, a commercial pilot was burned and partially incapacitated when lightning struck his Boeing 757. The Air Accidents Investigations Branch in Great Britain recently made a report of the incident public. The agency is the U.S. equivalent of the National Transportation Safety Board. The 757 was approaching Amsterdam airport on October 10, 2000, with the first officer attempting to steer the jet through two storm cells. The first officer was seated with his right hand and part of his right arm resting on the cockpit coming close to the right forward windscreen. The jet was flying at about 5,000 feet when it was hit by lightning just below the right windscreen. "The first officer was aware of a loud bang and bright flash and described feeling as if he had been kicked in the chest," the report on the incident stated. The first officer found that he could not use his right arm and turned over control to the captain, who made an otherwise uneventful landing. When doctors examined him later, the first officer was found to have a burn wound in his chest. He returned to his flying duties two weeks later, but has since developed a medical condition that may be a result of the incident. (Wallace, 2001).

THE MOST COMMON TYPES OF LIGHTNING

Cloud-to-Ground Lightning

Cloud-to-ground lightning is the most damaging and dangerous form of lightning. Although not the most common type, it is the one, which is best understood. Most flashes originate near the lower-negative charge center and deliver negative charge to Earth. However, an appreciable minority of flashes carry positive charge to Earth. These positive flashes often occur during the dissipating stage of a thunderstorm's life. Positive flashes are also more common as a percentage of total ground strikes during the winter months (Commercial considerations on detecting lightning, 2005).

Intra-Cloud Lightning

Intra-cloud lightning is the most common type of discharge. This occurs between oppositely charged centers within the same cloud. Usually the process takes place within the cloud and looks from the outside of the cloud like a diffuse brightening which flickers. However, the flash may exit the boundary of the cloud and a bright channel, similar to a cloud-to-ground flash, can be visible for many miles. The ratio of cloud-to-ground and intra-cloud lightning can vary significantly from storm to storm. Storms with the greatest vertical development may produce intra-cloud lightning almost exclusively. Some suggest that the variations are latitude-dependent, with a greater percentage of cloud-to-ground strikes occurring at higher latitudes. Others suggest that cloud-top height is a more important variable than latitude. Details of why a discharge stays within a cloud or comes to ground are not understood. Perhaps a flash propagates toward the Earth when the electric field gradient in the lower regions of the cloud is stronger in the downward direction. Depending upon cloud height above ground and changes in electric field strength between cloud and Earth, the discharge stays within the cloud or makes direct contact with the Earth. If the field strength is highest in the lower regions of the cloud a downward flash may occur from cloud to Earth (Commercial considerations on detecting lightning, 2005).

Inter-Cloud Lightning

Inter-cloud lightning as the name implies, occurs between charge centers in two different clouds with the discharge bridging a gap of clear air between them (Commercial considerations on detecting lightning, 2005).

DESCRIPTION OF LIGHTNING DISCHARGE PROCESSES

Figure 1 illustrates the lightning model (Commercial considerations on detecting lightning, 2005). With the initial breakdown of the air in a region of strong electric fields, a streamer may begin to propagate downward toward the Earth. It moves in discrete steps of about 50 meters each and is called a stepped leader. As it grows, it creates an ionized path depositing charge along the channel, and as the stepped leader nears the Earth, a large potential difference is generated between the end of the leader and the Earth. Typically, a streamer is launched from the Earth and intercepts the descending stepped leader just before it reaches the ground. Once a connecting path is achieved, a return stroke flies up the already ionized path at close to the speed of light. This return stroke releases tremendous energy, bright light and thunder. Occasionally, where a thunderstorm grows over a tall Earth grounded object, such as a radio antenna, an upward leader may propagate from the object toward the cloud. This "ground-to-cloud" flash generally transfers a net positive charge to Earth and is characterized by upward pointing branches. The initial breakdown and propagation are similar for intra-cloud lightning, but the discharge generally occurs between regions of opposite charge. Without the benefit of air conducting Earth, intra-cloud lightning does not produce a return-stroke-like feature. Rather, it is characterized by slower propagating "recoil streamers". Nevertheless, tremendous energy, bright light, and thunder are still produced by intra-cloud lightning (Commercial considerations on detecting lightning, 2005).

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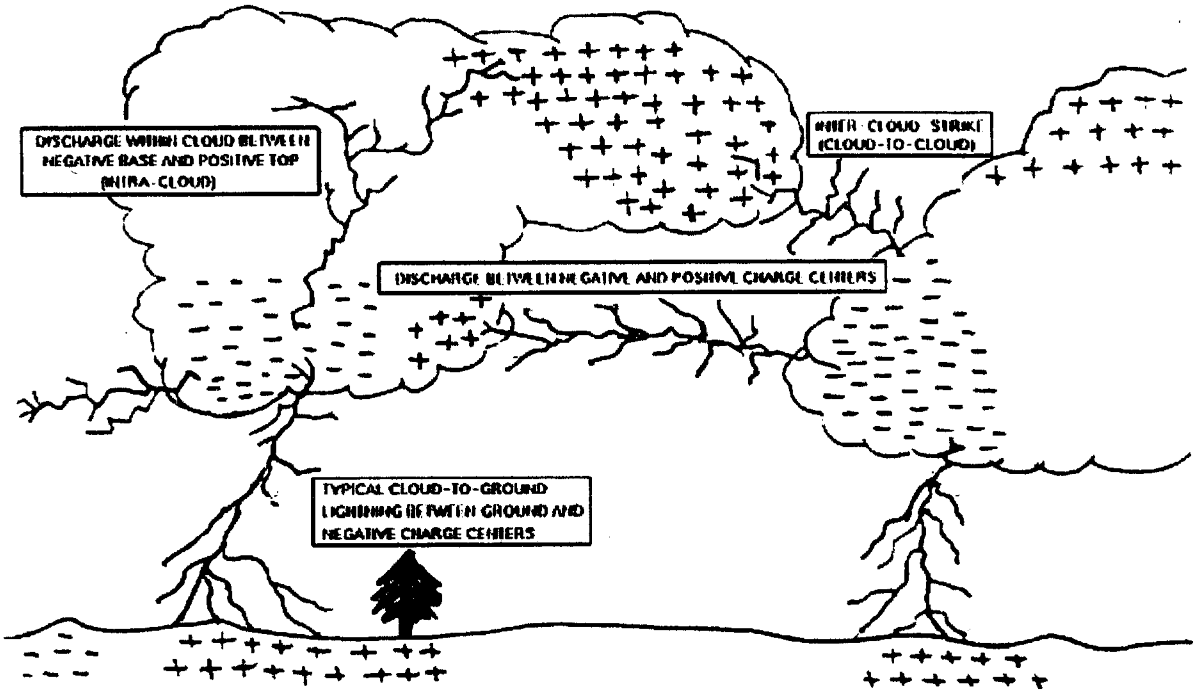

The lower part of a thundercloud is usually negatively charged. The upward area is usually positively charged. Lightning from the negatively charged area of the cloud generally carries a negative charge to Earth and is called a negative flash. .

Figure 1. The Lightning Model

Impact of Lightning Strikes on Commercial Aircraft

Lightning costs about $ 2 billion annually in airline operating costs and passenger delays (Northeast States Emergency Consortium, 2002).

On December 8, 1963, a lightning bolt blew up the fuel tank of a Pan American 707. The plane was hit over Maryland by a bolt that ignited fuel in the reserve tank, blowing the left wing off the plane, turning the airplane into a fireball and killing all 81 on board. That disaster, is the only one caused by lightning in U.S. commercial aviation. Since then, at least 40 strikes of planes have caused deaths or injuries. Planes carrying the governors of Florida and Illinois have been zapped in the last three years (Howe, 1998).

In June 2001, 44 passengers died when an aircraft run by Chinese regional carrier Wuhan Airlines exploded on landing after being struck by lightning (Espiner, 2001).

In February 1988, 21 people aboard a German regional airline died after the right wing of a Swearingen turboprop plane broke off during an uncontrolled descent after a lightning strike (Espiner, 2001)

It may shock you to learn, no pun intended that each commercial aircraft is struck by lightning, on average, once per year or every 3,000-flight hours. And although it is very frightening for passengers to experience the flash of white light and loud noise that usually accompanies a lightning strike, they are protected from electrocution because they are inside the metal shell of the airplane. There is no electric field, or current, inside a charged shell – the current is experienced as one passes through the shell, so you would have to touch the outside of the fuselage in order to get a shock. It's not a sure bet at 35,000 feet! (Pauwels, 2002).

Airplanes build up static just by virtue of flying through the air, lightning or not. Bonding strips made of conductive material to equalize charges are usually placed throughout the aircraft, and static wicks, devices that look like small antennas, are installed on the trailing edge of the wings and tail surfaces to help dissipate static electricity that would interfere with radios and other electrical components (Pauwels, 2002).

Although people fare well during lightning strikes, sometimes the airplane itself is not so lucky: Lightning strikes can and have caused serious damage to the aircraft structure and systems. The prospect of damage, and the fact that nowadays composite materials less conductive than metal are more commonly used to build airplanes, makes avoidance of areas that are known to produce lightning, such as thunderstorms, the best risk-management tool (Pauwels, 2002).

PREVENTING LIGHTNING STRIKE MISHAPS

Engineering Lightning Safety into the Aircraft

As stated, it is estimated that, on average, each airplane in the U.S. commercial fleet is struck lightly by lightning more than once each year. In fact, aircraft often trigger lightning when flying through a heavily charged region of a cloud. In these instances, the lightning flash originates at the airplane and extends away in opposite directions (McGill, 2001).

Although passengers and crew may see a flash and hear a loud noise if lightning strikes their plane, nothing serious should happen because of the careful lightning protection engineered into the aircraft and its sensitive components. Initially, the lightning will attach to an extremity such as the nose or wing tip. The airplane then flies through the lightning flash, which reattaches itself to the fuselage at other locations while the airplane is in the electric "circuit" between the cloud regions of opposite polarity. The current will travel through the conductive exterior skin and structures of the aircraft and exit off some other extremity, such as the tail. While this is happening, pilots occasionally report temporary flickering of lights or short-lived interference with instruments (McGill, 2001).

Most aircraft skins consist primarily of aluminum, which conducts electricity very well. By making sure that no gaps exist in this conductive path, the engineer can assure that most of the lightning current will remain on the exterior of the aircraft. Some modern aircraft are made of advanced composite materials, which are significantly less conductive than aluminum. In this case, the composites contain an embedded layer of conductive fibers or screens designed to carry lightning currents (McGill, 2001).

Modern passenger jets have miles of wires and dozens of computers and other instruments that control everything from the engines to the passengers' headsets. These computers, like all computers, are sometimes susceptible to upset from power surges. So, in addition to safeguarding the aircraft's exterior, the lightning protection engineer must make sure that no damaging surges or transients can reach the sensitive equipment inside the aircraft. Lightning traveling on the exterior skin of an aircraft has the potential to induce transients into wires or equipment beneath the skin. These transients are called lightning indirect effects. Careful shielding, grounding and the application of surge suppression devices avert problems caused by indirect effects in cables and equipment when necessary. Every circuit and piece of equipment that is critical or essential to the safe flight and landing of an aircraft must be verified by the manufacturers to be protected against lightning in accordance with regulations set by the Federal Aviation Administration (FAA) or a similar authority in the country of the aircraft's origin (McGill, 2001).

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The other main area of concern is the fuel system, where even a tiny spark could be disastrous. Engineers take extreme precautions to ensure that lightning currents cannot cause sparks in any portion of an aircraft's fuel system. The aircraft skin around the fuel tanks must be thick enough to keep lightning from entering, as it did in a Pan American 707 in December 1963. That disaster prompted the FAA to require that aluminum wing surfaces of fuel tanks be at least .08 of an inch thick (Zorpette, 1988). All of the structural joints and fasteners must be tightly designed to prevent sparks, because lightning current passes from one section to another. Access doors, fuel filler caps and any vents must be designed and tested to withstand lightning. All the pipes and fuel lines that carry fuel to the engines, and the engines, must be protected against lightning. In addition, new fuels that produce less explosive vapors are now widely used (McGill, 2001).

Airline Lightning Strike Project

One of the most important resources for lightning strike information comes from flight crews who voluntarily report their encounters in a database maintained by Lightning Technologies, Inc. (LTI). The program is called the Airlines Lightning Strike Project (ALSRP), and it receives financial support from several sources including the FAA's Hughes Technical Center. Recently, the program has been expanded to capture data from regional and corporate flight crews. One of the objectives of the expanded project is to obtain data on the experiences of commuter airlines operating newer regional jet and turboprop airplanes. Database managers are especially interested in tracking in-service experience of aircraft employing greater amounts of composite materials, electronic controls and integrated cockpit displays crews. Another objective is to obtain more details on the effects of especially "severe" strikes. Since aircraft experience lightning strikes somewhat more frequently in Europe than in the continental United States, and some of the occasional "severe" strike incidents have occurred in Europe, European airline participants are especially welcome. A third objective is to obtain data on physical effects on metal and composite structures, and effects on electronic equipment brought to maintenance centers for repair or replacement (Share Your Electrifying Experience, 2001).

LSRP focuses on experiences of turbojet-powered transport aircraft. Five U.S. airlines participated in the project initially, but due to consolidations and changing economic conditions only two of the original participants remain -- American and Delta. Participating crewmembers complete a one-page questionnaire-type form detailing their in-flight lightning strikes or static discharge events. Flight engineers add brief descriptions of observed effects on the exterior of the aircraft. The lightning and static discharge reports are combined at LTI with reports received from other aviation interests worldwide and studied to identify flight and weather conditions when aircraft are struck and the effects these strikes are having on cockpit avionics, control systems, and structures. Of particular interest are effects on integrated cockpit displays, digital engine controls and fly-by-wire flight control systems, as well as composite skin subsections including windshields, radomes, and flight control surfaces (Share Your Electrifying Experience, 2001).

Weather data are used by meteorologists to improve hazardous weather prediction and avoidance guidelines, and the strike effects data are studied by design engineers to be sure that protection methods are functioning properly, and by certification test engineers throughout the industry to validate or improve lightning protection. Benefits to the participating parties are continued improvement in the flight safety records of modern aircraft, together with the reduced costs afforded by improved lightning and static protection designs, which require less frequent repairs. Since 1992, the FAA Technical Center at Atlantic City, N.J. and its contractor Galaxy Scientific Corp., have been assisting the program by inputting all of the data to a computerized database, from which statistical examinations can be made of various parameters. Data summaries have been published periodically by LTI, and are available to technical groups concerned with protection design and certification of aircraft (Share your electrifying experience, 2001).

The project has always kept the identities of flight crew personnel; specific airline, and flight number involved in any reported strike incident confidential, and individual data reports do not reach the authorities. These details are not necessary for the technical objectives of the project. Pilots are urged to participate in the reporting program. It was discovered that lightning strikes can be "triggered" by and originate at the aircraft. Many of these are intra-cloud flashes, which never reach the earth. Aircraft are sometimes struck by lightning in regions where no convective activity exists or is reported, in layered or stratiform cloud situations and at all flight altitudes. Strikes have occurred most frequently when aircraft are flying in clouds with liquid precipitation, at temperatures within plus or minus 5° C of freezing. Lightning strikes are characterized by a bright flash accompanied by a loud report, whereas static discharges are characterized by lower energy discharges of longer duration, visible at night as an ultraviolet glow about the nose or other extremities of the aircraft, or as small sparks dancing across windshields. Early DC-10 operators reported outages or erroneous readings from indicators, which were traced to lightning-induced transients in engine-to-cockpit wire harnesses. This resulted in precautionary in-flight engine shutdowns on several occasions. Details reported by pilots helped airframe and instrument designers diagnose the problem and design a "fix," and the problem has not been reported since. (Share Your Electrifying Experience, 2001).

Pilot Actions

Certainly a lightning strike can be unnerving. The flash can be blinding and your vision can be lost for as long as 30 seconds. If you are flying in the conditions discussed above, especially at night, it's a good idea to employ the time-honored procedure recommended to protect vision near thunderstorms: Lower the seat, drop the visors, adjust the cockpit lights to full bright, and keep your attention focused inside the aircraft (Aarons, 2001).

If you do take a strike, you'll get the flash and a "pop" or "bang" and, perhaps, a jolt. The EFIS may flicker a moment and the autopilot may disconnect. Stay calm -- at least as calm as possible -- treacquire the instruments visually and make a quick crosscheck including the standby instruments. Keep the wings level and ride it out until you can see clearly and are assured that the avionics and electrical systems are stable. If the airplane is relatively modern and well maintained, all critical systems should survive just fine. When able, let the passengers know what happened and calm them down. Be especially alert for smoke or fire. There have been cases in which direct strikes caused arcing in poorly maintained wiring, which in turn ignited adjacent insulation. A direct strike on a com or nav antenna may disable that component, and radomes are notoriously vulnerable to strikes, but the basics should be there for you. Typically, all will be well and you can continue to your destination (Aarons, 2001).

On rare occasions -- put the emphasis on rare -- lightning has been known to shut down engines or take out major systems. A lightning stroke generates both pressure shock waves (the bang) and temperature shock waves (the flash). If those shock waves occur close enough to the engine inlet, the engine may exhibit compressor stalls or even a flameout. Engines with small nacelle areas are more vulnerable than those with large- aperture intakes. However, generally only one engine is affected when they are mounted on either side of the fuselage. Be aware that restart can take longer than normal in this situation because of water ingestion; however, the igniter and starter circuits should survive the strike. Basically you have to deal with major failures stemming from a lightning strike the way you handle a similar failure at any other time. Do the critical stuff first, hit the memory items, follow up with checklists and remember the old admonition to navigate and then communicate (Aarons, 2001).

Cockpit Lightning Display System

With the emergence of high-speed wireless data transfer via geosynchronous and Low Earth Orbiting satellites and new VHF ground station networks, the FAA can finally fulfill its promise to provide airline pilots with graphical weather products directly into the cockpit (Gormley, 2002). The FAA has approved the VHF Data Link Mode 2 avionics to support Flight Information Services Broadcast, thus providing pilots with up-to-date weather information in the cockpit. Under the system, pilots will receive text messages, including routine and special weather reports, Terminal Area Forecasts, and Pilot Reports issued by the FAA or the National Weather Service at no cost. There also will be graphic products such as NEXRAD maps, and other flight information services products available through a subscription service (Airline Industry, 2002). The system could help major airlines save up to $6 million each year in fuel, time, and rerouting costs due to weather. By displaying virtually real-time weather information on cockpit displays -- including lightning activity -- the Cockpit Weather Information Needs (CWIN) system would reduce voice communication errors and pilot workload. The purpose of developing the CWIN concept centers on the difficulties pilots often encounter in obtaining a large volume of en route weather information, assimilating that data, using it to evaluate routes for weather avoidance, and to determine weather trends while en route (Phillips, 1993).

Integrated Terminal Weather System

The FAA is focused upon improved ways to collect, process, transmit, and display weather information to users and providers, during flight planning and in flight. Since December 2003, users receive more weather data in the cockpit to enhance situation awareness. The integrated terminal weather system (ITWS), provides near-term (0-30 minutes) prediction of significant weather in the terminal area. It generates products, including windshear and microburst predictions, storm cell hazards, lightning information, and terminal area winds. ITWS integrates data from radar, weather sensors, National Weather Service models, and automated aircraft reports. Weather and radar processor (WARP) receives and processes real-time weather data from multiple sources for the en route environment. It prepares national and regional weather mosaics and mosaics for the controller's displays and provides gridded forecast data from the National Weather Service to other automated systems. Delivery of weather and other flight information services to the cockpit via a private service provider primarily targeted to supporting general aviation users (NAS Architecture Highlights, 2001).

Future Technology

The aviation world is on the edge of being able to present to pilots a clear picture of conflicting air traffic, dangerous terrain, and threatening weather even in the thickest clouds and on the blackest nights. Generally called "free flight," the concept aimed at enhancing safety and efficiency of the nation's airways rests on recent advances in computer processing ability and Global Positioning System satellite navigation. It will provide pilots with "situational awareness" tools so they have the same information as air-traffic controllers. "Now the pilot will be presented with a picture of where the airplanes are, where the course is, where the mountains are, where the weather is, where the airport is, all at a glance," said Ron Crotty with Honeywell

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corporation, one of the manufacturers of free-flight systems (Bacque, 2000, p. C 1).

Under the present system, airline pilots file an instrument flight plan, in effect a contract governing the flight, with air-traffic control. The plan requires the aircraft to fly along a specific route, and an air-traffic controller has to approve any deviation from that path. For example, if an airliner runs into a thunderstorm, its pilot must notify the air-traffic controller of the need to change course, and the controller designates a course to avoid the storm. Under the free-flight concept, the pilot would be able to choose the route, speed, and altitude to follow the most economical path for the conditions. However, air-traffic controllers would still be needed. "Conventional air-traffic control, for all its faults, does provide human oversight to mistakes, like being off altitude," said pilot and technology consultant William Campenni of Herndon, Virginia. The aviation community intends to move gradually toward free flight in the next 10 to 20 years (Bacque, 2000).

THE BUREAUCRACY AND DELAYS

The FAA provides oversight for the largest, busiest and most complex aviation system in the world. As part of its mission, the FAA and its staff of 49,000 operate and maintain our nation's air traffic system, orchestrating the take-off, landing and routing of 93,000 aircraft a day. The FAA also regulates aviation safety and security, which entails standard setting for, and oversight of, commercial airlines, private aircraft, aircraft manufacturers and the air traffic system (U.S. Newswire, 2000).

Why does it sometimes take disaster or the passage of years for the FAA to take significant action? It is embedded in the conflicted nature of the FAA. Serving two masters, the agency not only is charged with nurturing the aviation industry but also must ensure the safety of the flying public. Whenever the FAA considers changes in safety and equipment regulations, the agency must balance safety against the cost to airlines. According to records and interviews, the result can be delays in addressing safety problems and more accidents related to them. Deadly delays have occurred in part because a law requires the FAA to justify the cost of implementing proposed safety measures by showing that enough lives will be saved (Brazil, 1994).

A four-month Los Angeles Times review of government documents revealed that in some cases years have passed and lives have been lost before the FAA acted on safety problems although the agency had long been aware of the hazards (Brazil, 1994).

For example, the FAA adopted (May, 2004) a new airworthiness directive (AD), applicable to certain Boeing Model 727-100 and -200; 737-100, -200, - 200C, -300, -400 500 and 747 series airplanes. This amendment requires preparation of the electrical bonding faying surfaces for the tubing penetrations of the hydraulic heat exchanger on the forward and aft surfaces of the rear spars of the fuel tanks of the left and right wings, a one-time measurement of the electrical bonding resistances, and follow-on actions. This action is necessary to ensure adequate electrical bonding between the penetration fittings of the hydraulic heat exchanger and the rear spars of the fuel tanks. Inadequate electrical bonding, in the event of a lightning strike, could cause electrical arcing and ignition of fuel vapor in the wing fuel tank, which could result in a fuel tank explosion. This action is intended to address the identified unsafe condition. If the FAA finds sufficient data exists to demonstrate that such potential remains. In addition, unless a fire or explosion results from an arcing event, there will not necessarily be evidence that such arcing occurred (Bahrami, 2004).

Three catastrophic accidents have occurred when transport airplanes were struck by lightning: a Model 707 airplane at Elkton, Maryland in 1963, a Boeing Model KC-135 airplane in Spain in 1974, and a Model 747 series airplane in Madrid, Spain in 1976. In one of those accidents, holes in metal debris from the accident pointed to a lightning strike that ignited fuel vapors inside a fuel tank. In the other two cases, observers from the ground confirmed that the airplanes had been struck by lightning and were in flames before crashing. These accidents have led the FAA to require using conservative lightning safety design practices to preclude ignition sources in fuel tanks due to lightning. Laboratory lightning tests in conjunction with analyses conducted by the airplane manufacturer demonstrate the potential for in-tank arcing associated with a high electrical bonding resistance between the hydraulic heat exchangers and the airplane structure. Such high bonding resistances are expected to exist on these airplanes because of the details of the original design and production practices. In addition, lightning strikes are expected to occur several times in the life of each airplane. Data collected by the airplane manufacturer indicates that Model 737 and 747 series airplanes are struck by lightning approximately once per year. The FAA and the airplane manufacturers are in agreement that a potential for arcing at the hydraulic line penetrations and at the heat exchanger exists in the event of a lightning strike to the engine or the wing for the Boeing Model 727, 737, and 747 series airplanes. The FAA also considered the aging of the fleet of these Boeing airplanes in determining the severity of the unsafe condition. The manufacturer has done a risk assessment analysis related to lightning strikes on the Model 727, 737, and 747 fleets and determined that an acceptable level of safety would be provided by a compliance time of five years for accomplishing the actions in the service bulletins. The FAA concurs with the manufacturer's assessment (Bahrami, 2004)

Effective June 22, 2004 after careful review of the available data, the FAA determined that air safety and the public interest require the adoption of the rule. The FAA determined that these changes will neither increase the economic burden on any operator nor increase the scope of the Airworthiness Directive (Bahrami, 2004).

CONCLUSION

Three catastrophic accidents have occurred when transport airplanes were struck by lightning: a Model 707 series airplane at Elkton, Maryland, in 1963; a Boeing Model KC-135 airplane in Spain in 1974; and a Model 747 series airplane in Madrid, Spain, in 1976. (Bahrami, 2004). Today, airplanes receive a rigorous set of lightning certification tests to verify the safety of their designs. Since then, aircraft have been made far more lightning-proof. (Howe, 1998).

With the emergence of high-speed wireless data transfer via geosynchronous and Low Earth Orbiting satellites and new VHF ground station networks, the FAA can finally fulfill its promise to provide airline pilots with graphical weather products directly into the cockpit (Gormley, 2002). Since December 2003, users receive more weather data in the cockpit to enhance situation awareness. Integrated terminal weather system (ITWS), provides near-term (0-30 minutes) prediction of lightning and other weather information in the terminal area (NAS Architecture Highlights, 2001).

Even the FAA's harshest critics don't believe that the agency knowingly waits for accidents to happen. But, because the FAA must justify changes that require expenditures by the aviation industry, the agency sometimes must use past accidents to help build its case. And once the agency decides to make safety-related changes, it can take years before new rules take effect because the agency must consider the effects on the airline industry. FAA is required by law to justify rules changes that cause financial burdens to government or private industry. Critics say that the FAA, in seeking changes in regulations, depends too heavily on accidents that have already occurred. The reason, they say, is that in an atmosphere of public outrage over a serious accident, it is easier to pass reforms through Congress. Before the FAA can act, the agency must calculate how a proposed safety rule will affect the aviation industry. The agency must consider everything from the public perceptions to the economic impact. Critics perceive that sometimes safety is secondary to economic concerns (Brazil, 1994).

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