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GLYNDŴR UNIVERSITY WREXHAM

EFFECTS & AVOIDANCE OF LIGHTNING STRIKES ON AICRAFT

by

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EFFECTS & AVOIDANCE OF LIGHTNING STRIKES ON AIRCRAFT

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ABSTRACT

The following report is based upon studying the effects of the lightning strikes on aircraft, attending to its direct and indirect effects.

To achieve this above, a number of key stages have been completed, including research and testing procedures, which then are taken into account for doing the project.

The research is about the effects, tests and standards and materials on aircraft, such as composite materials, which are really used nowadays for manufacturing aircrafts.

ACKNOWLEDGEMENTS

I would like to take this opportunity to pay my upmost gratitude to my supervisor, Cedric Belloc, for the constant help, knowledge and guidance throughout the duration of the project.

I would also like to thank Olivier Duriex, for lending me carbon fibre for doing the tests and give me information about composites.

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CHAPTER 1. INTRODUCTION

1.1 Background to Proposal

Weather conditions in a flight route are important since they involve passenger's safety. Thunderstorms are accompanied with lightning, squalls and sometimes, hail and tornadoes. Storms are an atmospheric phenomenon produced by cumulonimbus. They built up when the atmosphere is unstable. This occurs when the air is colder than usual in the highest part of the troposphere[1] (it happens when a cold front passes or in a low pressure situation).

Lightning is associated with thunderstorms. A light is a static electricity discharge generated in the cloud. The effects caused in the aircraft due to lightning are divided into direct and indirect effects:

- Direct effects: Any physical damage to the aircraft and/or electrical/electronic systems due to the direct attachment of the lightning channel. This includes tearing, bending, burning, vaporization or blasting of aircraft surfaces/structures and damage to electrical/electronic systems.
- Indirect effects: Voltage and/or current transients induced by lightning in aircraft electrical wiring which can produce upset and/or damage to component within electrical/electronic systems. [1]

Nowadays, storms and lightning strikes are observed thanks to a device that can detect them. This is based on radar systems. Weather radar system allows the pilot to identify the weather conditions attending o the colour showed on the display. The strikefinder is a recently developed device that, being used with a stormscope, it gives more accurate information about lightning strikes.

Besides, composite materials also help to avoid electrical discharges. They are based on fibres, meaning that stiffness and strength in all directions are not the same. These materials have advantages and disadvantages to take into account related to lightning strikes.

[1] **Troposphere**: It is the lower part of the atmosphere, extending from the surface up to a height varying about 7 to 9 km at polar regions to approximately 17 km in tropics. The troposphere is characterized by decreasing temperature with height, appreciable vertical wind motion, appreciable water vapor content, and weather. [2]

1.2 Aims

To research and investigate:

a) Lightning effects on aircraft and weather radar systems;
b) Design and testing of aircraft in order to avoid electrical discharges;
c) Lightning simulation.

1.3 Objectives

In order to achieve the aim, a set of objectives have been carried out as follows:

- To research atmospheric phenomena;
- To be familiar with the layers of the atmosphere;
- To do a research on thunderstorms;
- To investigate lightning;
- To be familiar with radar systems;
- To look information about weather radar system;
- To investigate Stormscope and Strikefinder;
- To study negative effects of electrical discharges on aircraft;
- To be familiar with electrical principles;
- To do a research of lightning testing standards;
- To study aircraft's design;
- To research on metallic and non-metallic materials;
- To study the advantages and disadvantages of composite materials;
- To be familiar with the simulation software.

1.4 Overview

Weather conditions in a flight route are important since they involve passenger’s safety. Thunderstorms are accompanied with lightning, squalls and sometimes, hail and tornadoes. Storms are an atmospheric phenomenon produced by cumulonimbus. They built up when the atmosphere is unstable. This occurs when the air is colder than usual in the highest part of the troposphere (it happens when a cold front passes or in a low pressure situation).

Losses in aviation due to lightning strikes are noticeable. The most dangerous moment for an aircraft is while taking off and landing. While doing any of these two actions, the aircraft is located under the thunderstorm that is the place in which occurs the majority of lightning. Since lightning from the clouds to the ground is the most common, the risk of being struck by lightning in this zone is higher. Besides, some zones of the aircraft are more prone to be struck. However, using non-metallic materials on the aircraft, the risk can be reduced.

1.5 Planning


Task/ Time
15/10/2009
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4/2/2010
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CHAPTER 2. WEATHER CONDITIONS FOR AIRCRAFT

2.1 Thunderstorms

The storms are atmospheric phenomena, produced by cumulonimbus. These clouds are developed when the atmosphere is unstable. This usually occurs when a cold front passes or in situations of low pressure [1].

Storms are developed according to the following process [2] (see Figure 2.1.1):

- Earth warming causes an ascending flow of air that gets colder progressively until it is condensed creating small cumulus.
- Unlike the good weather, the ascending air flow does not stop and the cloud grows vertically very fast.
- The cumulus keeps on growing vertically and it is becoming a storm cloud. Now, the electrical charges start to disorder in the cloud. The top of the cloud will be positive and the bottom will be negative. Inside the cloud, there are drops kept in suspension due to the air flow.
- The cumulus has become a cumulonimbus. It can be of 10km height and the temperature in its top can be around -20°C or -30°C.
- Now, the earth is colder and it starts raining.

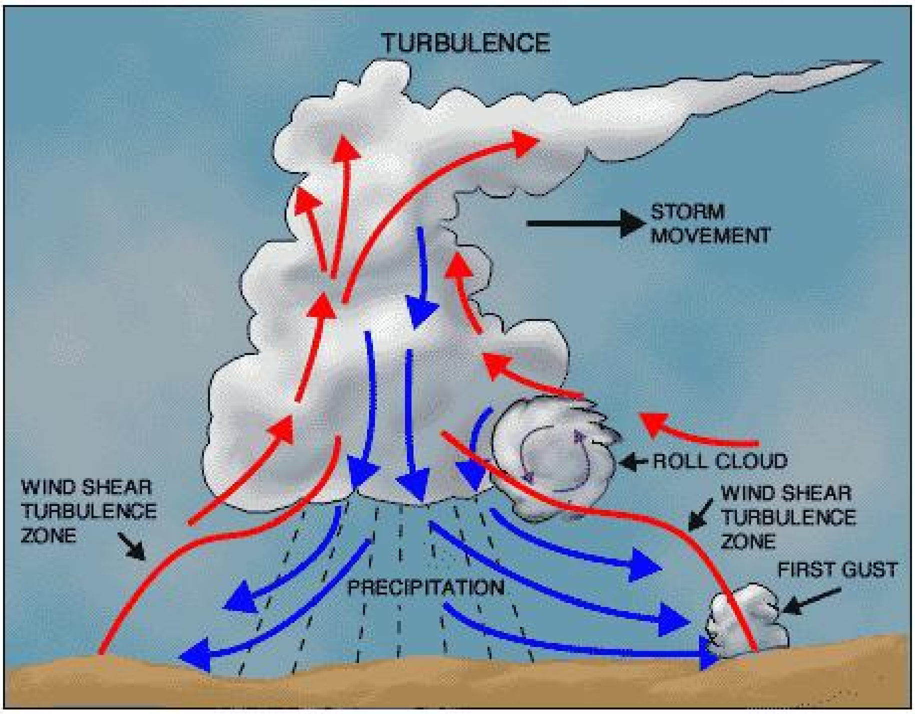

Figure 2.1.1 Process of the storm [3]

This process can be divided into three stages [4]: developing stage, mature stage and dissipating stage (See Figure 2.1.2, 2.2.3 and 2.1.4).

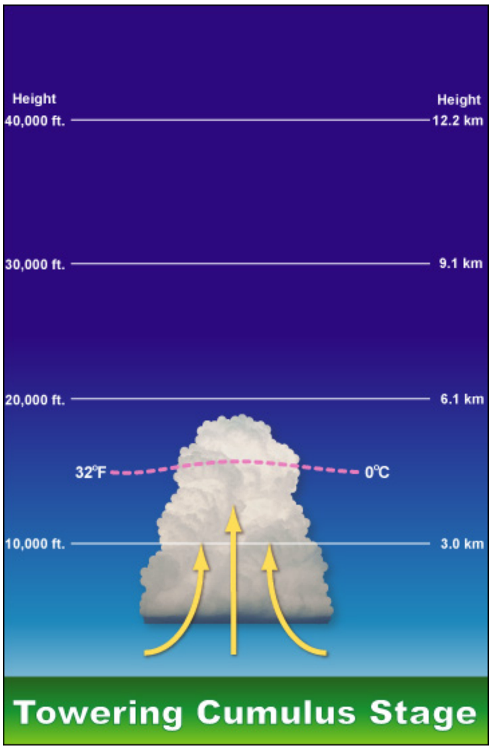

Figure 2.1.2 Developing stage [4]

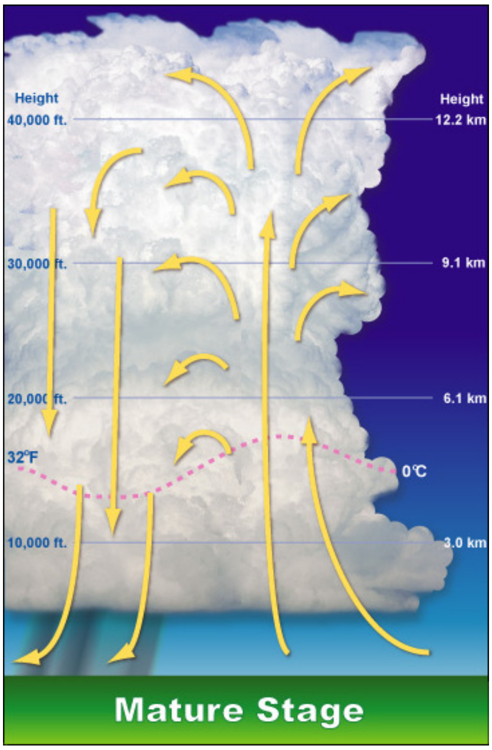

Figure 2.1.3 Mature stage [4]

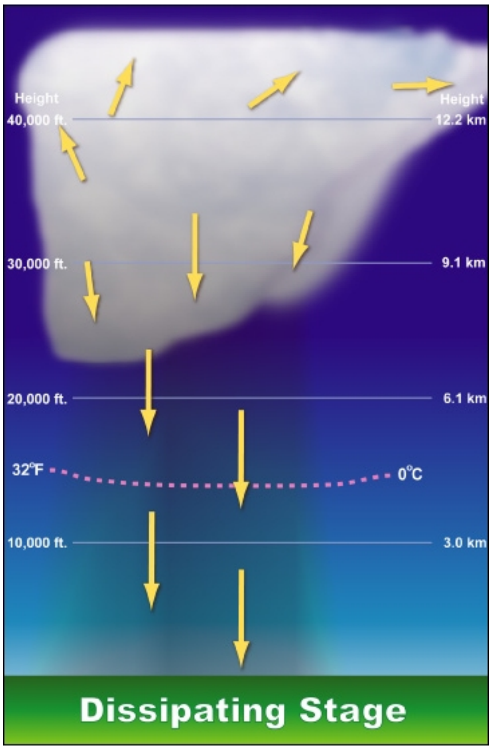

Figure 2.1.4 Dissipating stage [4]

Thunderstorms can be classified in four types [5] (see Figure 2.1.5):

- Single-cell;
- Isolated multicell cluster;
- Multicell squall line;
- Supercell.

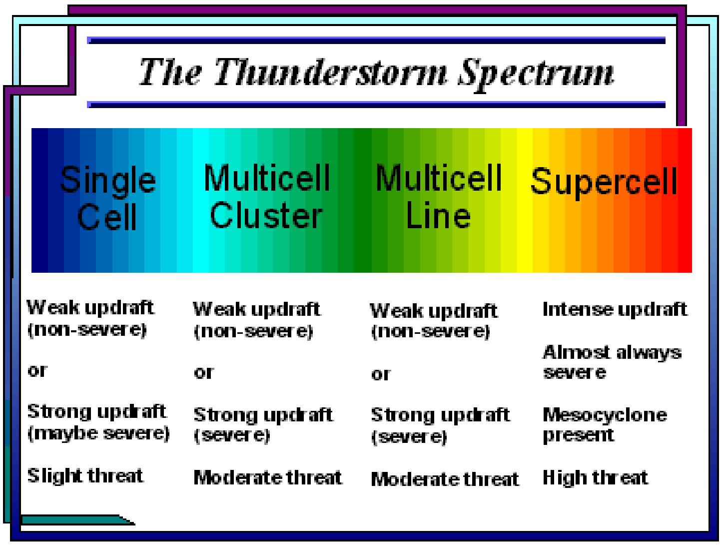

Figure 2.1.5 The thunderstorm spectrum [5]

2.1.1 Single-cell thunderstorm

The term of single-cell is applied to an isolated thunderstorm with one main draft (see Figure 2.1.1.1). They are more common during summer time and they also occur in winter when cold and unstable air follows the way of a cold front from the sea. “Cell” refers to single air draft. Single-cell thunderstorms are not longer last 20-30 minutes [6].

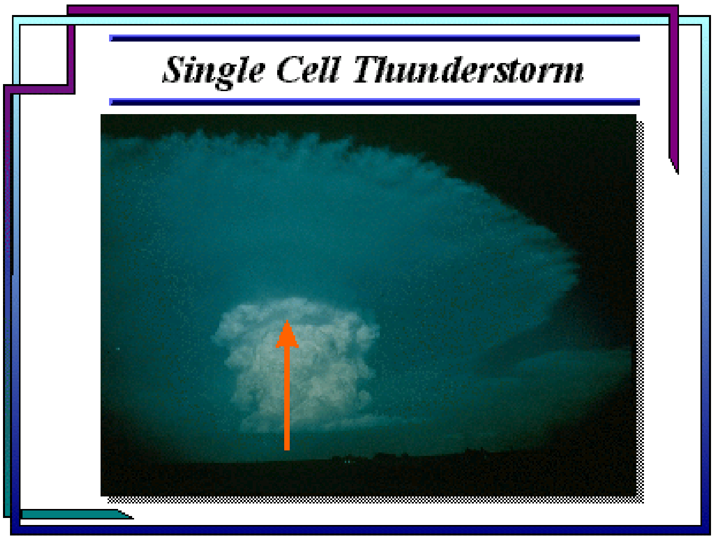

Figure 2.2.1.1 Single-Cell Thunderstorm [5]

2.1.2 Isolated multi-cell cluster thunderstorm

This type of thunderstorms is the most common. They consist of a group of cells that move as a single unit, but every cell is in a different stage of the lifecycle of the thunderstorm [7] (see Figure 2.1.2.1). The hazards of this type of thunderstorms are: hail (moderated size), flash flooding and weak tornadoes.

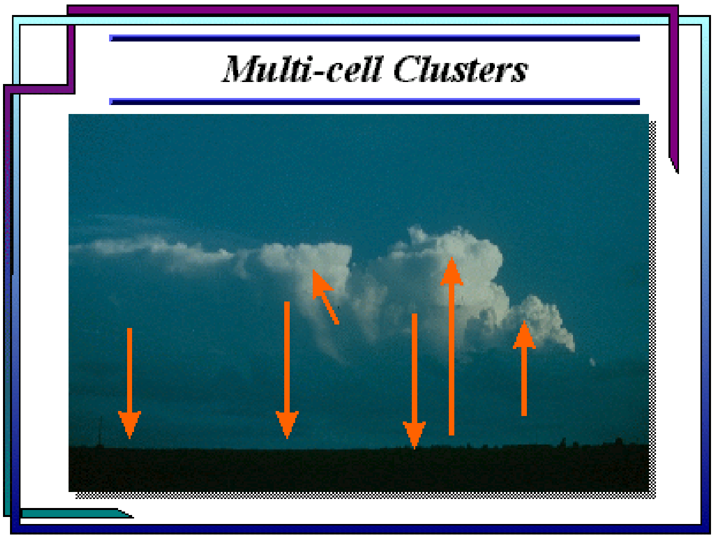

Figure 2.1.2.1 Multi-cell cluster thunderstorm [5]

2.1.3 Multi-cell squall line thunderstorm

The multicell line storm (see Figure 2.1.3.1), or squall line, consists of a long line of storms with a continuous well-developed gust front at the leading edge of the line. The line of storms can be solid, or there can be gaps and breaks in the line [7]. These storms can produce small to moderate size hail, heavy rainfall and weak tornadoes.

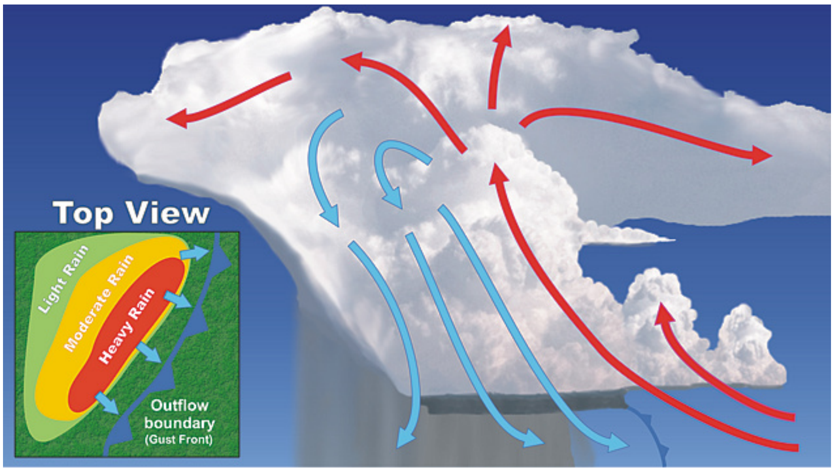

Figure 2.1.3.1 Multi-cell squall line thunderstorm [8]

2.1.4 Supercell thunderstorm

They are the strongest and longest lasting type of thunderstorms. The supercell thunderstorms (see Figure 2.1.4.1) can produce destructive tornadoes, extremely large hail, straight-line winds (80 mph, 130 km/h), floods and tornadoes [9].

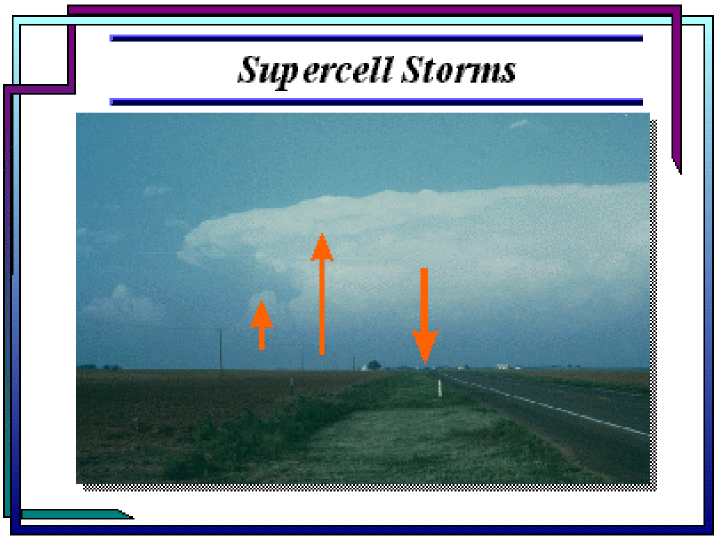

Figure 2.1.4.1 Supercell thunderstorms [5]

2.2 Lightning

2.2.1 Introduction

Lightning refers to a visible electrical discharge produced by thunderstorms. It is the result of the build up of electrostatic charge in clouds. Positive and negative charges separate (see Figure 2.2.1.1), negative usually towards the bottom of the cloud, while positive goes to the top. After a certain amount of time, the negative charge leaps, connecting with either another cloud or even the ground [10].

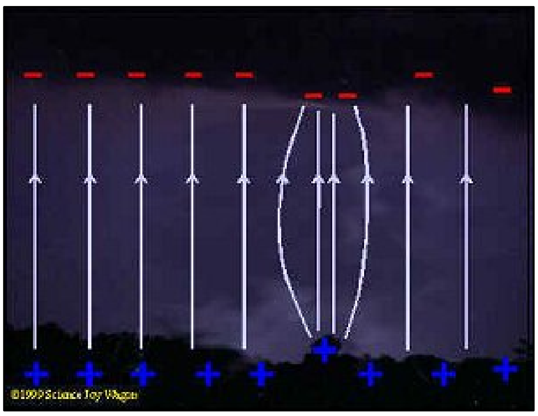

Figure 2.2.1.1 Charges in a cloud [10]

Relating to electric fields, the stronger the field, the more likely lightning is attracted to the ground. If field lines are closer together the field in that area is stronger and plausibility of a lightning strike is higher [10].

The primary forms of lightning discharges are cloud-to-ground (CG), cloud-to-cloud (CC), in-cloud (IC) and cloud-to-air (CA) [11] (see Figure 2.2.1.2). Lightning optical output is equivalent to some 100 million light bulbs going on and off.

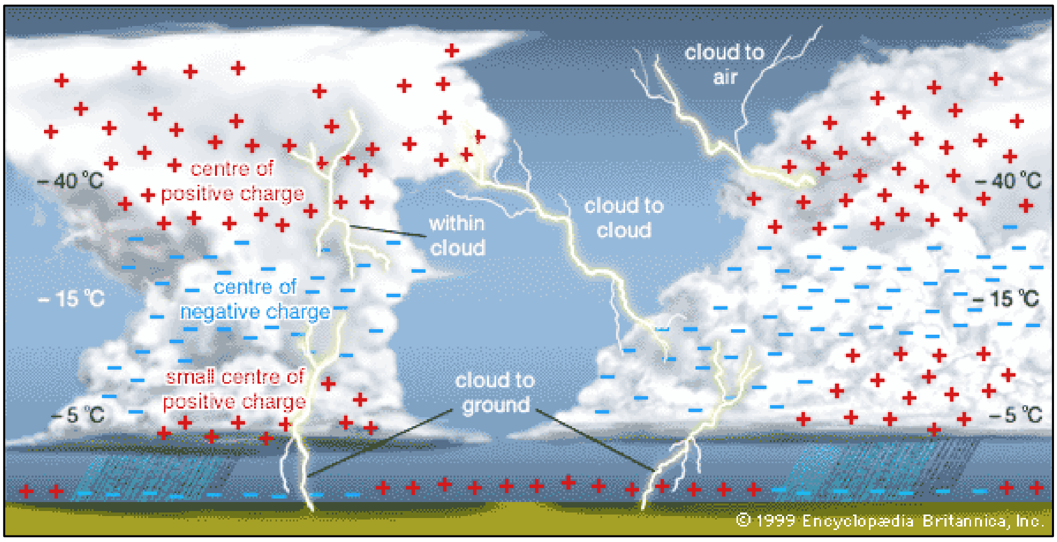

Figure 2.2.1.2 Types of Lightning [12]

2.2.2 Types of lightning

2.2.2.1 Cloud-to-ground lightning

This is the best known and second most common type of lightning. Of all the different types of lightning, it poses the greatest threat to life and property since it strikes the ground. Cloud-to-ground lightning (see Figure 2.2.2.1.1) is a lightning discharge between a cumulonimbus cloud and the ground. It is initiated by a leader stroke moving down from the cloud [13].

Figure 2.2.2.1.1 Cloud-to-ground lightning [14]

Bead lightning

Bead lightning (see Figure 2.2.2.1.2) appears to break up into a string of short, bright sections, which last longer than the usual discharge channel. It is relatively rare. Several theories have been proposed to explain it; one is that the observer sees portions of the lightning channel end on, and that these portions appear especially bright. Another is that, in bead lightning, the width of the lightning channel varies; as the lightning channel cools and fades, the wider sections cool more slowly and remain visible longer, appearing as a string of beads [15]. The whole phenomenon lasts about 0.2 to 0.5 seconds.

Figure 2.2.2.1.2 Bead Lightning [14]

Ribbon lightning

Ribbon lightning (see Figure 2.2.2.1.3) occurs in thunderstorms with high cross winds and multiple return strokes. The wind will blow each successive return stroke slightly to one side of the previous return stroke, causing a ribbon effect [13].

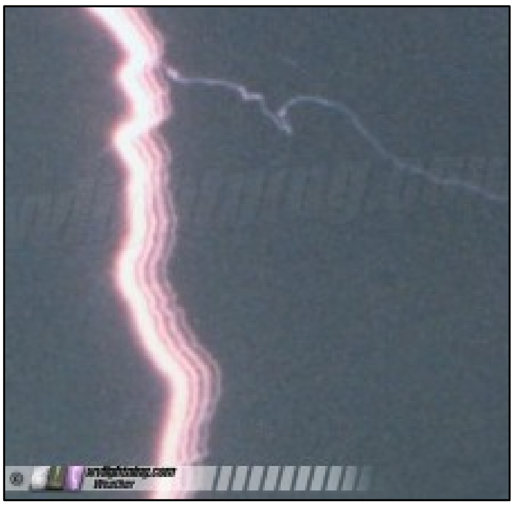

Figure 2.2.2.1.3 Ribbon Lightning [14]

Staccato lightning

Staccato lightning (see Figure 2.2.2.1.4) is a cloud to ground lightning strike which is a short-duration stroke that appears as a single very bright flash and often has considerable branching [15].

Figure 2.2.2.1.4 Staccato Lightning [16]

Forked lightning

Forked lightning (see Figure 2.2.2.1.5) is a name, not in formal usage, for cloud-to-ground lightning that exhibits branching called forked lightning [17].

Figure 2.2.2.1.5 Forked Lightning [18]

2.2.2.2 Ground-to-cloud lightning

Ground-to-cloud lightning (see Figure 2.2.2.2.1) is a lightning discharge between the ground and a cumulonimbus cloud initiated by an upward-moving leader stroke. It is much rarer than cloud-to-ground lightning. This type of lightning forms when negatively charged ions called the stepped leader rises up from the ground and meets the positively charged ions in a cumulonimbus cloud. Then the strike goes back to the ground as the return stroke [15].

Figure 2.2.2.2.1 Ground-to-cloud Lightning [14]

2.2.2.3 Cloud-to-cloud lightning

Lightning discharges may occur between areas of cloud without contacting the ground. When it occurs between two separate clouds it is known as inter-cloud lightning (see Figure 2.2.2.3.1) and when it occurs between areas of differing electric potential within a single cloud, it is known as intra-cloud lightning (see Figure 2.2.2.3.2). Intra-cloud lightning is the most frequently occurring type [13].

Figure 2.2.2.3.1 Inter-cloud Lightning [19]

Figure 2.2.2.3.2 Intra-cloud Lightning [20]

These are most common between the upper anvil portion and lower reaches of a given thunderstorm. This lightning can sometimes be observed at great distances at night as so-called "heat lightning". In such instances, the observer may see only a flash of light without hearing any thunder. The "heat" portion of the term is a folk association between locally experienced warmth and the distant lightning flashes [15].

Another terminology used for cloud-cloud or cloud-cloud-ground lightning is "Anvil Crawler", due to the habit of the charge typically originating from beneath or within the anvil and scrambling through the upper cloud layers of a thunderstorm, normally generating multiple branch strokes which are dramatic to witness. These are usually seen as a thunderstorm passes over the observer or begins to decay. The most vivid crawler behaviour occurs in well developed thunderstorms that feature extensive rear anvil shearing [16].

Sheet lightning

Sheet lightning (see Figure 2.2.2.3.3) is an informally applied name to cloud-to-cloud lightning that exhibits a diffuse brightening of the surface of a cloud caused by the actual discharge path being hidden [15].

Figure 2.2.2.3.3 Sheet Lightning [21]

Heat lightning

Heat lightning (see Figure 2.2.2.3.4) occurs too far away for the thunder to be heard. This occurs because the lightning occurs very far away and the sound waves dissipate before they reach the observer [16].

Figure 2.2.2.3.4 Heat Lightning [22]

2.2.2.4 Other different types of lightning

Dry lightning

Dry lightning (see Figure 2.2.2.4.1) is a term in the United States for lightning that occurs with no precipitation at the surface. This type of lightning is the most common natural cause of wildfires [9]. Pyrocumulus clouds produce lightning for the same reason that it is produced by cumulonimbus clouds. When the higher levels of the atmosphere are cooler, and the surface is warmed to extreme temperatures due to a wildfire, volcano, etc, convection will occur, and the convection produces lightning. Therefore, fire can beget dry lightning through the development of more dry thunderstorms which cause more fires [13].

Figure 2.2.2.4.1 Dry Lightning [23]

Rocket lightning

It is a form of cloud discharge, generally horizontal and at cloud base, with a luminous channel appearing to advance through the air with visually resolvable speed, often intermittently [13] (see Figure 2.2.2.4.2).

Figure 2.2.2.4.2 Rocket Lightning [24]

Positive lightning

Positive lightning (see Figure 2.2.2.4.3) is a type of lightning strike that comes from apparently clear or only slightly cloudy skies; they are also known as "bolts from the blue" because of this trait. Unlike the more common negative lightning, the positive charge is carried by the top of the clouds (generally anvil clouds) rather than the ground. The leader forms in the sky travelling horizontally for several miles before veering to down to meet the negatively charged streamer rising from below. Positive lightning makes up less than 5% of all lightning strikes. During a positive lightning strike, huge quantities of ELF and VLF radio waves are generated [15].

Positive lightning has also been shown to trigger the occurrence of upper atmosphere lightning. It tends to occur more frequently in winter storms, as with thundersnow, and at the end of a thunderstorm [16].

Figure 2.2.2.4.3 Positive Lightning [25]

Ball lightning

Ball lightning refers to reports of luminous, usually spherical objects which vary from pea-sized to several meters in diameter. It is sometimes associated with thunderstorms, but unlike lightning flashes, which last only a fraction of a second, ball lightning reportedly lasts many seconds.

One theory is that ball lightning may be created when lightning strikes silicon in soil, a phenomenon which has been duplicated in laboratory testing. Natural ball lightning appears infrequently and unpredictably [26].

Upper-atmospheric lightning [13]

The upper-atmospheric lightning has sometimes been called megalightning.

Sprites

Sprites are large scale electrical discharges which occur high above a thunderstorm cloud, or cumulonimbus, giving rise to a quite varied range of visual shapes. They are triggered by the discharges of positive lightning between the thundercloud and the ground. They often occur in clusters, lying 50 miles (80 km) to 90 miles (145 km) above the Earth's surface. (See Figure 2.2.2.4.4)

Blue jets

Blue jets differ from sprites in that they project from the top of the cumulonimbus above a thunderstorm, typically in a narrow cone, to the lowest levels of the ionosphere 25 miles (40 km) to 50 miles (80 km) above the earth. They are also brighter than sprites and, as implied by their name, are blue in colour. (See Figure 2.2.2.4.4)

Elves

Elves often appear as dim, flattened, expanding glows around 250 miles (402 km) in diameter that last for, typically, just one millisecond. They occur in the ionosphere 60 miles (97 km) above the ground over thunderstorms. (See Figure 2.2.2.4.4)

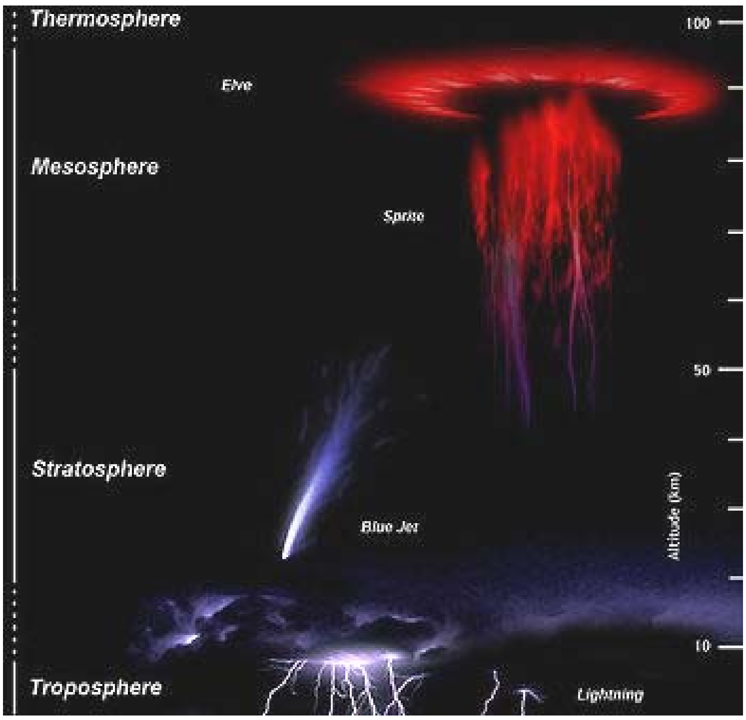

Figure 2.2.2.4.4 Upper-atmospheric lightning [13]

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CHAPTER 3. WEATHER RADAR SYSTEMS IN AIRCRAFT

3.1 Radar

RADAR is the acronym for **RA**dio **D**etection **A**nd **R**anging. Radar is a device that using electromagnetic waves can identify the position, altitude or speed of the object. In this particular case, the radar can identify the speed, altitude, direction and position of the aircraft [1].

Radar systems operate in an echo principle (see Figure 3.1.1): high energy radio waves in pulse form are directed in a beam toward a reflecting target. When the pulse strikes the target, a portion of the pulse is reflected back to the receiving section of the radar system [2].

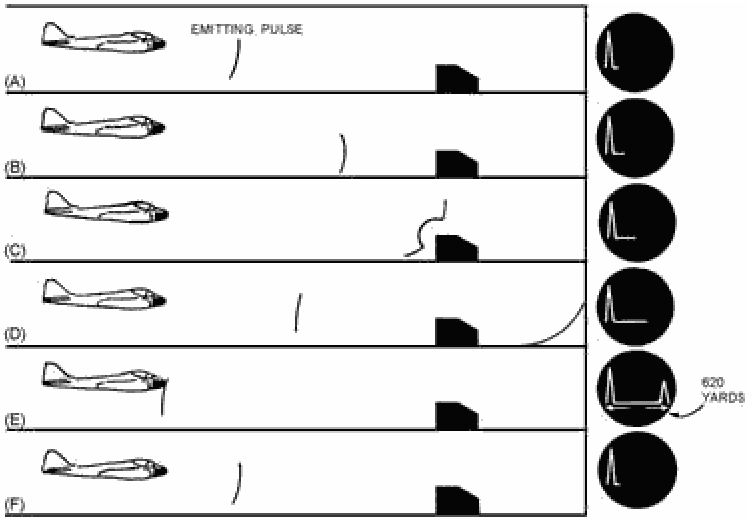

Figure 3.1.1 Pulse Radar System [3]

3.2 Weather radar

The weather radar system of an aircraft is called weather mapping system. This device can detect electrical activity caused by storm conditions. All the information is displayed on the CRT (cathode ray tube) or liquid display screen [4].

The weather mapping systems became as a substitute for the radar systems since the new ones were less expensive than the old ones. In many cases, they are used in conjunction [4].

The advantage of the weather mapping systems is that they can detect thunderstorm that are behind other storms. Thus, a weather mapping systems is like a secondary “back up” weather detection system [4].

Weather radar has several modes of operation:

- Standby mode
- On
- Weather / Nav
- EFIS
- Tilt
- Range select
- Target alert
- Weather alert

Colour is added to weather radar displays enhances the storm activity image and provides more effective means to detect severe weather (see Figure 3.2.1 and 3.2.2). The colour shows the intensity [4]:

- Black areas: indicate clear weather conditions.
- Green areas: indicate light clouds.
- Yellow areas: indicate increasing thickness of the weather condition.
- Red areas: indicate an extreme weather formation.
- Magenta areas: indicate an extreme weather condition (such as hail o thunderstorm) or terrain (cumulo granite, very solid weather)

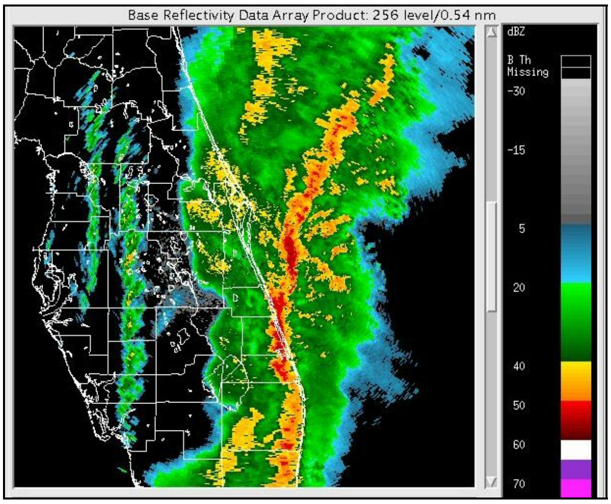

Figure 3.2.1 Weather radar display [5]

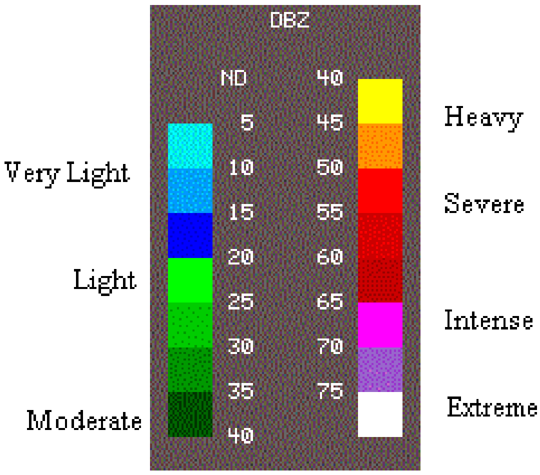

Figure 3.2.2 Intensity by colours [6]

Radar intensity is a way to "see" through rain. A pulse of energy is beamed through a cloud and the amount of *echo* returned will give the intensity of precipitation. The *echo* is actually a reflection of the energy and a computer will generate a colour code to indicate the amount of precipitation [6].

3.3 Stormscope

There is a device that can “see” lightning strikes due to the noise that they produce. Thanks to this, the pilot is able to avoid the hazards of the strikes, such us convective wind shear and turbulence. This device is called Stormscope (see Figure 3.3.1), and it is now produced by B. F. Goodrich Flight System. Stormscope comes in two basic types: the three-part WX-1000-series with a CRT display, and the WX-900, which features a less-expensive super-twist liquid crystal; display (LCD). The WX-900 has two parts with the processor unit collocated in the indicator box. [4]

3.4 Strikefinder

Strikefinder is a similar systems developed recently (see Figure 3.4.1). This device also has its processor incorporated within the display case. Its range is similar to that of the WX-100, but it is smaller and easy to install, with the prebuilt harness on which only one end must be terminated. Because of the strikefinder’s compact configuration it is less susceptible to noise interference. In fact, the strikefinder is virtually immune to onboard noise generators. The device is quite light thanks to its orange plasma display flat screen and self-contained processor [4]. It detects and analyzes the electrical activity emanating from thunderstorms within a 200 nautical mile (nm) radius of the aircraft [7].

Figure 3.3.1 Stormscope [8]

Figure 3.4.1 Strikefinder [8]

3.4 References

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CHAPTER 4. EFFECTS OF LIGHTNING STRIKES IN AIRCRAFT

4.1 Introduction

In the 1980s, it was demonstrated that most of the lightning strikes to airplanes (as many as 90%) are created by the planes themselves since they fly through clouds charged heavily (it means that they are prone to produce lightning). However, in the other 10%, airplanes fly into a lightning storm or intercept the lightning flash.

An idealised concept of aircraft lightning protection would be to have the entire exterior surface highly conductive and electrically continuous (All sides must be connected to each other and there can't be any large windows [1]).

4.1.1 Defining terms

Terms commonly used to describe lightning strikes are given below:

- Attachment point: A point of contact between the lightning flash and the aircraft. [2].
- Coupling: the electromagnetic phenomenon by which currents are induced in an object in a strong electric field [3].
- Corona: a luminous discharge caused by a difference in potential between the aircraft and the surrounding atmosphere [3].
- Lightning Flash: The total lightning event on which charge is transferred from one charge centre to another. It may occur within a cloud, between clouds, or between a cloud and ground. It can consist of or more strikes, plus intermediate or continuing currents [2].
- Lightning leader: The leader is the preliminary breakdown that forms an ionized path for charge to be channeled towards the opposite charge centre. The "stepped" leader advances in a series of short, luminous steps prior to the first return stroke. The "dart" leader reionized the return stroke path in one luminous step prior to each subsequent return stroke in the lightning flash [2].
- Lightning strike: Any attachment of the lightning flash to the aircraft [2].
- Lightning stroke (return stroke) – A lightning current surge that occurs when the lightning leader makes contact with the ground or another charge [2].
- Swept stroke: A series of successive attachments due to sweeping of the flash across the surface of the airplane by the motion of the airplane [2].

4.1.2 Measurements

When lightning strikes a plane, it may take more than a second before the extremely fast and interactive electromagnetic effects die away. Currents between 10,000 and 200,000 amperes may flow through the airplane's metal skin, setting up electromagnetic fields that may propagate into the airplane's interior through open apertures, diffusion, or other mechanisms [4] (see Table 4.1.2.1).

Table 4.1.2.1 radiated parameters of lightning strike [5]

Rate of change of Magnetic Field (dH/dt)	$\frac{1.6\times10^{10}}{R}$ $Am^{-1}s^{-1}$
Rate of change of Electric Field (dE/dt)	$\frac{6\times10^{12}}{\sqrt{1+\frac{R^2}{50^2}}}$ $Vm^{-1}s^{-1}$
Maximum Electric Field	$\frac{3\times10^{6}}{\sqrt{1+\frac{R^2}{50^2}}}$ Vm^{-1}
NOTE R is distance in m from strike and must be > 10m.	

<u>4.2 Categories of lightning</u>

Lightning can be divided into three different categories [6]:

a) Precipitation Static is the building up of charging on the aircraft by its passage through charged particles in the air. It is unlikely to cause damage to the aircraft but does interfere with radio, especially HF and ADF frequencies, and causes serious navigation and communication problems. It can be attenuated by fitting static dischargers on the aircraft wing tips and empennage.

b) St. Elmo's fire is the visible corona of static discharge when passing through densely charged conditions, and is a very clear indication that the local areas are intensely charged and lightning may occur.

c) Lightning strikes, these are caused either by discharge between highly charged cloud formations or between a cloud formation and the ground. The results in voltages and currents of an extremely high order passing through the structure and are capable of damaging component assemblies or destroying wiring and equipment if not adequately protected.

4.3 Zoning

The aircraft can be divided into three lightning zones as shown below (see Figure 4.3.1). These zones are defined as follows [2]:

- Zone 1: Surface of the vehicle for which there is a high probability of direct lightning flash attachment or exit
  - Zone 1A: Initial attachment point with low probability of flash hang-on, such a nose
  - Zone 1B: Initial attachment point with high probability of flash hang-on, such as tail cone.
- Zone 2: Surface of the vehicle across which there is a high probability of a lightning flash being swept by the airflow from Zone 1 point of direct flash attachments
  - Zone 2A: A swept-stroke zone with low probability of flash hang-on, such as a wing mid-span
  - Zone 2B: A swept-stroke zone with high probability of flash hang-on, such as a wing trailing edges
- Zone 3: Zone 3 includes all of the vehicle areas other than those covered by Zone 1 and Zone 2 regions. In Zone 3 there is a low probability of any direct attachment of the lightning flash arc, but Zone 3 areas may carry substantial amounts of electrical current by direct conduction between some pairs of direct or swept-stroke attachments points in other zones.

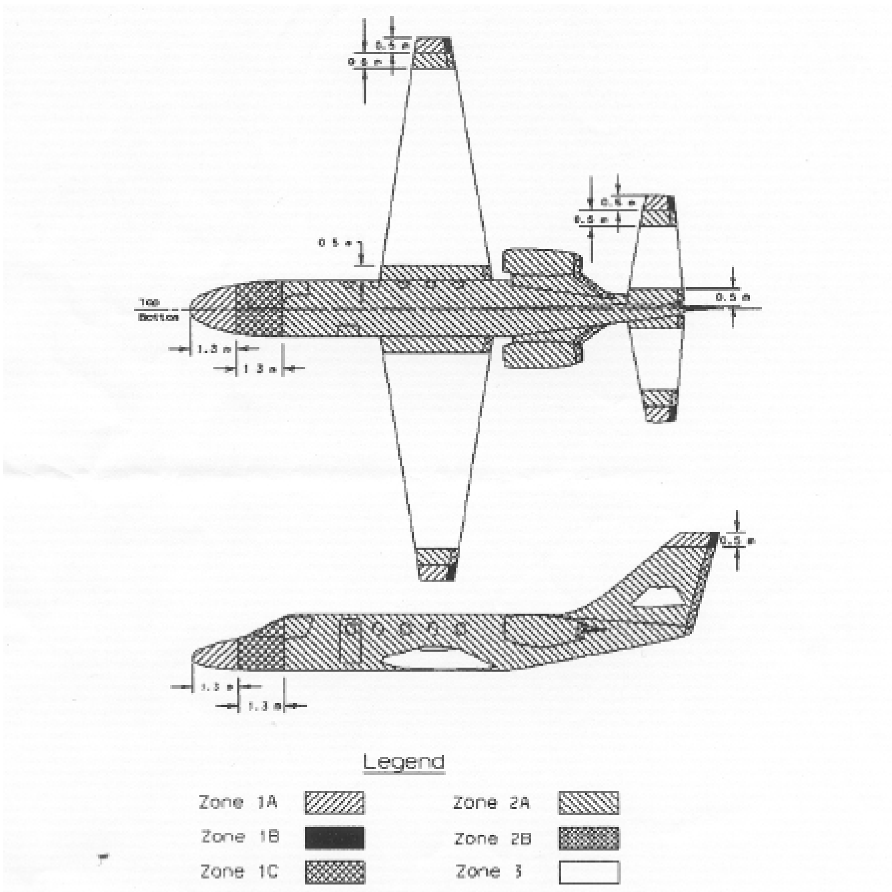

Figure 4.3.1 Aircraft Zoning [7]

Results of recorded data of several companies show the difference of strikes depending on the zone (see table 4.3.1).

Table 4.3.1 Zone distribution of lightning strike on various aircraft [7]

Company	Zone 1 (%)	Zone 2 (%)	Zone 3 (%)
Boeing Data	87	12	1
Airbus Data	66	34	0
Dassault Data	55	22	23
Fokker Data (jets)	53	41	6
McDonnell Douglas Data	69	27	4
Lightning Strike Database	77	20	3

4.4 Effects on aircraft due to lightning

The effects caused in the aircraft due to lightning are divided into direct and indirect effects:

- Direct effects: Any physical damage to the aircraft and/or electrical/electronic systems due to the direct attachment of the lightning channel. This includes tearing, bending, burning, vaporization or blasting of aircraft surfaces/structures and damage to electrical/electronic systems [2].

Some of these effects are melting of the aircraft skin, deformation due to pressure waves and magnetic forces, explosive vaporization of conductors, sparks in the fuel systems which can cause explosion and damage in externally mounted composite materials [8].

- Indirect effects: Voltage and/or current transients induced by lightning in aircraft electrical wiring which can produce upset and/or damage to component within electrical/electronic systems. [2]

Problems caused by indirect effects in cables and equipment are averted by carefully shielding, grounding and the application of surge suppression devices 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 accordance to the authority in the country f the aircraft's origin [9].

This is of increased importance nowadays for two reasons: one is the high dependence of modern aircraft on sophisticated electronic circuits to perform flight critical operations. These circuits operate at low voltage and current levels which makes them more sensitive to electromagnetic interference. Another reason is that the composite material used increasingly in modern aircraft, since they offer advantage in terms of mechanical strength and weight. However, these materials are poor conductor of electricity and do not offer as much shielding as the traditional metal structures [8].

4.5 Fatal accidents due to lightning strikes

Losses in aviation are less frequent nowadays than years ago. Here is a list of the losses in aviation from 1959 to 1988 [10].

1. **26.06.59 (ca. 17.35) Lockheed L-1649A Starliner**
   N7313C (1015) Trans World Airlines - TWA
   Occupants: 9 crew + 59 passengers = 68
   Fatalities: 9 crew + 59 passengers = 68.
   Accident Occurred: During Climb

Location: Milano; 20 mi NW (Italy)

Flight: Milano-Malpensa APT - Paris-Orly Flight.: 891

Source: ICAO Accident Digest Circular 62-AN/57 (132-152)

2. **12.08.63 (13.19 GMT) Vickers 708 Viscount**
   F-BGNV (39) Air Inter [year built: 1954]
   Occupants: 4 crew + 16 passengers
   Fatalities: 4 crew + 16 passengers
   3rd party fatalities: 1
   Accident Occurred: Initial Approach
   Location: Lyon; 24 km N (France)
   Flight: Lille - Lyon-Satolas APT Flight.: 2611
   Source: ICAO Accident Digest No.15 - Volume II, Circular 78- AN/66 (179-185)

3. **08.12.63 Boeing 707-121**
   N709PA (17588/3) Pan American World Airways [year built: 1958]
   Occupants: 8 crew + 73 passengers
   Fatalities: 8 crew + 73 passengers
   Accident Occurred: Initial Approach
   Location: Elkton, MD (USA)
   Flight: Washington-Baltimore IAP, DC - Philadelphia IAP Flight.: 214
   Total airframe flying hours: 14,609; cycles
   Comments: Inflight explosion of fuel tank due to lightning strike.
   Source: ICAO Accident Digest No.15 - Volume II, Circular 78- AN/66 (121-133)

4. **24.12.71 (12.36) Lockheed L-188A Electra**
   OB-R- 941 (1086) LANSA [year built: 1959]
   Occupants: 6 crew + 86 passengers
   Fatalities: 6 crew + 85 passengers
   Accident Occurred: Cruise
   Location: Puerto Inca (Peru)
   Flight Lima-Jorge Chavez IAP - Flight: 508
   Comments: About forty minutes after take-off, the aircraft entered a zone of strong turbulence and lightning. After flying for twenty minutes in this weather at FL210 lightning struck the aircraft, causing fire on the right wing which separated, along with part of the left wing. The aircraft crashed in flames into mountainous terrain. Structural failure occurred because of the loads imposed on the aircraft flying through a severe

thunderstorm, but also because of stresses resulting from the manoeuvre to level out the aircraft.

5. **09.05.76 (14.35 GMT) Boeing 747-131F**
   5-8104 (19677/73) Islamic Republic of Iran Air Force [year built: 1970]
   Occupants: 10 crew + 7 passengers
   Fatalities: 10 crew + 7 passengers
   Accident Occurred: Descent
   Location: Madrid; nr (Spain)
   Flight Tehran-Mehrabad IAP - Madrid-Torrejon AFB Flight.: 48
   Comments: The Boeing was operated on a military logistic flight from Tehran to McGuire AFB via Madrid. The flight took off from Tehran at 08.20h GMT and climbed to a cruising altitude of FL330. After establishing contact with Madrid control, clearance was received to CPL VOR via Castejon. At 14.25h the flight was cleared to FL100. At 14.30 the crew advised Madrid that they were diverting to the left because of thunderstorm activity, and at 14.32 Madrid cleared ULF48 to 5,000ft and directed him to contact Madrid approach control. At 14.33 the crew contacted approach control and advised them that there was too much weather activity ahead and requested to be vectored around it. Last radio contact was when ULF48 acknowledged the 260º heading instructions and informed Madrid that they were descending to 5,000ft. The aircraft was later found to have crashed in farmland at 3,000ft msl (mean sea level [11]) following left wing separation. It appeared that the aircraft had been struck by lightning, entering a forward part of the aircraft and exiting from a static discharger on the left wingtip. The lightning current's conductive path to the static discharger at the tip was through a bond strap along the trailing edge. Concentration of current at the riveted joint between this bond strap and a wing rib were sufficient conductive to cause the flash to reattach to this rivet and to leave the discharger. Fuel vapours in the no.1 fuel tank then ignited. The explosion caused the upper wing skin panel to separate, causing a drastic altering of the aeroelastic properties of the wing, and especially the outboard section of wing. The outer wing began to oscillate, developing loads which caused the high-frequency antenna and outer tip to separate. The whole wing failed a little later.
   Source: FI 15.5.76 (1283); NTSB-AAR-78-12

6. **05.09.80 Lockheed L-100-20 Hercules**
   KAF317 (4350) Kuwait Air Force
   Occupants: crew + passengers
   Fatalities: crew + passengers
   Location: Montelimar; nr (France)

Comments: Crashed after lightning strike.

Source: FI 03.01.1981 (29)

7. **08.02.88 (07.58) Swearingen SA.227AC Metro**

   D-CABB (AC-500) Nurnberger Flugdienst - NFD

   Occupants: 2 crew + 19 passengers

   Fatalities: 2 crew + 19 passengers

   Accident Occurred: Initial Approach

   Location: Mulheim; nr (Germany)

   Flight Hannover-Langenhagen APT - Dusseldorf Flight: 108

   Comments: The Metro aircraft suffered a lightning strike, following which the electrical system falied. The right wing broke off in an uncontrolled descent and the aircraft disintegrated.

8. **22.06.2000 Shitai, China** [12]

   Wuhan AL

   Struck by lightning causing the plane to explode and crash

9. **10/10/01 Off Valencia, Spain** [12]

   Flightline

   Electrical power was lost following a lightning strike.

10. **27/12/02 Anjouan, Comoros Islands** [12]

    Ocean Airlines

    Struck by lightning causing loss of artificial horizons and gyro compasses.

4.6 References

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CHAPTER 5. PROTECTION AND LIGHTNING TESTING

5.1 Faraday cage

A Faraday Cage is a shell made of an electrical conducting material. If there is a large electric field outside the conducting shell, the electric charges on the shell will move around and redistribute themselves until the electrical field inside the shell is zero (see Figure 5.1.1). Therefore, a Faraday Cage acts as a shield for large electric fields or for electromagnetic waves. It is an application of *Gauss's law*, one of *Maxwell's equations*. Gauss's law describes the distribution of electrical charge on a conducting form, such as a sphere, a plane, a torus, etc [1].

Even if a Faraday cage experiences the large electric field of a lightning strike, the electric field inside the Faraday cage will be zero. Hence a Faraday cage makes an effective shield against lightning strikes [2].

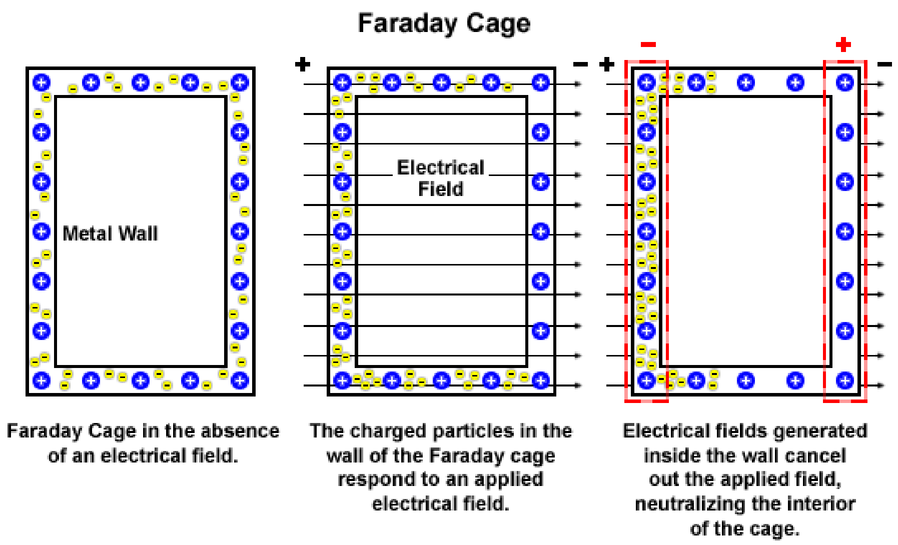

Figure 5.1.1 Principles of Faraday cages [3]

An aircraft with a fuselage that is made of aluminum or any other electrically conducting metal will form a Faraday cage around the pilots and passengers [2]. In aircraft, the fuselage is used as the common voltage ground and is referenced as 0volts. Then any circuits that need voltage take the voltage from the aircraft's generators referenced to the fuselage, regardless of the actual voltage of the fuselage above earth ground [4]. If the plane flies through an electrical storm and is struck by lightning, the electric field inside the hollow metal fuselage remains zero and the occupants are safe, as long as they are not in electrical contact with the exterior. For the electric field to be zero inside the Faraday cage, the electric charges must rearrange themselves on the surface. These moving charges on the outside of the Faraday cage can produce strong electric currents. Hence the occupants of the airplane should not be in electrical contact with the outside shell of the aircraft [2] (see Figure 5.1.2).

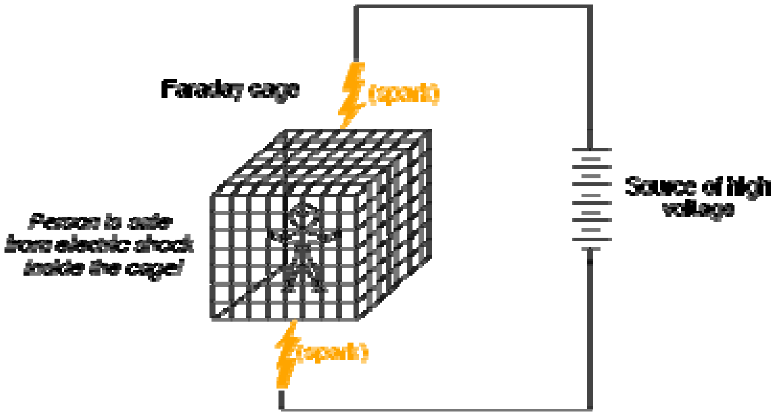

Figure 5.1.2 Faraday cage and passengers [5]

5.2 New techniques. Protection

The objectives of the lightning protection design direct effects are [6]:

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 vapours.

The regulations state that compliance can be shown by either bonding components (electrical connections among components sufficient to withstand lightning currents) to the airframe or by designing components so that a strike will not endanger the airframe.

The steps in protection design and certification may vary somewhat from one program to another, but most programs include the following basic steps [6]:

- Step a - Establish the Lightning Zone Locations
- Step b - Identify Systems and Components that are Performing Flight Critical or Essential Functions
- Step c - Establish Protection Criteria
- Step d - Design Protection
- Step e - Verify Protection Adequacy

When the aircraft fails due to lightning strikes, the failure condition can be divided into 3 categories (see Table 5.2.1) [7]:

Table 5.2.1 Lightning Failure conditions and certification Levels [7]

FAILURE CONDITION DEFINITION	FAILURE CONDITION	SYSTEM LIGHTNING CERTIFICATION LEVEL
Failure conditions that prevent continued safe flight and landing. The definition is: failure conditions that are expected to result in multiple fatalities of the occupants, or incapacitation or fatal injury to a flight crewmember normally with the loss of the airplane.	***Catastrophic***	**A**
Failure conditions that reduce the aircraft's or the crew's ability to cope with adverse operating conditions that would: • Greatly reduce safety margins or functional abilities; • Cause physical distress or larger workload that could prevent flight crew members from performing their tasks accurately or completely; or • Seriously injure a few occupants	***Hazardous / Severe-Major***	**B**
Failure conditions that reduce the aircraft's or the crew's ability to cope with adverse operating conditions that would, for example: • Significantly reduce safety margins or functional abilities; • Significantly increase crew workload or decrease crew efficiency; or • Cause discomfort to occupants, possibly including injuries.	***Major***	**C**

The protection can be divided into three different parts:

- Skin and surface protection
- Protection of radomes and antenna fairings
    - Solid bar diverters
    - Segmented diverters

- Protection of composites with conductive applications
    - Thermal sprayed metals
    - Woven wire fabrics
    - Solid metal foils
    - Expanded metal foils
    - Aluminized fibreglass
    - Conductive paints
    - Metalized fabrics
    - Interwoven wires [6]

5.2.1 Surface protection

5.2.1.1 Diverters

This protection consists of a segmented diverter strip which provides maximum multiple strike protection with negligible effect on RF patterns characteristics. Attached to an aircraft's radome (see Figure 5.2.1.1.1), the system allows a lightning stroke to travel directly to ground in an ionized channel created in the air above the diverter strip (see Figure 5.2.1.1.2). [8]

Figure 5.2.1.1.1 Diverter stripes on the nose [9]

Figure 5.2.1.1.2 Ionized channel above the diverter [9]

The small diameter of the disc segments (1/10 wavelength or less at X band[2]) makes the strip compatible with radar systems (see Figure 5.2.1.1.3)

[2] **X band**: is a segment of the microwave radio region of the electromagnetic spectrum. In some cases, such as in communication engineering, the frequency range of X-band is rather indefinitely set at approximately 7.0 to 11.2 gigahertz (GHz). In radar engineering, the frequency range is specified at 8.0 to 12.0 GHz. [10]

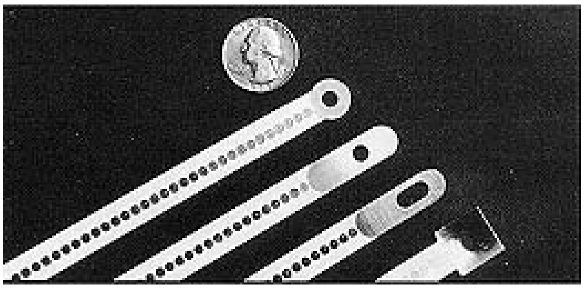

Figure 5.2.1.1.3 Lightning Diverter Stripes [8]

5.2.1.2 Static Wicks

Static wicks are small pieces of metal connected electrically to the frame of the airplane on the tail and wings (see Figures 5.2.1.2.1 and 5.2.1.2.2). The static charges that build up on an aircraft during flight tend to accumulate near sharp edges like the trailing edges of wings and tail surfaces. The purpose of static wicks is to provide a conductive path for these excess electrons to flow or "leak" from the aircraft back into the atmosphere. This transfer of electrons reduces the charge on the plane's skin and structure [11].

The wicks are composed of hundreds of individual carbon fibres wrapped into a cylinder around 7.6 to 20.3cm long and about the diameter of a soda straw. Each fibre ends in a sharp point to create a strong gradient in the local electrical field. This gradient attracts the static charge and encourages the electrons to flow off the aircraft and back into the atmosphere. Instead of an ionized corona building up on vital communication antennas, the electrical charges find these wicks more attractive [11].

Static discharge wicks also provide other important safety benefits. In the event of a lightning strike, a plane is designed to conduct the excess electricity through its skin and structure to the wicks to be safely discharged back into the atmosphere [11].

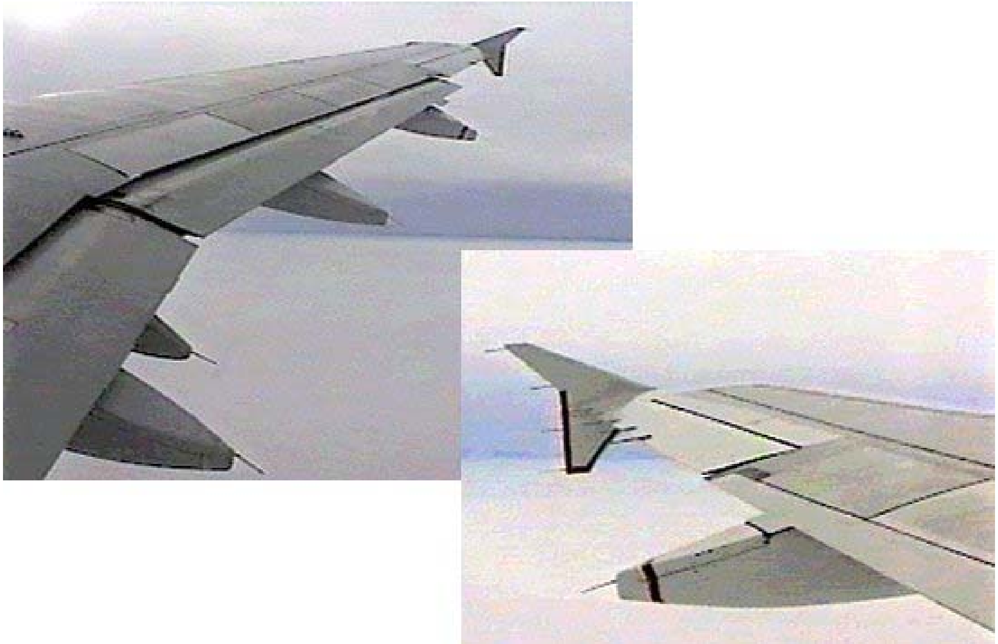

Figure 5.2.1.2.1 Static Wicks on Airbus A320 [11]

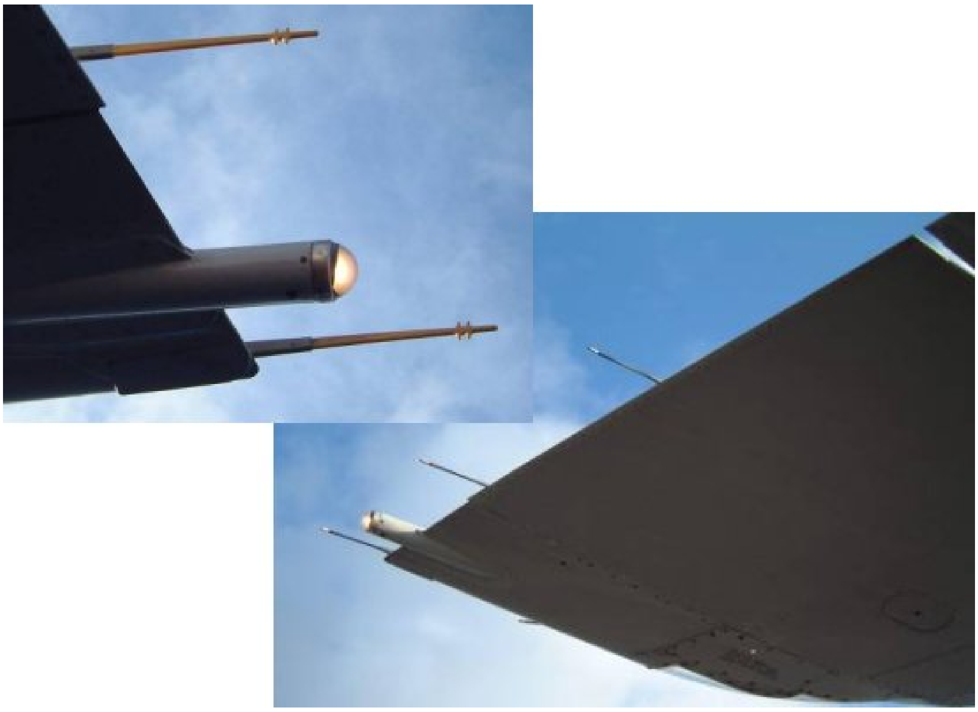

Figure 5.2.1.2.2 Static Wick on a Boeing 737 [11]

5.2.1.3 Wing tips

Wing must be protected since they are prone to be stricken by a lightning (see Figure 5.2.1.3.1).

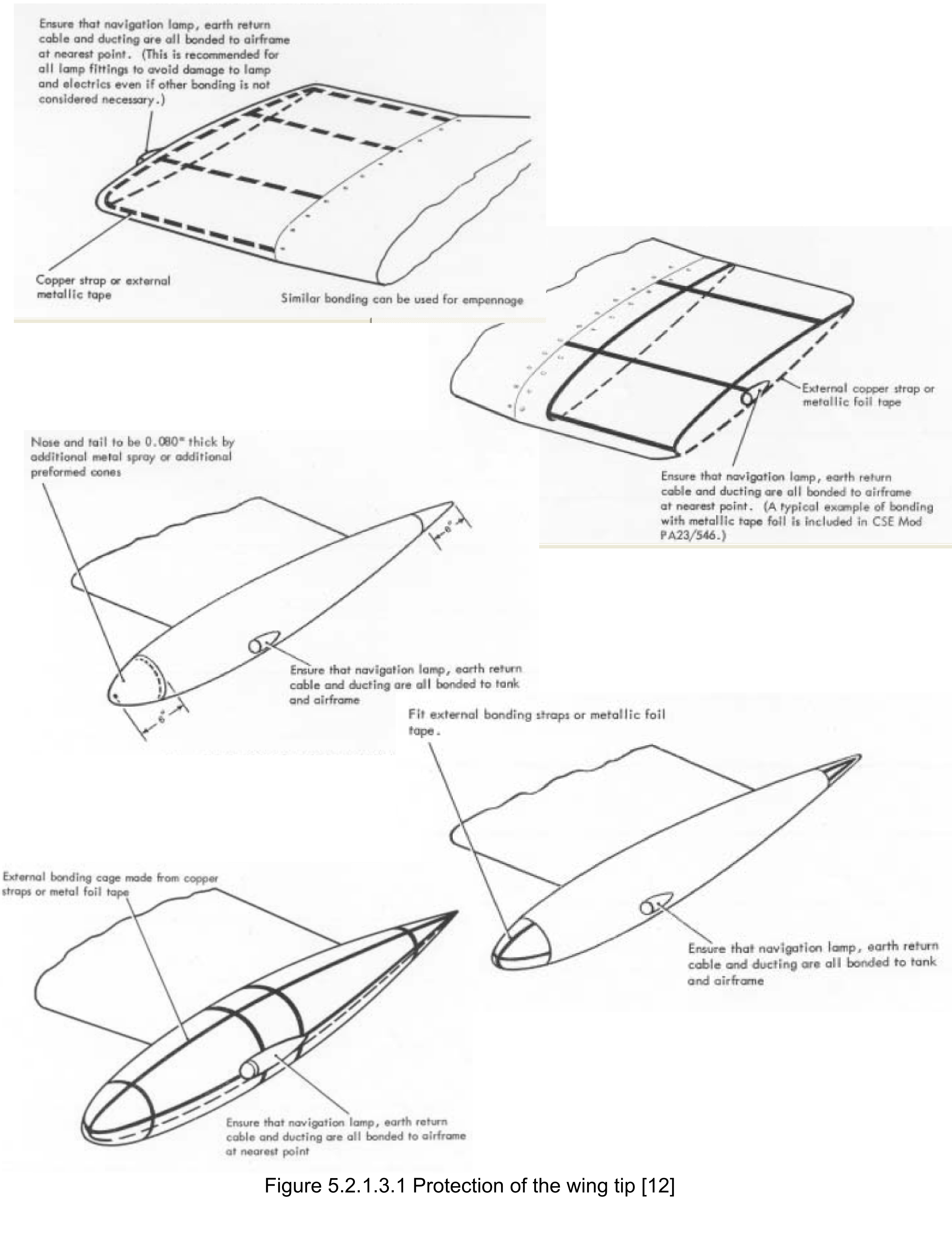

Figure 5.2.1.3.1 Protection of the wing tip [12]

5.2.1.4 Solid bars

Nose of aircrafts is one of the most important parts since it is the place where the antenna and radar (radome) are located (see Figure 5.2.1.4.1).

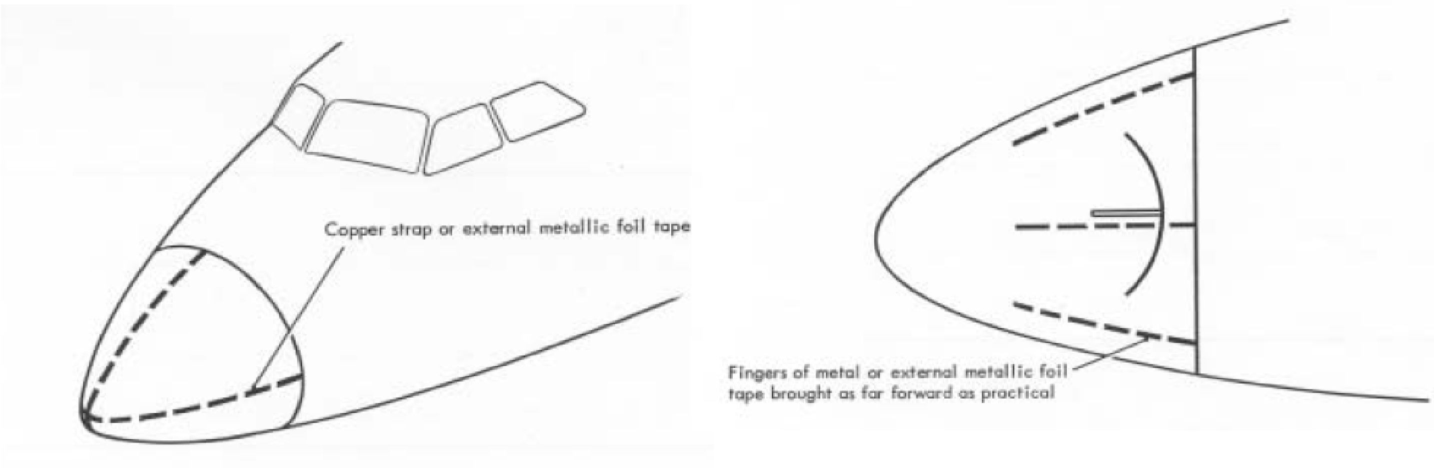

Figure 5.2.1.4.1 Protection of nose cone and radome [12]

5.2.2 Fuel tank

To ensure the protection of the tank (see Figures 5.2.2.1 and 5.2.2.2), some aspects have to be taken into account since even a tiny spark could be disastrous. Extreme precautions are taken to assure 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 withstand a burn through. All the structural joints and fasteners must be tightly designed to prevent sparks as 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 themselves, must be verified to be protected against lightning. In addition, new fuels that produce less explosive vapours are now widely used. [13]

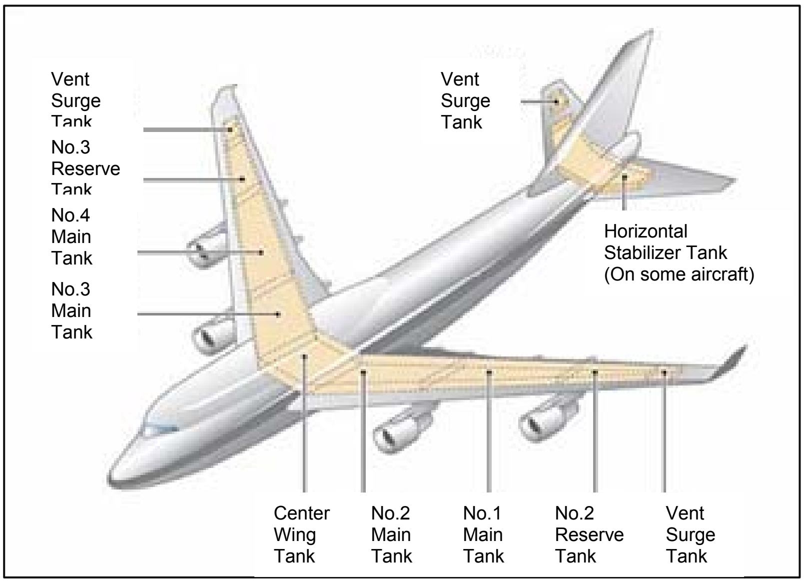

Figure 5.2.2.1 Fuel tank location in Boeing 747 [14]

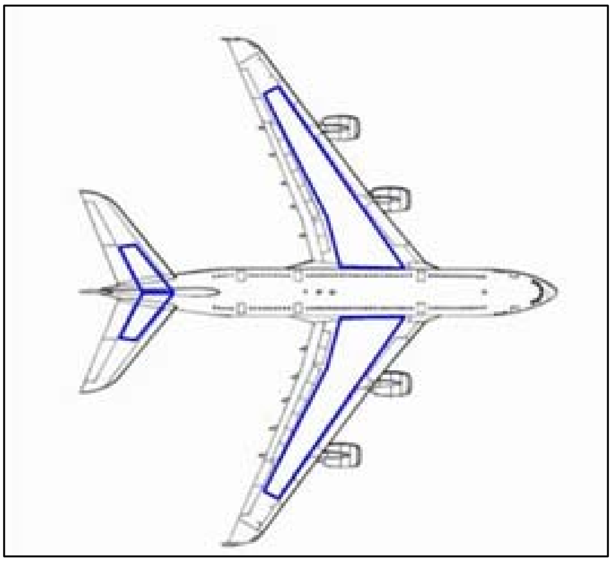

Figure 5.2.2.2 Fuel tank location in Airbus 380 [15]

Often the potential failure mode is at a fastened joint or other interface within a tank where only a portion of the total lightning current is to be expected (see Figure 5.2.2.3). A fastener in the fuel tank skin may be exposed to the full currents, but the current flowing through the fastener to internal structural elements is usually not the full current [16].

Analyses or tests of representative tank sections may be used to determine current magnitudes throughout a fuel tank due to lightning currents. This is especially important in composite tanks, where fasteners may transfer significant amounts of lightning current to interior structural elements. Internal structure currents are usually lower in tanks made completely of aluminum, and worst case assumptions might be made of these currents in place of more sophisticated analysis methods. In either type of tank, the currents that are expected to be conducted through each part of the design need to be defined so that they can be conducted through test [16].

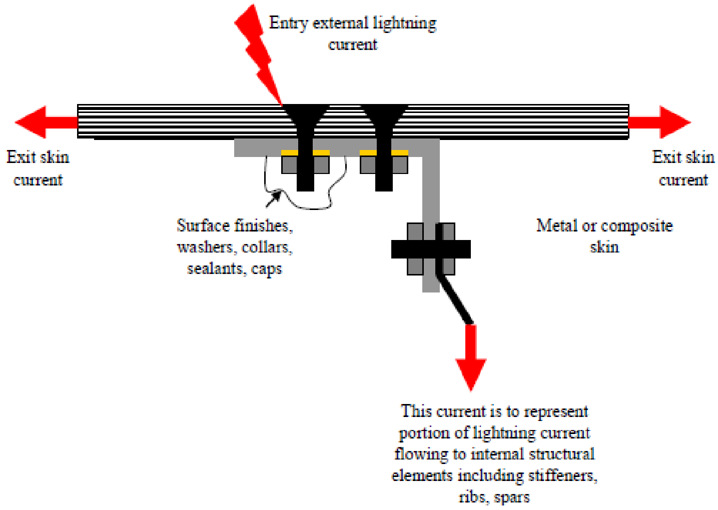

Figure 5.2.2.3 Test currents that need to be defined for assessments of failure conditions by test at external fastener installation [16]

5.3 Lightning tests

5.3.1 Visual Lightning Test Procedures

When an aircraft is hit by a lightning during flight, it has to be checked when landing (see Figures 5.3.1.1; 5.3.1.2; 5.3.1.3 and 5.3.1.4). Those procedures for checking depend on the company but, in all cases are quite similar (see Appendix B and C).

Figure 5.3.1.1 Lightning hit in fuselage 1 [17]

Figure 5.3.1.2 Lightning hit in fuselage 2 [17]

Figure 5.3.1.3 Lightning hit in nose 1 [18]

Figure 5.3.1.4 Lightning hit in nose 2 [19]

5.3.2 Indirect effects Lightning Tests

Several lightning tests are applicable to aircraft in relationship with the voltage and current (see Appendix D). These tests are governed by the standard DO-160.

5.4 Applicable standards

In order to avoid lightning strikes on aircrafts, these ones have to deal with some regulating law and standards (see Appendix E), to certificate that the different parts can work after a lightning strike.

5.5 References

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CHAPTER 6. AIRCRAFT DESIGN

6.1 Materials used on aircraft

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-fibre reinforced composites (CFC), sometimes referred to as graphite epoxy (GR/E) [1].

The non-conductive composites generally include fibreglass and aramid fibre 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 [1].

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 [1].

6.2 Aircraft components

Almost any airframe may be split into four main components [2]:

- The mainplane or wing;
- The fuselage or body;
- The tail unit (or foreplanes, for a canard-type aircraft);
- Mounting for all other systems (undercarriage, engines, etc.).

Each main component is designed to perform a specific task, so that the complete airframe can carry out the job which it was designed in a safe and efficient way.

All aircraft are made up of a great many individual parts, and each part has its own job to do. But even if it were possible to build an aircraft in one single piece, this would not be the best option. Some parts will become damaged, wear out or crack during service, and provision must be made for their repair or replacement. If a part begins to crack, it is imperative that the structure does not fail completely before it is found during maintenance inspection, or the safe operation of the aircraft may jeopardise [2].

The materials used in structural areas of airframe construction must have adequate strength with minimum weight, in other words, a high *strength-to-weight ratio* (SWR). This is not the only consideration, however. Stiffness of the material is often as important as its strength, and other factors need to be considered as well [3]:

- The material must be consistent and predictable in its properties, so that it can be known what behaviour to expect from it. All materials vary slightly in their basic properties, so it is normal to take the lowest or worst properties, plus an appropriate factor of safety, when using them in design. This gives a reasonable guarantee that the material properties will not be worse than the specified properties [3].
- It should ideally be homogeneous (having the same properties in all parts and in all directions), although the way a particular material is processed may mean this is not possible. Aluminium alloys are frequently rolled to produce plate and thin sheets, and this means the material properties may be different in different in different directions, but plate does not. Of the properties are affected in his way, the final properties must be predictable and the rolling direction clearly marked on the plate, to leave the material in a useful state [3].
- Metals must not suffer serious deterioration from corrosion caused by exposure to the weather, sea water or any chemicals that they come into contact with. The effect of stress is likely to accelerate the effects of corrosion. Similarly, non-metals should not be prone to significant degradation under these environments [4].
- It should be non-flammable or of low flammability (magnesium burns fiercely when exposed to fire, but needs very high temperature to ignite it). It should be present no other safety hazard, such as toxicity, in use, manufacture or repair [3].
- It should be readily available and at reasonable cost, and should be suitable for manufacturing using standard processes. Where a material's properties are particularly useful, new processes can sometimes be devised to make its use more practical.
- It should not be highly susceptible to *fatigue*, or must be used at stress levels low enough to ensure an acceptable life [3].
- It must have good stiffness for a given weight [4].
- It must retain adequate strength at the temperatures to which it will be subjected, particularly with materials used in supersonic aircraft, or certain regions of the aircraft [4].

So these requirements limit the types of materials used in airframes, but there are still many options available to the designer. Usually, the particular needs lead directly to one or a small group of materials, but new alloys and new ways of working can change the situation. The following groups of materials meet the requirements listed above, and are used for the main structure of an airframe [4]:

- Aluminium and magnesium alloys (light alloys);
- Steels;

- Titanium and titanium alloys;
- Nickel alloys;
- Plastics and composites.

6.2.1 Aluminium and magnesium alloys

Pure aluminium and pure magnesium are completely unsuitable as structural materials for airframes, because they have very low strength. However, when alloyed (chemically mixed) with each other metals, their strength is vastly improved, and they form the most widely used group of airframe materials. Alloying metals include zinc, copper, manganese, silicon and lithium, and may be used singly or in combination (see Table 6.2.1.1). There are very many different variations, each having different properties and so suited to different uses [5].

Magnesium alloys are very prone to attack by sea water, and their use in carrier-based aircraft is generally avoided. Aluminium alloys, although denser than magnesium alloys, are much less prone to chemical attack, and are cheaper, so are more widely used [5].

2024 Alloy

2024 alloy, known as *duralumin*, consist of 93.5% aluminium, 4.4% copper, 1.5% manganese and 0.6% magnesium, and is the most widely used of all materials in aircraft structures [5].

Aluminium alloys are more prone to corrosion than pure aluminium, so pure aluminium is often rolled onto the surfaces of its alloys to form a protective layer. The process is known as cladding, and sheets of alloy treated like this are known as *clad* sheets or *Al-clad*. Another common means of protecting aluminium alloys is *anodising* (conversion of the surface layer to a form which is more corrosion-resistant by and electro-chemical process) [5].

Aluminium-lithium alloys are superior to aluminium-zinc and aluminium-copper alloys in strength and stiffness so can be used to save weight. Their use is limited because they are around three times as expensive [5].

SPS alloys

An interesting property which certain aluminium alloys share with titanium is that they can be super-plastically formed (SPF). When the material is heated to a certain temperature, far below its melting point, is capable of being stretched by several times its own length without tearing or local thinning. It can then be deformed, using an inert gas such as argon, to fill a mould and take its shape exactly, with no spring-back when the pressure is released. There are various techniques based on this property, which can be used to make extremely complicated shapes accurately and with minimum weight. The high initial cost of tooling means SPF is limited to certain high-cost items, and it is not yet suited to mass production. Items such as pressure vessels, small tanks and reservoirs may be made using this technique [5].

Advantages of aluminium and magnesium alloys [5]

- High strength-to-weight ratios;
- A wide range of different alloys, to suit a range of different uses;
- Low density, so greater bulk form same weight means they can be used in a greater thickness than denser materials, and thus are less prone to local buckling; this applies to magnesium alloys even more than aluminium alloys;
- Available in many standard forms (sheet, plate, tube, bar, extrusions);
- Aluminium alloys are easy to work after simple heat treatment;
- Can be super-plastically formed (certain aluminium alloys only).

Disadvantages [5]

- Prone to corrosion, so need protective finishes, particularly magnesium alloys;
- Many alloys have limited strength, especially at elevated temperatures;
- Magnesium alloys have low strength (but high strength-to-weight ratio);
- No fatigue limit.

Table 6.2.1.1Details of aluminium alloys [4]

Alloy Designation	**Type/Composition**	**Application/Description**
1000 series	Min. 99.0% Al	Little use
2000 series	Al-Copper	Most common type in general use (good fatigue life and fracture toughness)
5000 series	Al- Magnesium	Low density, susceptible to corrosion
6000 series	Al-Magnesium-Silicon	Lower strength than 2000 series, weldable
7000 series	Al-Zinc	High strength, but poor fatigue performance
	Al-Lithium	Superior strength and stiffness to other Al alloys, lower density, superior fatigue performance: expensive

6.2.2 Steels

Steel is an alloy of pure iron and carbon (except in stainless steels), with a wide range of other materials. In addition to carbon, steels may contain chromium, nickel and titanium. Steels can be produced with a wide range of properties, ranging from extremely hard and brittle to very soft and *ductile* (able to be bent and stretched). Many steels are prone to corrosion, including those which have the highest strength. By excluding carbon from the composition, it is possible to produce stainless steel, which does not corrode easily. However, even stainless steels should not be considered totally corrosion-resistant.; they may corrode in certain circumstances. Other steels may be protected by plating with another metal, such as zinc or cadmium, although cadmium is used less in modern applications because it is toxic [4].

All steels share one property, they are dense. Steel finds most usage where its strength can be used to best advantage, for instance where space is limited, or where its hardness and toughness are needed. The most common use is in bolts, shafts and bearing surfaces. It has one more advantage: it performs much better at higher temperature than many other materials [4].

<u>Advantages of steel [4]</u>

- Cheap and readily available;
- Consistent strength;
- Wide range of properties available by suitable choice of alloys and heat treatment;
- High strength useful where space is limited;
- Some stainless steels are highly resistant to corrosion;
- High-tensile steels have SWR;
- Hard surface is resistant to wear;
- Suitable for use at higher temperatures than light alloys;
- Most steels easily joined by welding;
- Very good electrical and magnetic screening;
- Shows a fatigue limit.

<u>Disadvantages [4]</u>

- Poor strength-to-weight ratio except high tensile alloys;
- Dense, so care must be taken not to use very thin sections, or buckling may result;
- Most steels very prone to corrosion.

6.2.3 Titanium and its alloys

Titanium and its alloys were little used before the 1950s, but are becoming more widely used now, despite their high cost. Properties are very similar to steel, but they have a superior strength-to-weight ratio. They are widely used in engine component, such as jet pipes and compressor blades, and other components that are subject to high temperatures. Titanium and its alloys can be quite difficult to machine, and suffer from high degree of spring-back when formed. Many alloys need to be formed at high temperatures, typically over 500ºC. Like some aluminium alloys, titanium can be super-plastically formed, allowing very strong and light items, such as pressure vessels, to be made. Titanium also has another related property, that it can undergo diffusion bonding. At elevated temperature (but far below the melting point), two pieces of titanium forced together under high pressure will fuse and become a single piece. In some ways this is similar to forge welding, but the process takes place at lower temperatures. When combined with super-plastic forming, this allows even greater flexibility if design [4].

Advantages of titanium and its alloys [4]

- High strength-to-weight ratio;
- Maintains its strength at high temperatures;
- Higher melting point and lower thermal expansion than other materials;
- Can be super-plastically formed and diffusion bonded;
- Very high resistance to corrosion, especially from salt water.

Disadvantages [4]

- Expensive;
- Can be difficult to work, especially machining;
- Poor electrical and magnetic screening;
- Very hard scale forms on the surface at high temperatures.

6.2.4 Nickel alloys (Nimonics)

Nickel-based high-temperature alloys (known as nimonic alloys) are used where very high temperatures (up to 1000ºC) will be experienced. For this reason, they find considerable use inside gas-turbine engines, where temperatures are higher than the melting point of many metals. Nickel-based alloys are heavy and difficult to form, so their use is limited to areas where their properties are essential [4].

Advantage of nickel alloys [4]

- High strength, maintained up to very high temperature.

Disadvantages [4]

- Very dense;
- Difficult to work with.

6.2.5 Plastics and composites

Pure plastics have a little structural use, although it is increasing. However, widespread use is being made of composite structures in aircraft, that is, cloths or tapes of glass, carbon or Kevlar (a trade name for aramid) fibres within a thermosetting resin such as epoxy. Often these materials are made into boards or composite panels, which consist of a sandwich of, for example, carbon fibre/Kevlar honeycomb/carbon fibre. This makes a panel of limited strength, but which is extremely light, giving a strength-to-weight ratio far higher than a pure metal panel [4]. They are often used for making galleys and bulkheads inside aircraft passenger compartment, but are increasingly used for aircraft structures. Composite panel are not exclusively made from plastics and aluminium skins or honeycomb cores are commonly used, either together or with plastics (see Figure 6.2.5.1). Boron fibres are also used. He latest generation of fighter aircraft no emerging have up to 30% of the airframe structure made of composite materials [4].

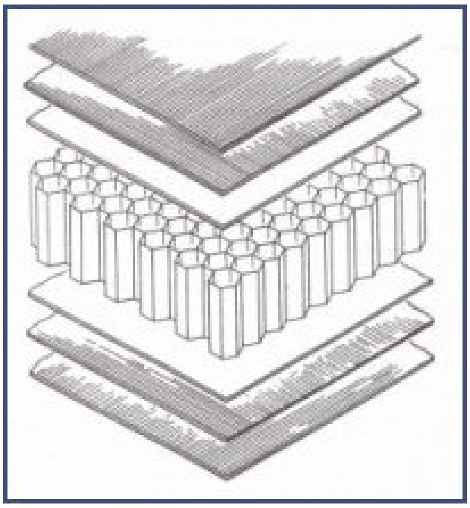

Figure 6.2.5.1 Honeycomb composite [6]

The fact that many composites are based on fires means that the strength and stiffness are not the same in all directions. This is not always a disadvantage since many structures are loaded primarily in one direction. By laying up the fibres mainly in that direction, the best use of the material's properties can be made. In this way, the structure can be tailored to its usage in the airframe [4].

Many plastic-based composites show lower tolerance of impact damage than metals (for instance from bird strikes) [libro]. Some composites can be quite difficult to repair safely. Kevlar, for example, absorbs water if damaged, which can make it difficult to make a satisfactory repair. In all cases, very carefully repairs are needed, usually requiring heater mats and vacuum pumps [7].

Another problem with the increasing use of composite, in leading edges for example, is that they do not provide electrical or magnetic shielding for cables. High voltages can be induced in the aircraft's electrical system (see Figure 6.2.5.2), which may cause it to fail, if the aircraft is operating close to strong electromagnetic fields. If the aircraft structure cannot provide enough protection, extra shielding is needed, which adds weight, costs and complexity [4].

However, with all these reservations, composites used carefully can produce great weight savings, and aircraft contain increasing amounts of composite structures [4].

<u>Advantages of composites</u> [4]

- Very high strength-to-weight ratio and low weigh (varies between materials);
- Non-corrodible (but some materials absorb water if damaged);
- Easily available in a wide range of forms;
- Can make complex shapes easily;
- Directional nature of fibres can be used to produce optimum strength in direction of highest loading;
- Low resistance to radar and radio signals is ideal for radomes and antenna covers.

<u>Disadvantages</u> [4]

- Need special manufacturing, inspection and repair methods;
- Some materials prone to impact damage;
- Strength and stiffness not the same in all directions;
- Poor electrical screening.

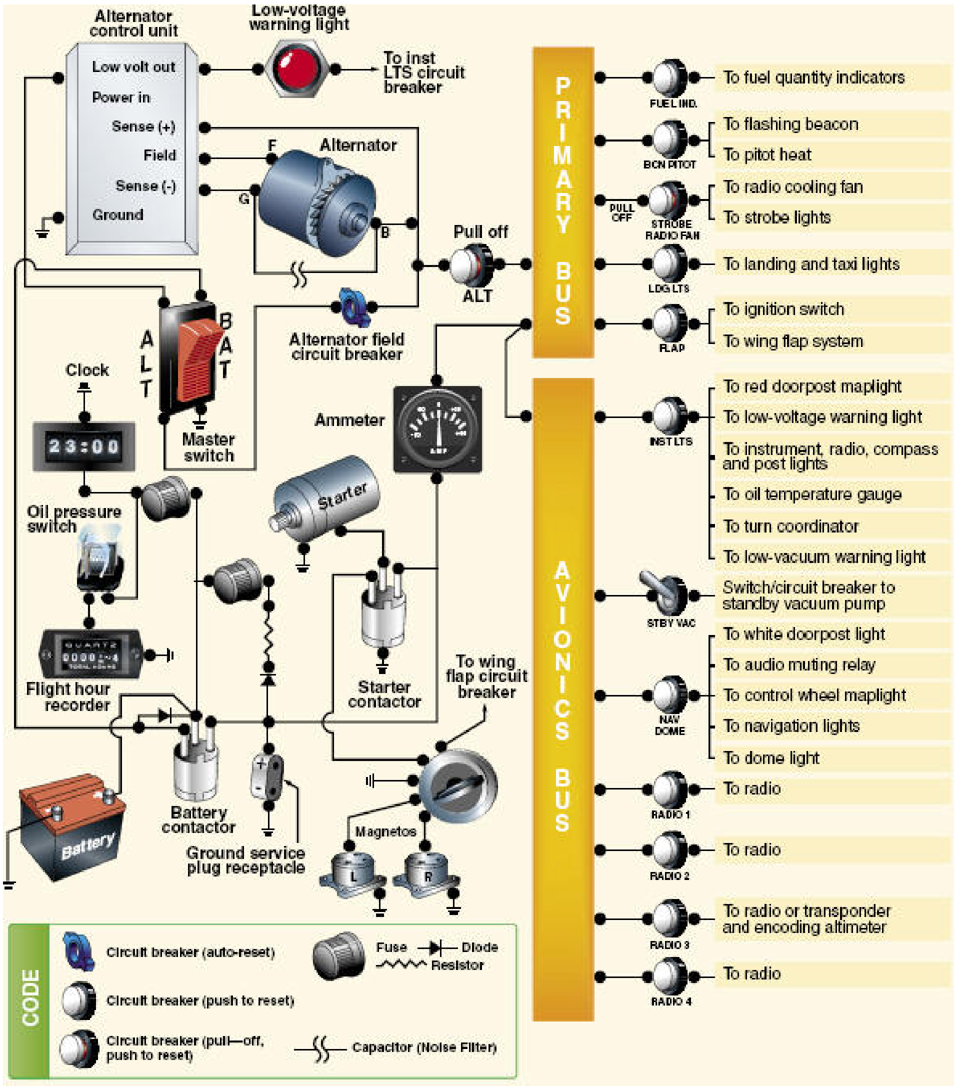

Figure 6.2.5.2 Aircraft electrical system SCAN [8]

6.2.6 Glass

The majority of modern aircraft have cabins pressurized for flight at high altitudes. Windscreens and windows are therefore subjected to loads normal to their midplanes. Glass is frequently the material employed for this purpose in the form of plain laminated plate or heat-strengthened plate. The types of plate glass used in aircraft have a modulus of elasticity between 70,000 and 75,000N/mm^2 with a modulus of rupture in bending of 45N/mm^2 [9].

6.3 Composites on aircraft

6.3.1 Structure of composites

Composites consist of two or more materials combined to give a material with properties distinct from the original constituents. They may be naturally occurring, or they may be synthetic.

A very significant proportion of polymers are used as composites.

Composites can be designed to produce a material with desired combinations of properties such as stiffness, strength and density.

Composites consist of a *matrix material* and a *reinforcing material*. The matrix and reinforcing materials may be metals, ceramics or polymers, but the composites used in airframe components are fibre reinforced polymer (FRP) matrix composites [10].

Airframe composites also have a relatively high cost, do not yield plastically in regions of high stress concentration and are subject to random property variation due to the nature of composite manufacturing processes [10].

The use of advanced composites in airframe construction has increased substantially over the past few decades. They are used as floor beams, doors, aerodynamic fairings and for control surfaces, such as rudders, elevators and ailerons, due to their low weight and high stiffness. [10]

Reinforced material fibres [10]

Reinforcing materials for polymer matrix composites are often referred to as fibres and they include (in order of increasing cost):

- E-glass;
- Aramid, e.g. Kevlar (see Figure 6.3.1.1);
- Carbon;
- Alumina;
- Silicon carbide;
- Boron.

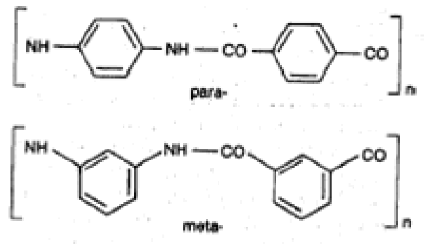

Figure 6.3.1.1 Structure of aramid (Kevlar) [10]

These fibre materials all have high specific strength and stiffness imparting high strength and stiffness to the composite (see Figure 6.3.1.2).

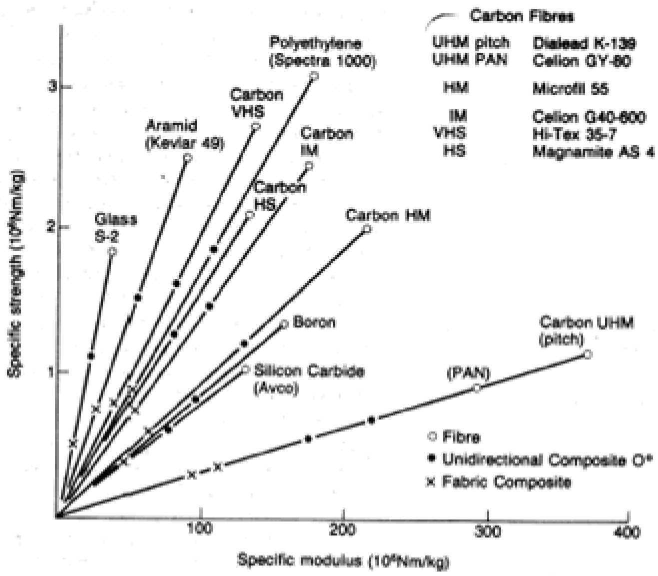

Figure 6.3.1.2 Properties of common reinforcing fibres.[10]

The matrix [10]

The purpose of the matrix in a polymer composite is to:

- Support the reinforcing fibres in the required position;
- Transfer load between the fibres;
- Increase the toughness of the composite;
- Protect the fibres from damage.

While the longitudinal tensile properties are dominated by the fibres, the properties of shear, compression and transverse tension are dominated by the matrix properties.

Matrix polymers can be thermoplastics or thermosets. Thermoplastics are fully polymerised materials that are solid at room temperature but may be melted and shaped at higher temperatures (100-300°C).

Thermosetting resins consist of a base resin and a catalyst (curing) agent. When the resin and catalyst are mixed together they react to form a heavily cross-linked solid resin that cannot be reshaped once set.

6.3.2 Evolution from aluminium to composites on Airbus

During the past two decades, the aviation sector has incorporated composite materials (or composites) to the design and construction. Using these materials, the carrying capacity, the flight range and scope of the aircraft have increased; while the fuel consumption and the gaseous emissions have being reduced (and therefore greenhouse gases as NO_X, CO_2, SO_2 and CO) [11].

The transition to the composite is due to an increase in physical and behavioural knowledge of aviation industry about these materials (see Figure 6.3.2.1).

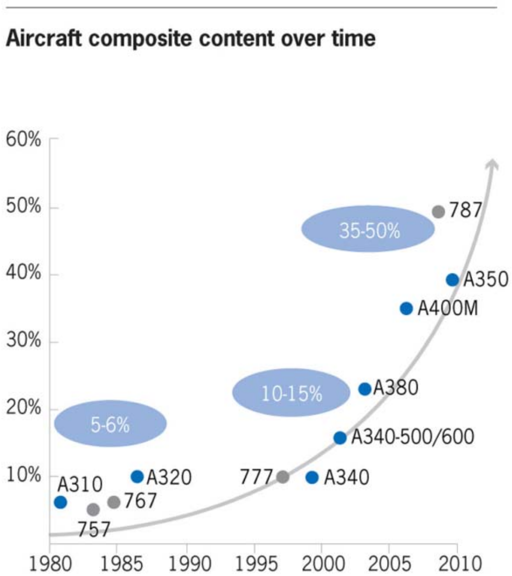

Figure 6.3.2.1 Evolution in use of composites for Boeing and Airbus [12]

Ferrous items (such as steel and aluminium) have properties that were widely known in the 70s, the composites were just appearing. Companies were researching and obtaining results in laboratories about composites while improvements in metallic materials were used for new aircraft, but in the 80s Airbus started pushing for development and incorporation of composite parts in its aircrafts [11].

<u>Evolution of metallic materials in Airbus</u> [11]

Metallic materials have been an evolution in the use of aluminium alloys, as well as lithium and titanium alloys, and there have been several improvements in production systems and machining.

Evolution of the A320 consists mainly on the addition of cast high strength aluminium, aluminium alloy 7150 to the wing, aluminium alloys 6013 and 6056 (A318) and new welding techniques. In the A330/A340 program, some important advances occurred related to high speed machining. Aluminium alloys 71551 and 2x24 started to be used, as well as aluminium alloy extrusions 7349.

The evolution of the A380 is more focused on incorporating biphasic elements such as lithium aluminium alloys, new titanium alloys and aluminium alloys and 7055HF 2024HCT.

<u>Composite material models in Airbus</u> [11]

Airbus models have evolved in terms of the amount of composite incorporated in its design. The model A300 (1972) incorporates a 5% composite (see Figure 6.3.2.2).

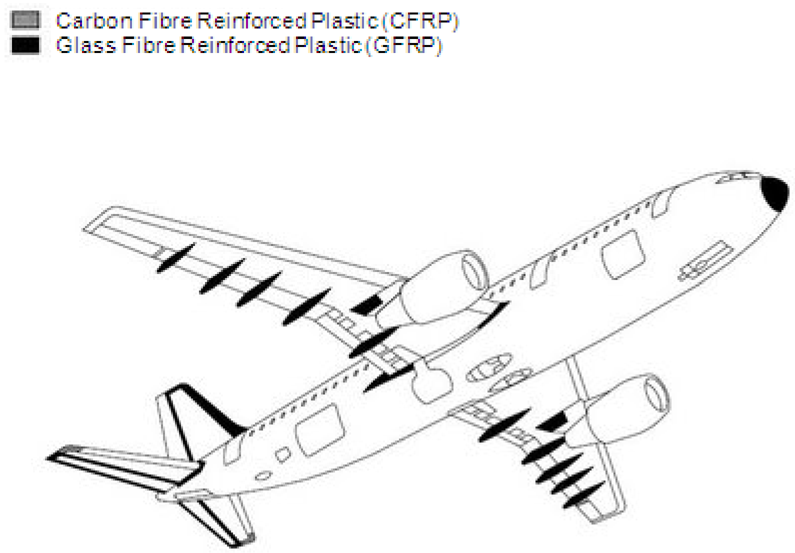

Figure 6.3.2.2 Airbus A300 [11]

The next evolution is the A310 (1982), which incorporates a 6% composite (see Figure 6.3.2.3).

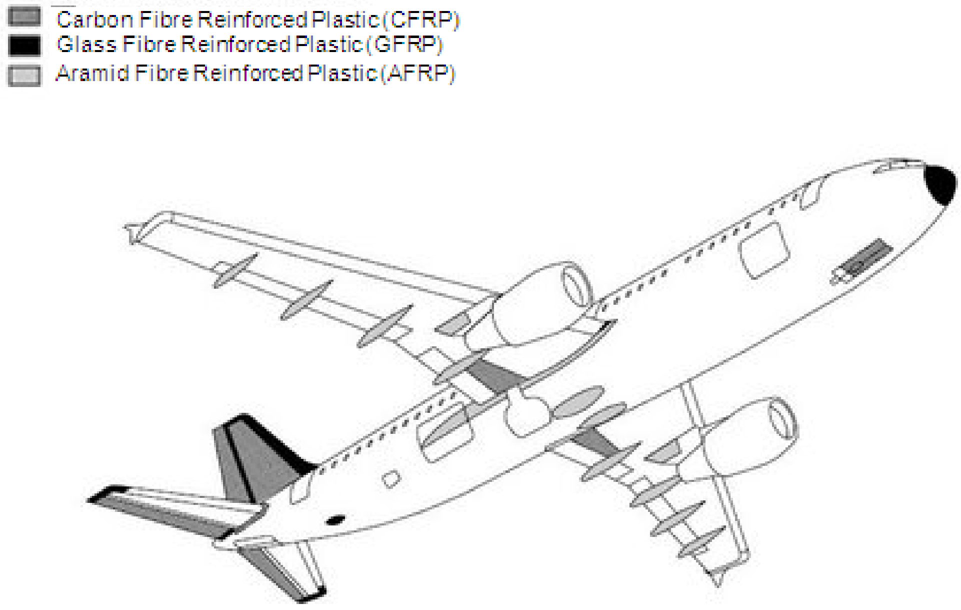

Figure 6.3.2.3 Airbus A310 [11]

The A320 (1987) is designed with an amount of 10% by weight of composite (see Figure 6.3.2.4).

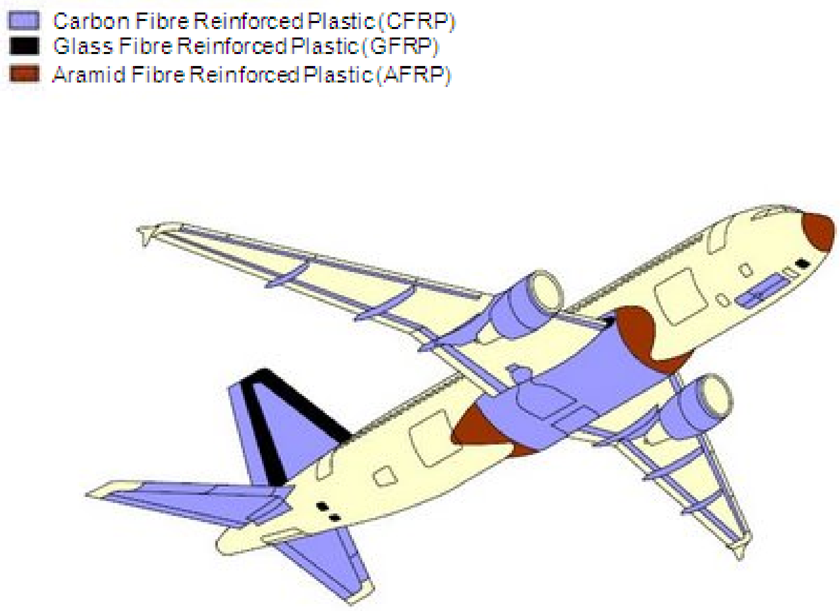

Figure 6.3.2.4 Airbus A320 [11]

A330 and A340 models (1992 to 2002) increased the amount of composite minimally, to 12% by weight (see Figure 6.3.2.5).

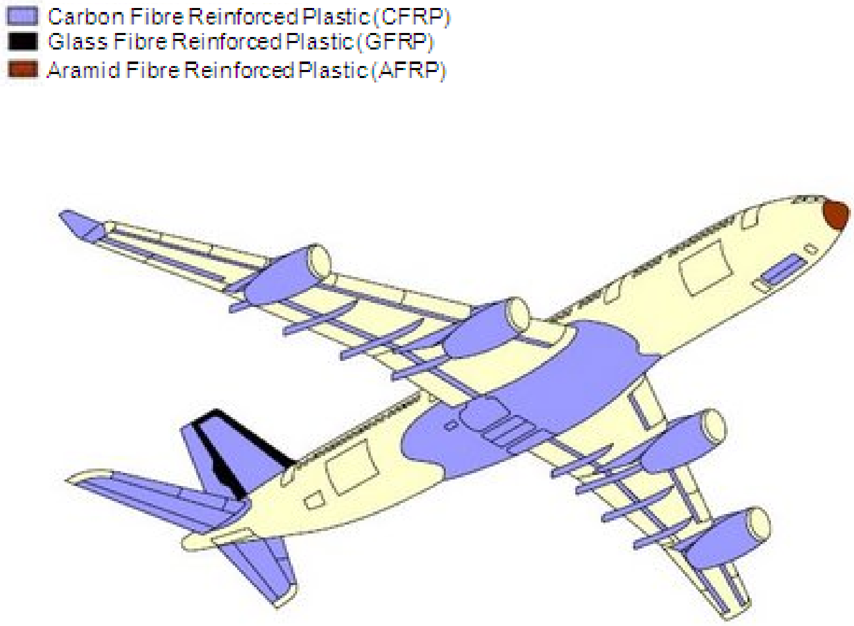

Figure 6.3.2.5 Airbus A340 [11]

The A380 has led the revolution in the composite, incorporating parts of the fuselage of glare. The amount by weight is 25% (see Figure 6.3.2.6).

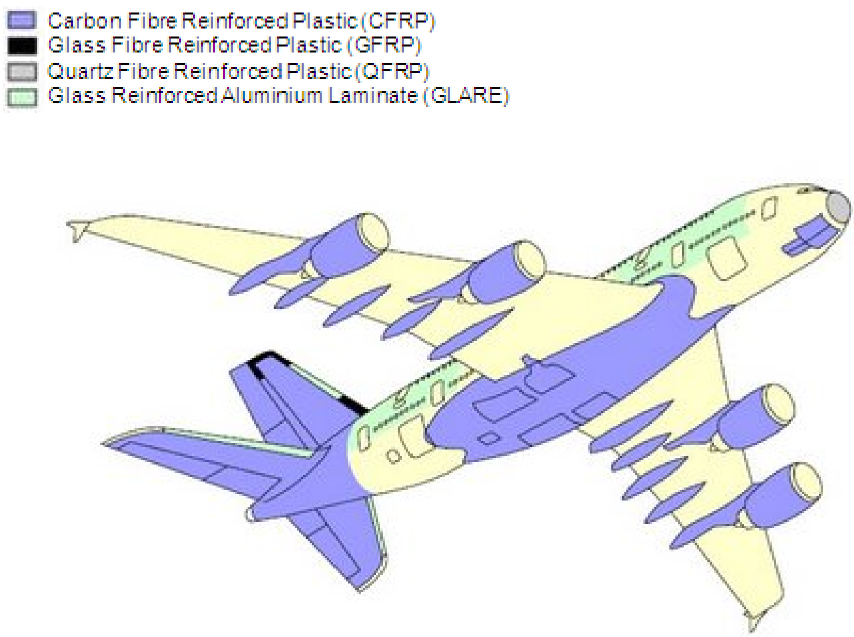

Figure 6.3.2.6 Airbus A380 [11]

The future is the A350, which incorporates 40%, and testing the full realization of composite wing sections (see Figure 6.3.2.7).

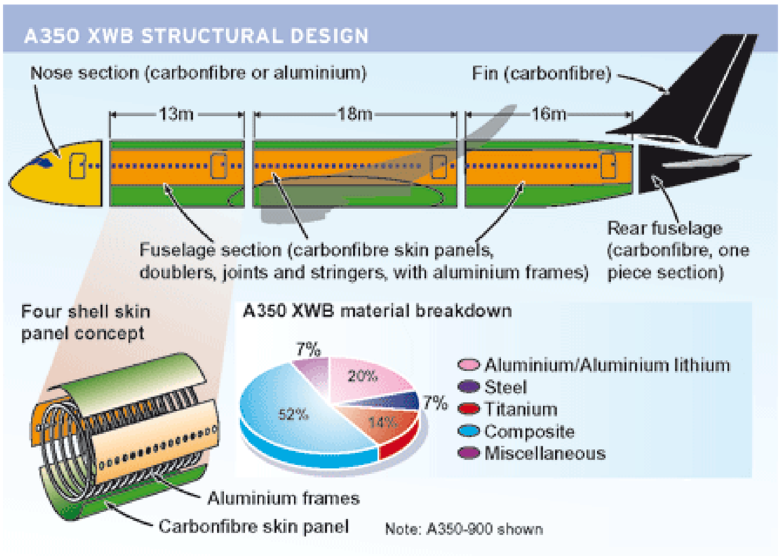

Figure 6.3.2.7 Airbus A350 [13]

6.3.3 Comparison in use of composites

A comparison between Airbus and Boeing shows the amount of composites used by each company in their aircraft (see Figures 6.3.3.1 and 6.3.3.2).

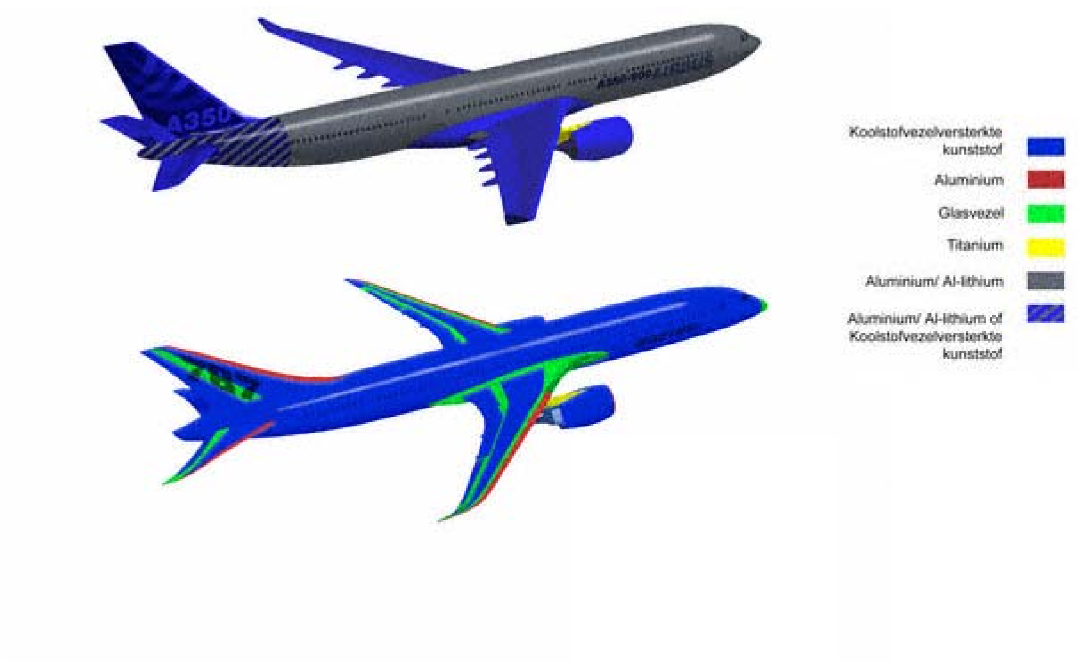

Figure 6.3.3.1 Graphic comparison on the materials used [14]

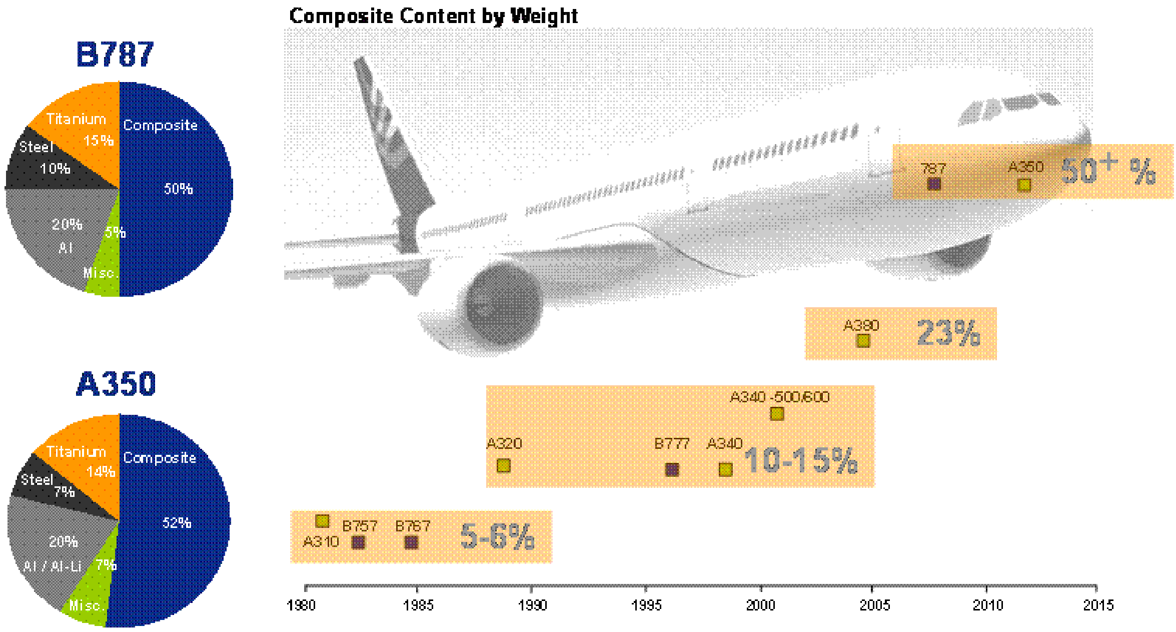

Figure 6.3.3.2 Comparison in the amount of composites [15]

6.4 References

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CHAPTER 7. TESTS ON MATERIALS

7.1 Introduction

In order to know the conductivity of a material, some tests can be carried out.

Resistance of an object is a measure of its opposition to the passage of a steady electric current (see Equation 7.1.1).

$$R = \frac{\rho \cdot L}{s}$$

Equation 7.1.1 Resistance of a material

Where:

R = resistance (Ω)

ρ = resistivity ($\Omega \cdot mm^2/m$)

L = length (m)

s = section (mm^2)

Resistivity is a constant that depends on the materials and the temperature. Inverse of resistivity is called conductivity (see Equation 7.1.2).

$$\sigma = \frac{1}{\rho}$$

Equation 7.1.2 Conductivity of a material

Where:

σ = conductivity (Siemens, S)

ρ = resistivity ($\Omega \cdot m = S^{-1}$)

When a difference of potential is applied between two points, a charge displacements is observed, defined as electrical current. The materials offer a resistance to the flow of charges, governed by Ohm's Law (see Figure 7.1.1).

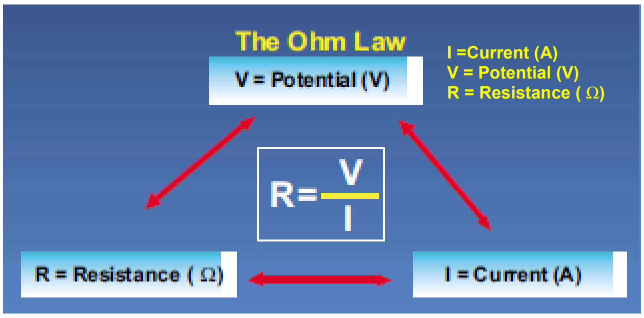

Figure 7.1.1 Ohm's Law [1]

Depending on the position of the electrodes, current can be conducted mainly by volume or surface material (see Figure 7.1.2).

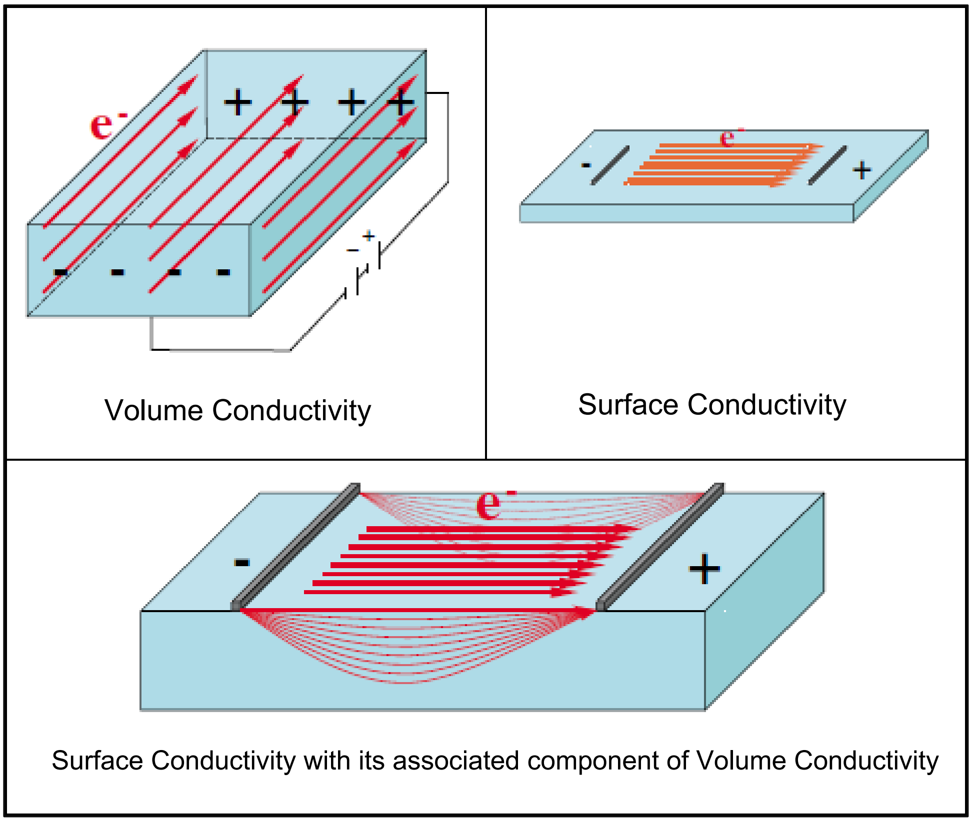

Figure 7.1.2 Differences between electrical current in surface and volume [1]

Two different types of resistivity for ESD applications and for semiconductor power cables can be defined:

- Surface resistivity (SR) in Ohm (see Figure 7.1.3)
- Volume resistivity (VR) in Ohm·cm (see Figure 7.1.4)

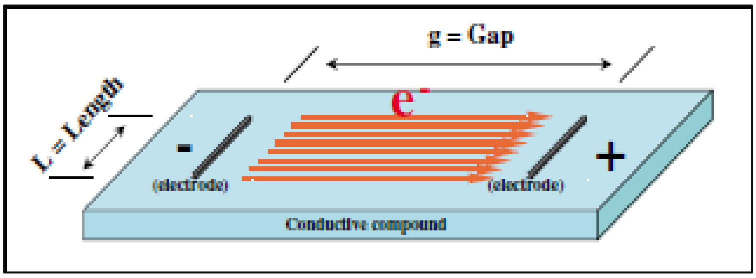

Figure 7.1.3 Surface resistivity test [1]

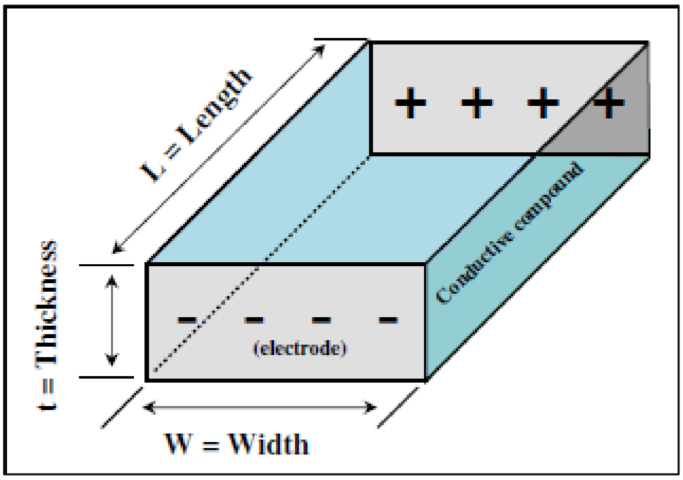

Figure 7.1.4 Two points Volume resistivity test [1]

The equations for these tests are:

- **Surface Resistivity** (see Equation 7.1.3):

$$SR = \frac{R \cdot L}{g}$$

Equation 7.1.3 Surface Resistivity of a material

Where:

SR= Surface Resistivity (Ohm)

R = Resistance (Ohm)

L = electrode length (cm)

g = electrode gap (cm)

- **Volume resistivity** (see Equation 7.1.4):

$$VR = \frac{R \cdot S}{L}$$

Equation 7.1.4 Volume Resistivity of a material

VR = Volume Resistivity (Ohm·cm)

R = Resistance (Ohm)

S = Electrode area (cm^2) defined as S = W· t

L = electrode gap (cm)

Knowing this, tests can be carried out. The basic circuit (see Figure 7.1.5) used consists of a DC voltage source (see Figure 7.1.6), a resistance and the material.

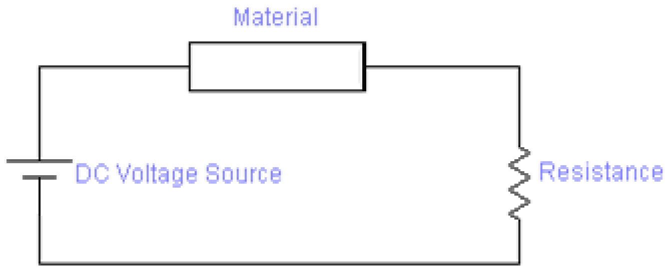

Figure 7.1.5 Circuit in Electronics Workbench

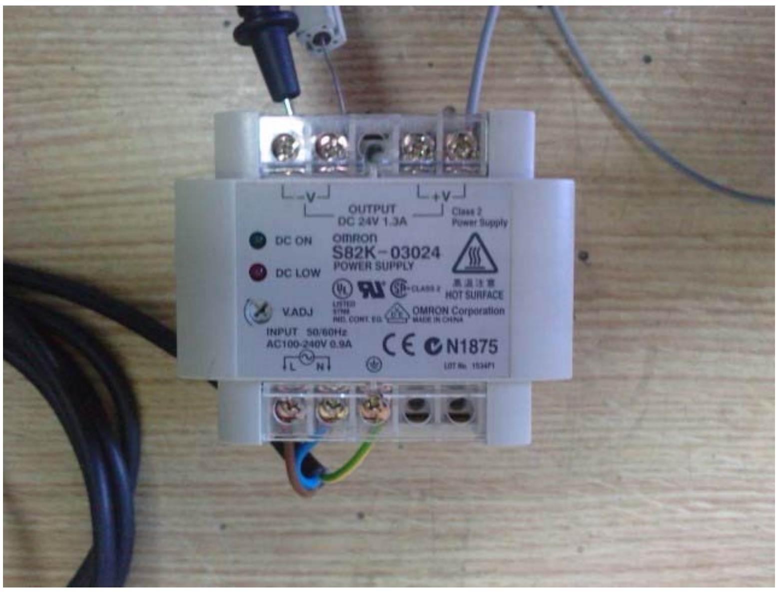

Figure 7.1.6 DC Voltage Source

Having the circuit modelled, the measures taken are voltage in the material (V_M in volts), the current (I in amps) and the voltage in the resistance (V_R in volts) (see Figure 7.1.7).

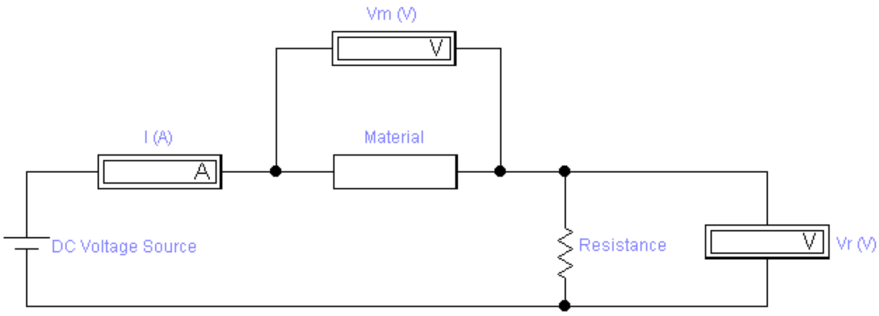

Figure 7.1.7 Measuring devices

First thing measured are the resistances. The theoretical values of them are:

- R_1 = 4700 Ω
- R_2 = 220 Ω
- R_3 = 120 Ω
- R_4 = 3.3 Ω

The real values, measured with the multimeter are:

- R_1 = 4720 Ω
- R_2 = 210 Ω
- R_3 = 120 Ω
- R_4 = 3.3 Ω

7.2 Tests

Tests have been done using different materials, measuring the voltage and current in the circuit (see Appendix G). These tests have been carried out with the following instruments:

- Demestres 260b (see Figure 7.2.1)
- Fluke 715 Calibrator (see Figure 7.2.2)
- Demestres ST 3600

Figure 7.2.1 Demestres [2]

Figure 7.2.2 Fluke [3]

7.3 Results and discussion

For discussing the results, resistance of the material has to be found. The way to do it is using Ohm's law.

From equation in Figure 7.1.1, the value of the resistance of the material (R_M) can be found (see Equation 7.3.1)

$$R_M = \frac{V_M}{I}$$

Equation 7.3.1 Value of R_M

After calculating the value of the material resistance, surface resistivity and volume resistivity (see Equation 7.3.3) can be found. As for doing the tests, the electrode gap is the same as the electrode length, the surface resistivity is the same as the resistance (see equation 7.3.2).

$$SR = \frac{R_M \cdot L}{g}, \quad L = g \quad \therefore \quad SR = R_M$$

Equation 7.3.2 Surface resistivity in the material

$$VR = \frac{R_M \cdot S}{L}$$

Equation 7.3.3 Volume Resistivity in the material

For calculating the resistance and resistivity, the worst values will be taken into account, since on manufacturing of aircraft the worst values are taken. Attending to the resistance and resistivity, the smallest values are the worst ones, since they will let flow more electrical charge of the lightning.

Test 1

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.1).

Table 7.3.1 Values of R and VR for carbon fibre

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0.639	0.612	0.611	0.599	0.589	0.591	0.592	0.567	0.589	0.584
I (A)	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.2	0.2
R (Ω)	3.195	3.06	3.055	5.99	5.89	2.955	5.92	2.835	2.945	2.92
VR (Ω·cm)	0.08076	0.07735	0.07722	0.15141	0.14888	0.07469	0.14964	0.07166	0.07444	0.07381

The most restrictive values obtained are:

From equation 5: **R = 2.92 Ω**

From equation 7: **VR = 0.07381 Ω·cm**

As the result shows, carbon fibre is a quite conductive material.

Test 2

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.2).

Table 7.3.2 Values of R and VR for galvanized carbon steel

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0	0	0	0	0	0	0	0	0	0
I (A)	0.1	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.1
R (Ω)	0	0	0	0	0	0	0	0	0	0
VR (Ω·cm)	0	0	0	0	0	0	0	0	0	0

The most restrictive values obtained are:

From equation 5: **R = 0 Ω**

From equation 7: **VR = 0 Ω·cm**

As the result shows, galvanized carbon steel is conductive since the opposition it makes to the current is null.

Test 3

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.3).

Table 7.3.3 Values of R and VR for stainless steel 304

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0.005	0.004	0.005	0.006	0.01	0.008	0.01	0.01	0.01	0.012
I (A)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
R (Ω)	0.025	0.02	0.025	0.03	0.05	0.04	0.05	0.05	0.05	0.06
VR (Ω·cm)	0.00013	0.00011	0.00013	0.00016	0.00027	0.00021	0.00027	0.00027	0.00027	0.00032

The most restrictive values obtained are:

From equation 5: **R = 0.02 Ω**

From equation 7: **VR = 0.00011 Ω·cm**

As the result shows, stainless steel 304 is conductive material since the results obtained are around zero ohms.

Test 4

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.4).

Table 7.3.4 Values of R and VR for aluminium

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0	0	0	0	0	0	0	0	0	0
I (A)	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2
R (Ω)	0	0	0	0	0	0	0	0	0	0
VR (Ω·cm)	0	0	0	0	0	0	0	0	0	0

The most restrictive values obtained are:

From equation 5: **R = 0 Ω**

From equation 7: **VR = 0 Ω·cm**

As the result shows, aluminium is a highly conductive material since the results for R and VR are zero.

Test 5

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.5).

Table 7.3.5 Values of R and VR for bronze

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
I (A)	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2
R (Ω)	0.015	0.015	0.015	0.015	0.015	0.03	0.015	0.015	0.015	0.015
VR (Ω·cm)	$7.1 \cdot 10^{-5}$	$7.1 \cdot 10^{-5}$	$7.1 \cdot 10^{-5}$	$7.1 \cdot 10^{-5}$	$7.1 \cdot 10^{-5}$	0.00014	$7.1 \cdot 10^{-5}$	$7.1 \cdot 10^{-5}$	$7.1 \cdot 10^{-5}$	$7.1 \cdot 10^{-5}$

The most restrictive values obtained are:

From equation 5: **R = 0.015 Ω**

From equation 7: **VR = $7.1 \cdot 10^{-5}$ Ω·cm**

As the result shows, bronze is a conductive material. The values obtained are around zero ohms.

Test 6

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.6).

Table 7.3.6 Values of R and VR for ungalvanized carbon steel

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
I (A)	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2
R (Ω)	0.03	0.03	0.03	0.03	0.03	0.03	0.06	0.03	0.03	0.03
VR (Ω·cm)	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.01019	0.0051	0.0051	0.0051

The most restrictive values obtained are:

From equation 5: **R = 0.03 Ω**

From equation 7: **VR = 0.0051 Ω·cm**

As the result shows, bronze is a quite conductive material, since the results show that there is not too much opposition of the material to the flow of current.

Test 7

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.7).

Table 7.3.7 Values of R and VR for copper

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0	0	0	0	0	0	0	0	0	0
I (A)	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2
R (Ω)	0	0	0	0	0	0	0	0	0	0
VR (Ω·cm)	0	0	0	0	0	0	0	0	0	0

The most restrictive values obtained are:

From equation 5: **R = 0 Ω**

From equation 7: **VR = 0 Ω·cm**

As the result shows, copper conducts electricity very well. The opposition that it makes to the flow of current is zero.

Test 8

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.8).

Table 7.3.8 Values of R and VR for glass fibre 1

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
R (Ω)	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$
VR (Ω·cm)	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$

The most restrictive values obtained are:

From equation 5: **R $\to\infty$ Ω**

From equation 7: **VR $\to\infty$ Ω·cm**

As the result shows, glass fibre does not conduct electricity. The values of R and VR are very high, that means that the material does not let the current flow pass.

Test 9

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.9).

Table 7.3.9 Values of R and VR for wood

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
R (Ω)	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$
VR (Ω·cm)	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$

The most restrictive values obtained are:
From equation 5: **R** $\to\infty$ **Ω**
From equation 7: **VR** $\to\infty$ **Ω·cm**

As the result shows, wood is insulating, since the values for its resistance and resistivity are very high.

Test 10

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.10).

Table 7.3.10 Values of R and VR for polyethylene

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
R (Ω)	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$
VR (Ω·cm)	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$

The most restrictive values obtained are:
From equation 5: **R** $\to\infty$ **Ω**
From equation 7: **VR** $\to\infty$ **Ω·cm**

As the result shows, polyethylene does not conduct electricity; it means that it is an insulating material. The values of R and VR tend to infinite, meaning that they are very high values.

Test 11

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.11).

Table 7.3.11 Values of R and VR for foam

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
R (Ω)	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$
VR (Ω·cm)	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$

The most restrictive values obtained are:

From equation 5: **R $\to\infty$ Ω**

From equation 7: **VR $\to\infty$ Ω·cm**

As the result shows, foam has very high values of R and VR. It is a good insulating since it does not conduct electricity.

Test 12

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.12).

Table 7.3.12 Values of R and VR for epoxy resin

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
R (Ω)	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$
VR (Ω·cm)	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$	$\to\infty$

The most restrictive values obtained are:

From equation 5: **R $\to\infty$ Ω**

From equation 7: **VR $\to\infty$ Ω·cm**

As the result shows, epoxy resin is an insulating material, since it has very high values of R and VR and it does not conduct electricity.

Test 13

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.13).

Table 7.3.13 Values of R and VR for semi-conducting self-fusing tape

	1	2	3	4	5	6	7	8	9	10
V_M (V)	21	21	21	21	21	21	21	21	21	21
I (A)	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
R (Ω)	105	210	210	210	210	210	210	210	210	210
VR (Ω·cm)	1.44273	2.88546	2.88546	2.88546	2.88546	2.88546	2.88546	2.88546	2.88546	2.88546

The most restrictive values obtained are:

From equation 5: **R = 105 Ω**

From equation 7: **VR = 1.44273 Ω·cm**

As the result shows, semi-conducting self-fusing tape is a semi-conductor, as its name says. The resistance value (that is repeated the most) is next to resistances used for doing the other tests (220Ω).

Test 14

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.14).

Table 7.3.14 Values of R and VR for glass fibre 2

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
R (Ω)	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$
VR (Ω·cm)	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$

The most restrictive values obtained are:

From equation 5: **R $\rightarrow\infty$ Ω**

From equation 7: **VR $\rightarrow\infty$ Ω·cm**

As the result shows, this glass fibre, as the one tested before, is not conductive. The values of R and VR tend to infinite what means that the resistance is so high that the current cannot pass through the material.

Test 15

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.15).

Table 7.3.15 Values of R and VR for plastic

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
R (Ω)	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$
VR (Ω·cm)	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$

The most restrictive values obtained are:

From equation 5: **R $\rightarrow\infty$ Ω**

From equation 7: **VR $\rightarrow\infty$ Ω·cm**

As the result shows, plastic is an insulating material. The results show that the value of the resistance and resistivity are very high, so it does not conduct electricity.

Test 16

The values of R and VR are calculated in order to know how much current the material conducts (see Table 7.3.16).

Table 7.3.16 Values of R and VR for glass

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
R (Ω)	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$
VR (Ω·cm)	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$	$\rightarrow\infty$

The most restrictive values obtained are:

From equation 5: **R $\rightarrow\infty$ Ω**

From equation 7: **VR $\rightarrow\infty$ Ω·cm**

As the result shows, glass in not a conductive material. From the results obtained it can be said that the resistance is so high that it did not let the current flow through the material.

From all the result obtained, the materials tested can be divided into: conducting, semi-conducting and non-conducting materials (see Table 7.3.17).

Table 7.3.17 Classification of the materials tested

CONDUCTING	SEMI-CONDUCTING	NON CONDUCTING (INSULATING)
Galvanized Carbon Steel Stainless Steel 304 Aluminium Bronze Ungalvanized Carbon Steel Copper	Carbon Fibre Self-fusing tape	Glass Fibre Wood Polyethylene Foam Epoxy Resin Glass Fibre Plastic Glass

7.3 References

[1] *ESD Test,* Cabot Corporation, [Electronically accessed 28 April 2010], <http://www.cabot-corp.com/wcm/download/en-us/sb/ESD-Test-Sp1.pdf>

[2] *Pinza amperimetrica digital Demestres,* Electroindustrial.com, [Electronically accessed 29 April 2010], <http://electroindustrial.com/instrumentacion/electropinzas/260.htm>

[3] *Fluke 715 Calibrador V/mA*, Pesa Electronica, Tecnologia Electronica, [Electronically accessed 29 April 2010], <http://www.pesaelectronica.com/product_info.php?currency=US&products_id=83&osCsid=518d9475bd0a94dd1095c56c80b9f39b>

CHAPTER 8. CONCLUSION

8.1 Overall conclusion

In order to carry out this project a great amount of research has been carried out. This research includes information about weather radar systems, such as the Stormscope and the Strikefinder, the effects of lightning strikes on aircraft, as well as the design of the aircraft to avoid lightning strikes, using materials called composites. After this research, some materials have been tested, in order to know the resistance they will offer to the flow of current.

Several objectives have been achieved, acquiring acknowledgement about radar systems, formation of thunderstorms, types of lightning, effects of lightning strikes on aircraft, protection techniques and applicable standards, materials used on aircraft (advantages and disadvantages), composite materials and test on different materials attending to its resistance. Initially, a simulation was going to be done, but unfortunately, it was impossible to do it with any software that the University has, so that, it was changed, and test were carried out.

From the result obtained, it can be said that the effects of lightning can be divided into direct and indirect effects. The first ones are related to physical damage of the aircraft structure: melting and deformation of the aircraft skin, explosive vaporization of conductors, or sparks in the fuel systems. These phenomena occur in the zones that are prone to be struck by lightning and damage can be reduced by using devices as: diverted stripes, static wicks or wing tips. The indirect effects affect to electrical or electronic systems due to voltage and/or current transients induced by lightning. To avoid these effects, all the electrical and electronic systems are tested according to the regulating laws.

Applicable standards deal with the avoidance of failures related to lightning strikes. These standards test the electrical and electronic devices, as well as the materials used on aircraft. These materials should be electrically continuous to favour the flow of the current through the skin of the aircraft, from the attachment point to the lightning stroke. Some areas as joints or non-conductive composites may require protection. Composite materials are increasingly used as they reduce the weight of the aircraft, but in many cases they are poor conductors of electricity and more sensible to lightning strikes. However, metals are good conducting materials facilitating the lightning path.

Regarding the last years, the amount of composites used in aircraft has increased in large. While in the 80s the percentage of composites used in aircraft was about a 5%, in 2010 the percentage has risen up to a 50% for companies as Boeing or Airbus. The last aircraft of Boeing (787) and Airbus (A350) have a 50% of composites in their structure. These materials reduce the weight of the aircraft; however some metals are still used. Accordingly to the test carried out, metals are good conductors while some composites are not. In the tests, it is shown how conducting materials present a very low resistance (around zero or zero) which allows them o conduct the electricity and therefore, the current from a lightning strike will pass through it, and it will leave the material. Other materials are semi-conducting ones, since their resistance is not very high, but it is not zero. On the other side, insulating materials (non-conducting) that do not allow the flow of electrical current were tested. This will end in a burst or a deformation of the material in case of hit by a lightning strike. So that, these materials require special protection in order to avoid the direct effects of lightning strikes.

Nowadays, the future of composites on aircraft industry looks pretty good. Using these materials the weight is considerably reduced which ends in a small consumption of fuel. With composite materials, structures can be designed combining the proportion and orientation of the layers in a certain direction, depending on the specific requirements of the structure. Besides, they reduce number of components and fasteners, and there will not be corrosion problem. However, regarding to lightning strikes and its avoidance, some measures have to be taken to prevent the aircraft from suffering damage due to lightning strikes.

In my opinion, to do this project has been challenging at the same time as enjoyable. Researching and reading information I had acquire a lot of acknowledgements about the topic, finding really interesting information. At the same time, this helped me to set goals and schedule my time in order to achieve them. In conclusion, I find all this year very satisfactory since I been studying what I really like, enjoying every time spend on it.

8.2 Further work

For improvements or future work, the project could be enhanced with:

- A research on information about how the use of solar panel in the wing of the aircraft will affect electrical discharges of lightning strikes.
- Test the materials with better devices, in order to obtain more accurate results.
- A test of materials with a Van der Graaf generator.
- A model of an aircraft, including the different materials used on the skin of it in real aircraft and test it.
- A simulation of a lightning strike in an aircraft with a suitable software, to see how the current flows through the skin when an aircraft is hit by a lightning strike

APPENDIX A. ATMOSPHERE

A.1 Atmosphere

The atmosphere of the earth consists of layers. These layers are defined by differences on temperature. The names for them are (see Figure A.1.1):

- Troposphere
- Stratosphere
- Mesosphere
- Thermosphere

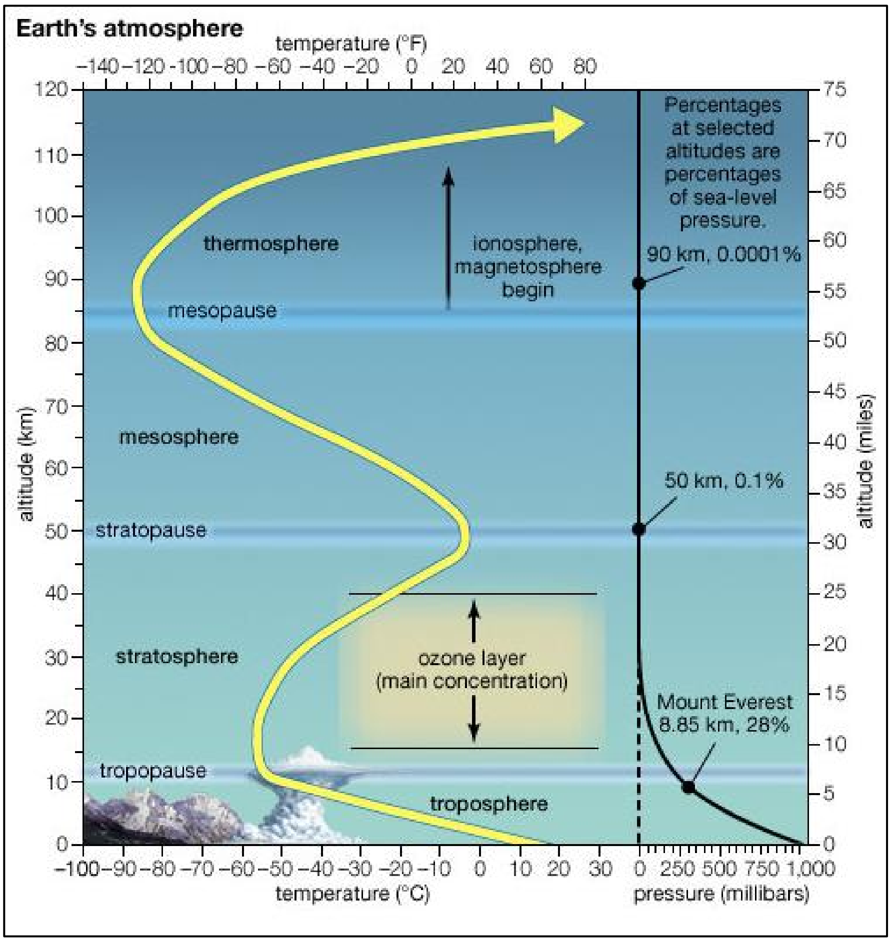

Figure A.1.1 Layers of the atmosphere [1]

Commercial aircraft flies on the highest part of the troposphere, called tropopause. The tropopause is the boundary between the troposphere and the stratosphere.

A.1.1 Troposphere

The troposphere (see Figure A.1.1.1) is the lowest layer where weather takes place. It contains almost 75% of the air of the atmosphere. The temperature decreases fairly constant with 1.98ºC per 1000ft (6ºC/km) [2]. The altitude varies from 15km at the equator and 8km at the poles [3].

This layer is capped by the tropopause. Its temperature is about -80ºC over the equator and over the poles is around -48ºC during summer.

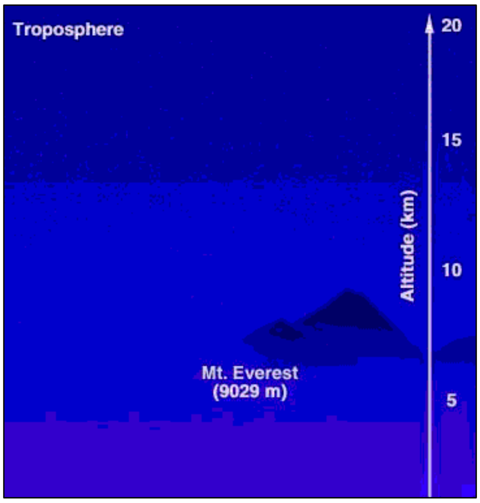

Figure A.1.1.1 Troposphere [4]

A.1.2 Stratosphere

The stratosphere (see Figure A.1.2.1) is about 40km thick. It gradually warms with height. The ozone layer is located here (see Figure A.1.2.2). Due to the radiation of the sun, the ozone layer is destroyed and the stratosphere gets warmer. Stratopause is the boundary between stratosphere and mesosphere [5].

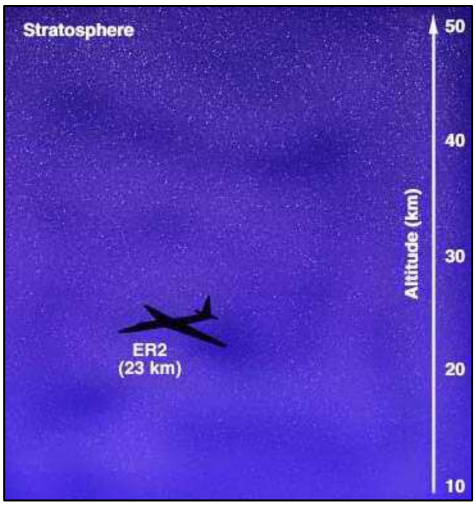

Figure A.1.2.1 Stratosphere [4]

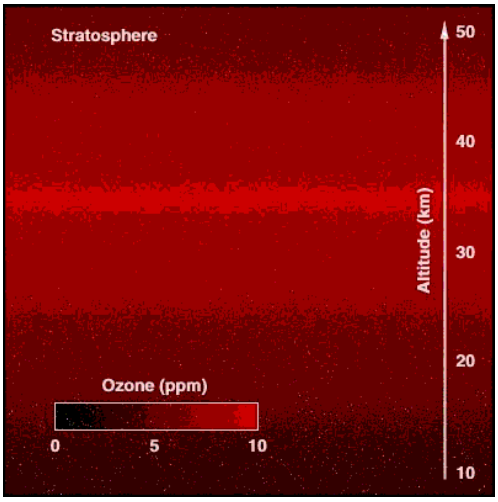

Figure A.1.2.2 Ozone layer [4]

A.1.3 Mesosphere

It starts at 50km up to 80 km height [6]. The temperature decreases as you go higher. At the top, called mesopause (boundary between mesosphere and thermosphere), the temperature reaches -90ºC (see Figure A.1.3.1).

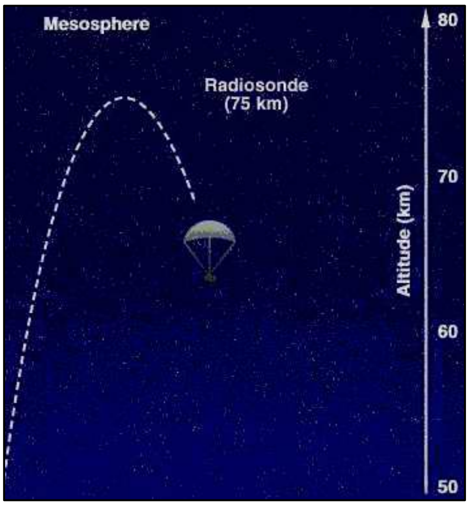

Figure A.1.3.1 Mesosphere [4]

A.1.4 Thermosphere

This layer goes from 80km to 300km height (see Figure A.1.4.1). Gas molecules are here bombarded by x-rays from the sun and the ionosphere [7]. This process creates oxygen and nitrogen atoms with positive charge capable of reflection short wave radio waves from radio station on earth. The temperature increases again since it receives ultraviolet radiation from the sun.

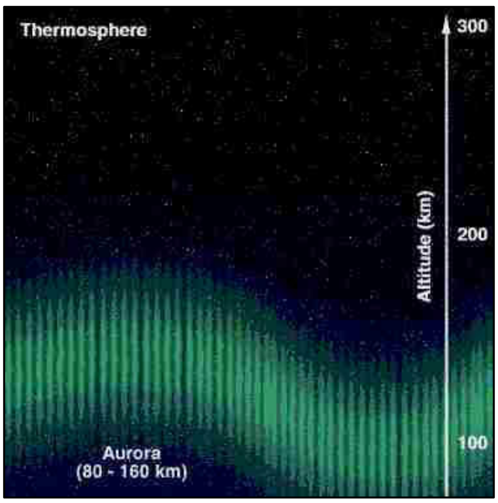

Figure A.1.4.1 Thermosphere [4]

A.2 References

[1] *Atmosphere layers,* Encyclopædia Britannica. 2010. [Electronically accessed 2 December 2009],< http://media-2.web.britannica.com/eb-media/56/97256-004-E3540AD9.jpg>

[2] *The atmosphere,* Transport Canada, Updated 27/11/2008 [Electronically accessed 7 December 2009], <http://www.tc.gc.ca/civilaviation/cam/tp13312-2/section2/atmosphere.htm>

[3] *Earth's Atmosphere*, The Ramman Scattering, [Electronically accessed 6 December 2009], <http://www.raman-scattering.eu/raman/texts/016_text_6.php>

[4] Kiliç, A. *Atmosphere*, Nature Research, Outdoor Sports and Rescue Society, [Electronically accessed 29 November 2009], <http://www.dask.org.tr/english/want_to_know/meteorology/atmosphere/atmosphere.htm>

[5] *Atmosphere,* The Ozone Hole, [Electronically accessed 29 November 2009], <http://www.theozonehole.com/atmosphere.htm>

[6] *Earth's atmosphere,* NobleEd News, [Electrically accessed 22 November 2009], <http://www.nobleednews.com/earth's_atmosphere.htm>

[7] *Earth's atmosphere,* Experimental Aircraft Info [Electronically accessed 22 November 2009], <http://www.experimentalaircraft.info/weather/weather-atmosphere.php>

APPENDIX B. LIGHTNING STRIKE REPORTING FORM

B.1 Reporting form

B.2 Refereces

[1] U.S. Department of Transportation Federal Aviation Administration, O'Loughlin, J.B. and Skinner S.R. (August 2004) *DOT/FAA/AR-047/13 General Aviation Lightning Strike Report and Protection Level Study,* Appendix C-2, faa.gov Federal Aviation Administration, [Electronically accessed 10 January 2010],
<http://www.tc.faa.gov/its/worldpac/techrpt/ar04-13.pdf>

APPENDIX C. LIGHTNING STRIKE INSPECTION AS PER AIRBUS

C.1 Inspection

LIGHTNING STRIKE INSPECTION AS PER AIRBUS AMM (Aircraft Maintenance Manual)

TASK 05-51-18-200-801

After a lightning strike, before the aircraft continues in service, you must:

- do a general inspection of the total surface of the aircraft to find the strike areas;
- do a careful inspection of the strike areas to find the type and quantity of possible damage;
- if you find damage, make a decision about the necessary repair/action.

A. General

(1) Lightning

(a) Lightning always has two or more attachment points (one entry and one exit) on the aircraft skin.

(b) Lightning moves back along the surface of the aircraft (swept stroke zone). This can cause a chain of scattered attachment points along a line in the direction of travel of the aircraft.

(c) Lightning hits some areas more frequently than others.

(2) Aircraft zoning

(Ref. Fig. 601/TASK 05-51-18-991-004)

(a) The aircraft is divided into three zones related to the probability of lightning strike:

1_ Zone 1:

- surfaces where there is a high probability of initial lightning attachment (entry or exit).

2_ Zone 2:

- surfaces where there is a high probability of a _swept stroke zone_. The lightning strike has its initial point of attachment in Zone 1 and moves into Zone 2.

3_ Zone 3:

- this zone includes all of the aircraft surfaces that are not in Zone 1 and 2. In Zone 3 there is a low probability of attachment of a lightning strike. However, high lightning m currents can go through Zone 3 by direct conduction between m 2 attachment points. Zone 3 currents will also go into Zones 1 and 2.

(b) Zones 1 and 2 are divided into A and B areas related to the probability of continued attachment of the arc (hang on). The probability of arc hang on is low in A areas and high in B areas.

1_ Zone 1A:

- area where there is a high probability of initial attachment and low probability of arc hang on, such as the forward-mounted pitot probes, the radome diverter strips and the nacelle leading edges.

2_ Zone 1B:

- area where there is a high probability of initial attachment and high probability of arc hang on, such as the wing, stabilizers and fin tips and some trailing edge areas.

3_ Zone 2A:

- a swept stroke zone with low probability of arc hang on, such as mid-chord regions of the wing surface, aft of an engine and the total fuselage surface.

4_ Zone 2B:

- a swept stroke zone with high probability of arc hang on, such as the wing trailing edge aft of Zone 2A.

(3) Effects on the aircraft structure and systems.

There are two types of possible risks to the aircraft:

- indirect effects;

- direct effects.

(a) Indirect effects.

1_ Electromagnetic fields:

- the electromagnetic fields related to the lightning attachment can cause unwanted transient voltages and currents in the aircraft wiring and systems. In some conditions (low intensity strike, high protection), the effect on the systems can be temporary and the systems can operate correctly again after the strike. In other conditions (low protection, no circuit protection devices), the damage can be permanent and it will be necessary to replace parts.

(b) Direct effects

The direct effects are the physical damage related to signs such as:

1_ Pitting/meltthrough:

- this is the action of the electrical arc formed when a lightning stroke attaches to the aircraft (arc root damage at the attachment points or damage caused by current flow which can appear also far from the attachment points).

- signs of a lightning attachment are pitting and scorch marks and paint discoloration. On composite components, in addition to paint discoloration and skin puncturing, some delamination of the fibers can occur. If there is skin puncturing, there can be damage to the grounded equipment below composite material fairings.

- you must always compare the damage you find with the limits given in the Structural Repair Manual (SRM).

2_ Magnetic force:

- the damage usually occurs where a small area causes the density of the current to be high (e.g. a bonding lead installed at a control surface hinge).

3_ Resistive heating:

- when lightning currents flow through an aircraft structure, energy is changed to heat along its path.

- resistive heating usually causes marks of the weld type, specially where the lightning current flows for some time.

4_ Acoustic shock wave:

- When a lightning strike occurs, there is an acoustic shock wave. If the intensity of this shock wave is high, it can cause deformation of thin metal skins or rupture of thin composite skins.

(4) Inspection requirements:

(a) Aircraft are designed to keep the effects of lightning to a minimum and make sure it can continue its flight and land safely after a lightning attachment.

(b) It is not possible to accurately know where the attachment will occur but Zone 1 and Zone 2 show the most probable areas of lightning attachment.

(c) Lightning strikes do not always give the same quantity of damage.

The quantity of damage comes from the intensity of the lightning strike.

(d) Therefore, it is necessary to do a full inspection after a lightning strike to make an estimate of the damage and make sure that the aircraft can, as a minimum, continue service in a Master Minimum Equipment List (MMEL) condition.

The inspection after a lightning strike refers to:

- the type of the system (critical/essential) to specify the tests that are necessary

- the requirements of the MMEL

NOTE

Critical function:

If a critical function fails, it can result in a failure condition that can prevent continued safe flight and landing of the aircraft.

Essential function:

If an essential function fails, it can result in a failure condition which can have an effect on :

- the performance of the aircraft

- or the ability of the flight crew to fly the aircraft in the adverse conditions.

Subtask 05-51-18-210-077

B. Inspection Preparation

(1) Before you start, we recommend that you get information from the crew about the flight condition.

(2) Make sure that you have the related aircraft Post Flight Report (PFR).

(3) All events reported by the crew or by the PFR must be checked in addition/ conjunction with this inspection.

Subtask 05-51-18-481-051

C. Safety Precautions

Make sure that the safety devices are installed on the landing gears

(Ref. TASK 32-00-00-481-801).

Subtask 05-51-18-866-051

D. Extension of the Flight Control Surfaces

(1) Extend the flaps and the slats (Ref. TASK 27-50-00-866-801).

(2) Extend the spoilers (Ref. TASK 27-60-00-866-801).

E. Get Access

(1) Open the nose gear doors and install the safety devices (Ref. TASK 32-22-00-010-801).

(2) Open the main gear doors and install the safety devices (Ref. TASK 32-12-00-010-801).

Subtask 05-51-18-860-051

F. Aircraft Maintenance Configuration

(1) Make sure that the electrical circuits are de-energized (Ref. TASK 24-41-00-862-801).

(2) Make sure that the hydraulic systems are depressurized (Ref. TASK 29- 00-00-864-804).

(3) Put warning notices in the cockpit to tell persons not to operate the systems.

(4) Put the adjustable access platform in position.

4 . Procedure

NOTE : All the necessary inspections are visual unless the text gives other instructions.

Operators can refer to the Non-destructive Testing Manual (NTM) and use non-destructive procedures.

|ITEM|INSP| INSPECTION TASKS |PHASE|PHASE|PHASE|INSP|REF.|

| |CODE| | 1 | 2 | 3 |SIGN|FIG.|

|----|----|--------------------------------------|-----|-----|-----|----|----|

|1. | | Inspection of the Radome and the Access Door 121AL (Glide/Slope Antenna access). | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

| A.| | Examine visually the radome external skin and the lightning diverters for burn marks, change of color, puncturing and other damage. | | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

| B.| | Examine the access door 121AL (glide/ slope antenna access) for burn marks, puncturing and other damage. | | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

|2. | | Inspection of the Windshield, Fixed Windows, Sliding Windows and Window Frames. | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

| A.| | Examine visually the windshield, fixed windows, sliding windows and the window frames for burn marks, change of color and other damage. | | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

|3. | | inspection of the Landing Gear Doors | | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

| A.| | Examine the skin of all landing gear doors for burn marks, change of color, puncturing and delamination. | | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

| B.| | Examine the electrical bonding leads for breakage and defective attachment.| | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

|4. | | Inspection of the Landing Gears. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| | | NOTE: Do these checks if the lightning strike occurred:

- when the LG was extended and locked down;

- during the extension of the LG.

- when you find a through hole during the inspection of the landing | | | | | |

|ITEM|INSP| INSPECTION TASKS |PHASE|PHASE|PHASE|INSP|REF.|

| |CODE| | 1 | 2 | 3 |SIGN|FIG.|

|----|----|-------------------------------------|-----|-----|-----|----|----|

| | | gears doors. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| A.| | Examine all the landing gears. | X | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| | | (1) Examine the LG structure and the points where it is attached for change of color, burn marks and other damage. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| | | (2) Examine the shock absorber for change of color and burn marks. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| | | (3) Examine all the components attached to the landing gear and fully examine the electrical looms and components for a change of color and burn marks. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

|5. | | Inspection of the Belly Fairing | | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

| A.| | Examine the belly fairing panels (including the wing-to-fuselage fairings) for change of color, burn marks, puncturing and delamination. Examine fairing screws and fasteners for burn marks. | | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

|6. | | Inspection of the Fuselage | | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

| A.| | Externally examine all of the fuselage skin including rivets and screws for change of color, burns marks and small holes. | | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

| B.| | Examine all the probes, sensors and drain masts and the adjacent area for burn marks and change of color. | | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

| C.| | Examine carefully all the communication and navigation antennas and the adjacent area for burn marks, change of color, puncturing and delamination. | | | | | |

|ITEM|INSP| INSPECTION TASKS |PHASE|PHASE|PHASE|INSP|REF.|

| |CODE| | 1 | 2 | 3 |SIGN|FIG.|

|----|----|--------------------------------------|-----|-----|-----|----|----|

R |----|----|--------------------------------------|-----|-----|-----|----|----|

| D.| | Examine all exterior lights and adjacent area for burn marks and other damage. | | | | | |

R |----|----|--------------------------------------|-----|-----|-----|----|----|

| E.| | Examine the APU exhaust for burn marks and change of color. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

|7. | | Inspection of the Wings | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| A.| | Examine the top and bottom skin of the wings and the leading and trailing | | | | | |

| | | edges for burn marks, change of color | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| B.| | Examine the slats for burn marks and damage. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| C.| | Examine the flap track fairings for burn marks, change of color, puncturing and other damage. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| D.| | Examine the flaps for burn marks, change of color, puncturing and delamination. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| E.| | Examine the spoilers for burn marks, change of color, puncturing and delamination. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| F.| | Examine the ailerons for burn marks, change of color, puncturing and delamination. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| G.| | Examine all the static dischargers for burn marks, damaged tip and breakage. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| H.| | Examine the wing tip for burn marks and burn holes. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| I.| | Examine the lights on the wing tip for burn marks and other damage. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

|8. | | Inspection of the Engine Nacelles and | | | | | |

|ITEM|INSP| INSPECTION TASKS |PHASE|PHASE|PHASE|INSP|REF.|

| |CODE| | 1 | 2 | 3 |SIGN|FIG.|

|----|----|-------------------------------------|-----|-----|-----|----|----|

| | | the Pylons. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| A.| | Examine each air intake, inlet cowl, fan cowl, thrust reverser, exhaust nozzle and the pylon for burn marks, change of color, puncturing and delamination. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

|9. | | Inspection of the Vertical Stabilizer | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| A.| | Examine all the static dischargers for burn marks, damaged tip and breakage. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| B.| | Examine the skin of the vertical stabilizer and the rudder (specially the leading and the trailing edges, the rudder surface in the hinge area and the antenna fairings), the fin tip cap, the fin and rudder tip cap lightning diverters for burn marks, change of color, puncturing, delamination and other damage. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

|10. | | Inspection of the Horizontal | | | | | |

| | | Stabilizer | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| A.| | Examine all the static dischargers for burn marks, damaged tip and breakage. | | | | | |

R |----|----|-------------------------------------|-----|-----|-----|----|----|

| B.| | Examine the skin of the horizontal stabilizer and elevators (specially the leading and the trailing edge, the elevator surface in the hinge area and the tip) for burn marks, change of color, puncturing, delamination and other damage. | | | | | |

C.2. References

[1] *Aircraft Turbulence and lightning strike damage assessment,* Aircraft technology, [Electronically accessed 20 November 2010], <http://www.aircrafttechtrng.com/apps/forums/topics/show/1644365-aircraft-turbulance-and-lightning-strike-damage-assesment?page=last>

APPENDIX D. INDIRECT EFFECTS LIGHTNING TESTS

D.1 Lightning tests

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). [1]

Some procedural steps that should be taken are (FAA[3] for U.S. or EASA[4] for E.U.):

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.
C. 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.
D. Schedule FAA witnessing of the test(s).
E. Conduct testing.
F. Submit a final test report describing all results.
G. Obtain FAA approval of the report. [1]

In lightning environmental standards, two simulations can be defined [2]:

- Simulation of direct strike current and voltage.
- Simulation of the induced currents and voltages within the aircraft resulting from the direct strike.

[3] **FFA**: The Federal Aviation Administration (FAA) is an agency of the United States Department of Transportation with authority to regulate and oversee all aspects of civil aviation in the U.S. (National Airworthiness Authority) [3]
[4] **EASA:** The European Advertising Standards Alliance (EASA) is the single authoritative voice on advertising self-regulation issues and promotes high ethical standards in commercial communications by means of effective self-regulation, while being mindful of national differences of culture, legal and commercial practice. [4]

Lightning current components can be divided into four types of components (see Figure D.1.1)

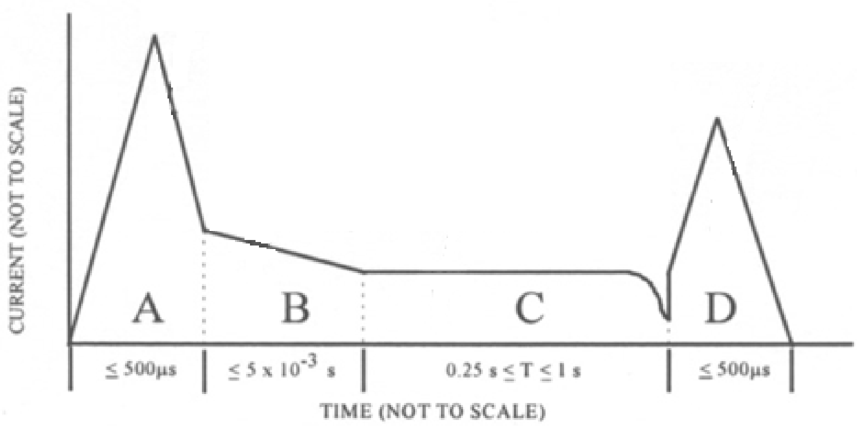

Figure D.1.1 Lightning current components [5]

COMPONENT A: Initial Stroke
Peak amplitude = 200 kA ± 10%
Action integral = 2 x 10^6 A^2.s ± 20%
Time duration ≤ 500 μs

COMPONENT B: Intermediate current
Maximum charge transfer = 10 coulombs
Average amplitude = 2 kA ± 10 %

COMPONENT C: Continuing current
Charge transfer = 200 coulombs ± 20 %
Amplitude = 200 - 800 A

COMPONENT D: Restrike
Peak amplitude = 100 kA ±10 %
Action integral = 0,25 x 10^6 A^2.s ± 20%
Time duration ≤ 500 μs

There are five test levels and six waveforms. Three sequences of pulses are used for induced lightning testing: [6]

- Single stroke (SS)
- Multiple Stroke (MS) (see Figure D.1.2)

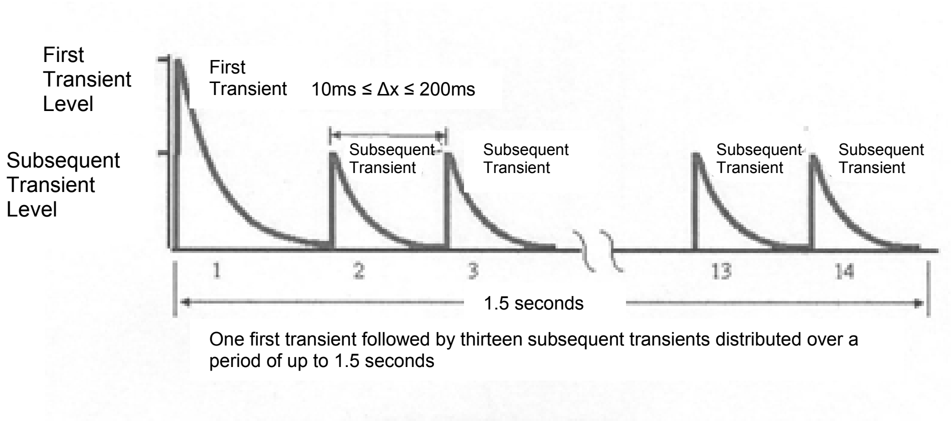

Figure D.1.2 Multiple Stroke application of a Waveform [6]

- Multiple Burst (MB) (see Figure A.1.3)

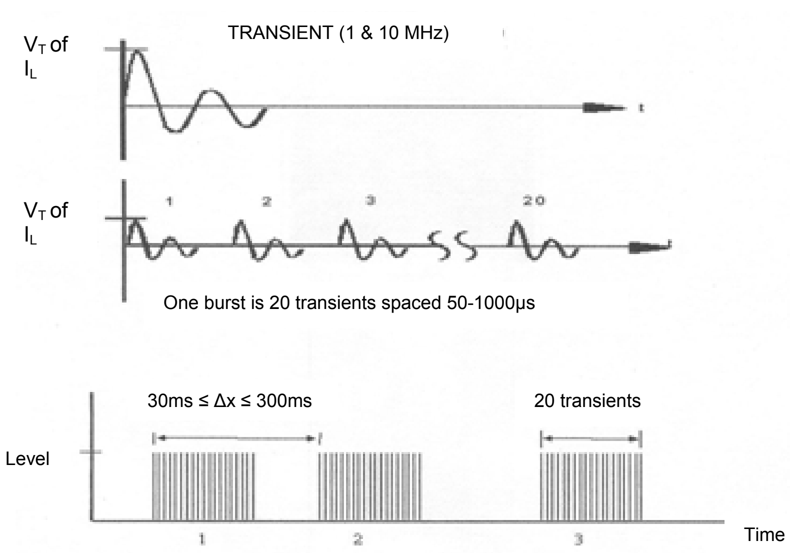

Figure D.1.3 Multi burst application [6]

There are three primary methods of testing aircraft components (see Table D.1.1) [7]:

- ***Pin Injection*** – This method is used to directly inject the waveform into connector pins of both cables and printed wiring boards.
- ***Cable Bundle Induction*** – This method uses a coupling transformer to inductively couple the waveform onto the cable bundle.
- ***Ground Injection*** – This method is often used as an alternate method to inject the waveform onto the ground wire of the unit under test, referenced to the ground plane that is located on the surface of the test table.

Table D.1.1 Test Capabilities [8]

Pin Injection – Single Stroke	Waveform 3 (1&10MHz), Levels 1 through 5
	Waveform 4 (6.4/70 µs), Levels 1 through 5
	Waveform 5A (40/120 µs), Levels 1 through 5
	Waveform 5B (50/500 µs, Not in DO 160) Levels 1 through 5
Cable Injection – Single Stroke	Waveform 1 (6.4/70 µs) , Levels 1 through 4 (Level 5 with 12µSec. rise time rather than 6.4 µSec.specified)
	Waveform 2 (0.1/6.4 µs) , Levels 1 through 3 (Level 4 on Cables > 3 m, Level 5 on Cables > 50 µH)
	Waveform 3 (1 &10MHz), Levels 1 through 3 (Level 4 on cables > 5 m, Level 5 on Cables > 47 µH)
	Waveform 5A, (40/120 µs), Levels 1 through 4 (Level 5 on cables < 1 m and with a cross section of 10mm2)
	Waveform 5B, (50/500 µs, Not in DO 160) Levels 1 through 4 (Level 5 on cables < 1 m and with a cross section of 10mm2)
Ground Injection – Single Stroke	Waveform 4 (6.4/70 µs), Levels 1 through 4 (Level 5 on cables > 20 ohms)
	Waveform 5A, (40/120 µs), Levels 1 through 4 (Level 5 on cables < 1 m and with a cross section of 10mm2)
	Waveform 5B, (50/500 µs, Not in DO 160) Levels 1 through 4 (Level 5 on cables < 1 m and with a cross section of 10mm2)
Cable Injection – Multiple Stroke	Waveform 1 (6.4/70 µs), Levels 1 through 5
	Waveform 2 (0.1/6.4 µs), Levels 1 through 3 (Level 4 on Cables > 3 m, Level 5 on Cables > 50 µH)
	Waveform 3 (1 &10MHz), Levels 1 through 3 (Level 4 on cables > 5 m, Level 5 on Cables > 47 µH)
	Waveform 5A, (40/120 µs), Levels 1 through 5
	Waveform 5B, (50/500 µs, Not in DO 160) Levels 1 through 5
Ground Injection – Multiple Stroke	Waveform 4 (6.4/70 µs), Levels 1 through 5
	Waveform 5A, (40/120 µs), Levels 1 through 5
	Waveform 5B, (50/500 µs, Not in DO 160) Levels 1 through 5
Cable Injection – Multiple Burst	Waveform 3, (1 and 10 MHz), Levels 1 through 5

There are five Test Power Levels, where Level 1 is the lowest and Level 5 is the highest [7]:

- ***Level 1:*** Equipment and wiring are installed in a ***well*** protected environment;
- ***Level 2:*** Equipment and wiring are in a ***partially*** protected environment;
- ***Level 3:*** Equipment and wiring are in a ***moderately*** protected environment;
- ***Level 4 and 5:*** Equipment and wiring are in ***severe*** electromagnetic environments.

Power levels specified in DO-160 Section 22 are often based upon how critical the component is for flight operation and/or where the unit is located within the aircraft. Greater resistance or spacing from apertures will result in lower power levels. Power levels can also be dictated by the component purchaser or plane manufacturer, based upon other factors. An example is a plane manufacturer may wish to increase the immunity level of entertainment systems on long range aircraft, with the idea that they are more likely to experience multiple lightning strikes and more likely to fail during a 14 hour flight [7]

The six waveforms are [7]:

- Waveform 1 – **Current** (see Figure D.1.4)
    - Double exponential 6.4μs X 69μs (to 50%)

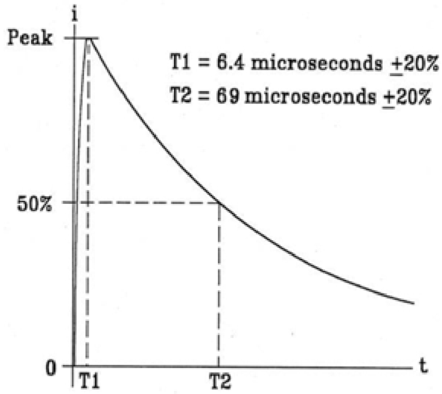

Figure D.1.4 Waveform 1 – Current Double exponential 6.4μs X 69μs (to 50%) [7]

- Waveform 2 – **Voltage** (see Figure D.1.5)
    - Double exponential 100ns X 6.4μs (at zero crossing)

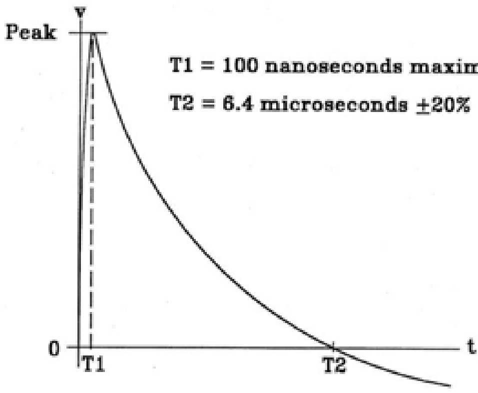

Figure D.1.5 Waveform 2 – Voltage Double exponential 100ns X 6.4μs (at zero crossing) [7]

- Waveform 3 – **Voltage**/**Current** (see Figure D.1.6)
    - Ringing wave, sine or cosine 1MHz and 10MHz

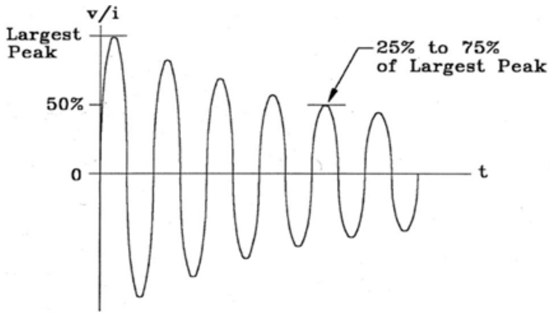

Figure D.1.6 Waveform 3 – Voltage/Current Ringing wave, sine or cosine 1MHz and 10MHz [7]

- Waveform 4 – **Voltage** (see Figure D.1.7)
    - Double Exponential 6.4μs x 69μs (to 50%)
        - o Same shape as Waveform 1 except this ones voltage

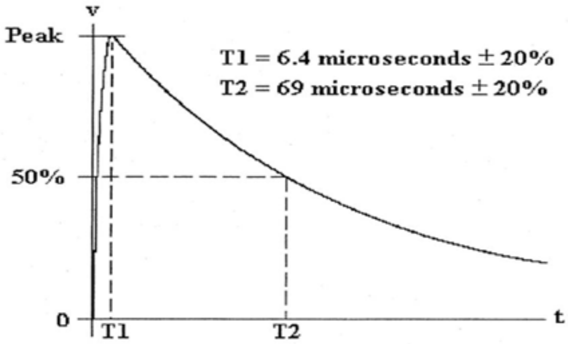

Figure D.1.7 Waveform 4 – Voltage Double Exponential 6.4μs x 69μs (to 50%) [7]

- Waveform 5A – **Voltage**/**Current** (see Figure D.1.8)
    - Double Exponential 40μs X 120μs (to 50%)
- Waveform 5B – **Voltage**/**Current** (see Figure D.1.8)
    - Double Exponential 50μs X 500μs (to 50%)

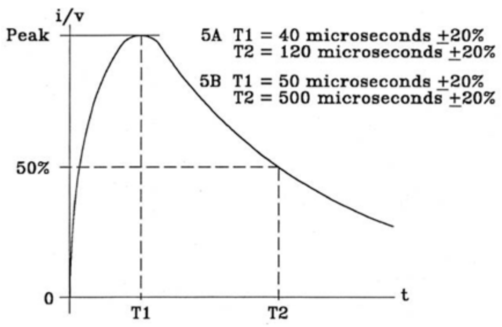

Figure D.1.8 Waveform 5A – Voltage/Current Double Exponential 40µs X 120µs (to 50%)
Waveform 5B – Voltage/Current Double Exponential 50µs X 500µs (to 50%) [7]

Methods of testing are often dictated using categorisations defined in DO-160, and involving specific waveform sets for different coupling means.

D.2. References

[1] Rupke, E. (2002) *Lightning Direct Effects Handbook,* AGATE Advanced General Aviation Transport Experiments, [Electronically accessed 22 December 2009], <http://www.niar.twsu.edu/agate/Documents/Lightning/WP3.1-031027-043.pdf>

[2] Lutz, M, Casanova,R and Revesz T. *Induced Lightning Testing of Avionics – with Single Stroke, Multiple Stroke, and Multiple Burst,* [Electronically accessed 3 February 2010], <http://www.emc-partner.com/resource/pdf/a_do-160.pdf>

[3] *FAA: Federal Aviation Administration,* Wikipedia, the free encyclopedia, Updated 03/02/2010, [Electronically accessed 10 February 2010], <http://en.wikipedia.org/wiki/Federal_Aviation_Administration>

[4] *EASA,* EASA Alliance, [Electronically accessed 1 February 2010], <http://www.easa-alliance.org/page.aspx/110>

[5] *Overview- Lightning Protection of Aircraft and Avionics,* IEEE, [Electronically accessed 10 February 2010], <http://www.ieee.li/pdf/viewgraphs/lightning_protection_aircraft_avionics.pdf>

[6] *Avionics Testing EMC Partner*, co-neckt.com, [Electronically accessed 12 January 2010], <http://www.conekt.net/docs/Avionics_Testing_EMC_Partner.pdf>

[7] *Fundamentals of DO-160F, Section 22: Lightning Induced Transient Susceptibility,* In Compliance Magazine, [Electronically accessed 22 February 2010], <http://www.incompliancemag.com/index.php?option=com_content&view=article&id=156:fundamentals-of-do-160f-section-22-lightning-induced-transient-susceptibility&catid=25:standards&Itemid=129>

APPENDIX E. APPLICABLE STANDARS

E.1 Applicable standards

These are some of the applicable standards related to the indirect effects of lightning on aircraft.

- **MIL-STD-461, Method CS11**, Conducted Susceptibility, Damped Sinusoidal Transients, Cables, 10 kHz to 100 MHz;
- **MIL-STD-461, Method CS12**, Conducted Susceptibility, Common Mode Cable, Current Pulse, Interconnecting and Power;
- **MIL-STD-461, Method CS13**, Conducted Susceptibility, Single Wire Coupled Pulse;
- **RTCA/DO-160, Section 17**, Voltage Spike;
- **RTCA/DO-160, Section 22**, Lightning Induced Transient Susceptibility;
- **AIRBUS ABD0100.1.2, Section 3.2.2**, Lightning Indirect Effects;
- **AIRBUS ABD0100.1.2, Section 3.4**, Onboard System Electromagnetic Environment;
- **BOEING D6-16050-4, Section 7.4**, Lightning Induced Transient Susceptibility Tests;
- **BOEING D6-16050-4, Section 7.5**, Transient Susceptibility Tests;
- **ISO 7637-1/-2**, Electrical Transients Power Leads;
- **SAE J1113-11**, Immunity to Conducted Transients on Power Leads
- **IEC 60945, Section 10.5**, Immunity to Fast Transients on AC Power, Signal, and Control Lines and Section 10.6, Immunity to Conducted Radio Frequency Disturbance [1 and 2]

For modern transport aircraft, the ANAC (Civil Aviation National Agency), FAA (Federal Aviation Administration) and EASA (European Aviation Safety Agency) include the Requirements [3]:

- **25.581** for structural parts lightning protection,
- **25.901** and **25.903** for engines,
- **25.954** for fuel system lightning protection,

Also SAE's (Society of Automotive Engineers) Aerospace Recommended Practices 5412, 5413 and 5414 are extensively used as the basis for the current aircraft lightning environment definition and for compliance demonstration. SAE has emitted ARP 5412 regarding lightning environment and waveforms, and ARP 5413 that provides guidance for compliance with indirect effects of lightning regulations. In addition to the 25.1301 and 25.1309 current airworthiness requirements, the ANAC, FAA and EASA have emitted 25.1316 requirement, which define operation condition for electrical-electronic system level A (critical system) and level B /C (essential system) [4].

The requirements of EMI (Electromagnetic Interference) and lightning direct and indirect effects are complied by incorporating, since the early design phases, special electrical bonding and EMI shielding protection devices and techniques [3]:

- Metal parts electrical bonding is extensively used;
- Composite materials parts include embedded expanded copper foil and specially developed electrical bonding interfaces to metal structure;
- Wiring harnesses are segregated by separately routing the different EMI categories of signal and power leads and shield termination make extensive use of 360º termination and bonding to connector backshells.

The use of the composite material in fuel tanks and fuel system are in development, where special attention will be given to protection against lightning direct effects.

<u>25.581 Structural parts lightning protection</u> [5]

(a) The airplane must be protected against catastrophic effects from lightning.
(b) For metallic components, compliance with paragraph (a) of this section must be shown by:
  1. Bonding components properly to airframe; or
  2. Designing the components so that the strike will not endanger the airplane.
(c) For non metallic 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.

<u>25.901 and 25.903 Engines</u> [5]

- **<u>25.901</u>**

(a) For the purpose of this part, the airplane powerplant installation includes each component that:
  1. Is necessary for propulsion;
  2. Affects the safety of the major propulsive units; or
  3. Affects the safety of the major propulsive units between normal inspections or overhauls.
(b) For each powerplant:
  1. The installation must comply with:
    (i) The installation provided under 33.5 (see Appendix F); and
    (ii) The applicable provisions of this subpart;

2. The components of the installation must be constructed, arranged, and installed so as to ensure their continued safe operation between normal inspections or overhauls;
3. The installation must be accessible for necessary inspections and maintenance; and
4. The major components of the installations must be electrically bonded to the other parts of the airplane.

(c) For each powerplant and auxiliary power unit installation, it must be established that no single failure or malfunction or probable combination failures will jeopardize the safe operation of the airplane except that failure of structural elements need to be considered if the probability of such failure is extremely remote.

(d) Each auxiliary power unit installation must meet the applicable provisions of this subpart.

- **25.903**

(a) *Engine type certificate.*

1. Each engine must have a type certificate and must meet the applicable requirements of part 34 (Fuel venting and exhaust emission requirements for turbine engine powered airplanes)
2. Each turbine engine must comply with one of the following:
   (i) Sections 33.76 (bird ingestion), 33.77 (foreign object ingestion - ice) and 33.78 (rain and hail ingestion) of this chapter in effect on December 13, 200, or as subsequent amended; or
   (ii) Section 33.77 and 33.78 of this chapter in effect on April 13, 2000, or as subsequently amended before December 13, 2000; or
   (iii) Comply with 33.77 of this chapter in effect on October 31, 1974, or as subsequently amended prior to April 30, 1998, unless that engine's foreign object ingestion service history has resulted in an unsafe condition; or
   (iv) Be shown to have a foreign object ingestion service history in similar installation locations which has not resulted in any unsafe condition.

(b) *Engine isolation.* The powerplants must be arranged and isolated from each other to allow operation, in at least one configuration, so that the failure or malfunction of any engine, or of any systems that can affect the engine, will not:

1. Prevent the continued safe operation of the remaining engines; or
2. Require immediate action by any crewmember for continued safe operation.

(c) *Control of engine installations.* There must be means for stopping the rotation of any engine individually in flight, except that, for turbine engine installations, the means for stopping the rotation of any engine need be provided only where continued rotation could jeopardize the safety of the airplane. Each component of the stopping systems on the engine side of the firewall that might be exposed to fire must be at least fire-resistant.

If hydraulic propeller feathering systems are used for this purpose, the feathering lines must be at least fire resistant under the operating conditions that may be expected to exist during feathering.

(d) *Turbine engine installations.* For turbine engine installations:

1. Design precautions must be taken to minimize the hazards to the airplane in the event of an engine rotor failure or of a fire originating within the engine which burns through the engine case.
2. The powerplant systems associated with the engine control devices, systems, and instrumentation, must be designed to give reasonable assurance that those engine operating limitations that adversely affect turbine rotor structural integrity will not exceeded in service.

(e) *Restart capability*

1. Means to restart any engine in flight must be provided.
2. An altitude and airspeed envelope must be established for in-flight engine restarting, and each engine must have a restart capability within that envelope.
3. For turbine engine powered airplanes, if the minimum windmilling speed of the engines, following when in-flight shutdown of all engines, is insufficient to provide the necessary electrical power for engine ignition, a power source independent of the engine-driven electrical power generating system must be provided to permit in-flight engine ignition for restarting.

(f) *Auxiliary Power Unit*. Each auxiliary power unit must be approved or meet the requirements of the category for its intended use.

25.954 Fuel system lightning protection [5]

The fuel system must be designed and arranged to prevent 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 to areas where swept strokes are highly probable; and
(c) Corona and streamering at fuel vent outlets

E.2 RTCA DO-160

RTCA DO-160 is a standard for environmental test of avionics hardware. DO-160 (see Appendix H), Environmental conditions and Test Procedures for Airborne equipment was published by RTCA (Radio Technical Commission for Aeronautics).

The DO-160 standard was first published on January 25, 1980 to specify test conditions for the design of avionics electronic hardware in airborne systems. Since then the standard has undergone subsequent revisions up through revision F [6].

This document outlines a set of minimal standard environmental test conditions (categories) and corresponding test procedures for airborne equipment. The purpose of these tests is to provide a controlled (laboratory) means of assuring the performance characteristics of airborne equipment in environmental conditions similar of those which may be encountered in airborne operation of the equipment [6]. The Standard includes sections on:

- Temperature
- Altitude
- Humidity
- Shock and Crash Safety
- Vibration
- Explosion proof
- Water proof
- Fluids susceptibility
- Sand and Dust
- Fungus Resist
- Salt and Fog
- Magnetic effect
- Power input
- Voltage Spike
- Audio frequency conducted susceptibility
- Induced signal susceptibility
- RF (radio frequency) emission and susceptibility
- Lightning susceptibility
- Icing
- ESD (electrostatic discharge)
- Flammability

Sections 22 and 23 are related to lightning:

- Section 22: Lightning induced transient susceptibility
- Section 23: Lightning direct effects. [7]

Revision E and F are driven by the use of composite materials used for airframe construction. Many composites **do not** conduct lightning currents the way metal airframes do; hence, the possibility of higher voltages and currents getting into cables and equipment of the aircraft. [8]

E.3 European Organisation for Civil Aviation Equipment (EUROCAE)

The applicable standards of EUROCAE are [9]:

- ED-84 (1997): Aircraft Lightning Environment and related Test Waveforms. Report of EUROCAE WG-31 and SAE Committee AE4L.
- ED-81 (1996) Lightning Environment
- ED-91 (1998)Aircraft Lightning Zoning Standard
- ED-113 (2002) Aircraft Lightning Direct Effects Certification

Group 31 in EUROCAE [9]

WG-31 - Lightning

The primary task of Working Group 31 is to prepare, in conjunction with other committees, documents concerning the effects of Lightning on aircraft and equipment.

During the Year 2005-2006, WG-31's activities included work on the following documents:

- ED-105 "Aircraft lightning testing standard", which has been published
- Continuing revision of DO-160 sect 22 for improvements to be included in DO-160 rev F
- Completely revisited section 23, which will be submitted to WG-14 for inclusion in the next
- ED-14 change to issue F
- Work in conjunction with AE2 on Fuel couplers for AS5830

Future activities

Possibilities for the development of new documents are being considered; these could include a restart of work on ED-81, AC 25.899-1 [9].

E.4 US Department of Transportation, Federal Aviation Authority (FAA)

Advisory Circular 20-136 (1990): Protection of Aircraft Electrical/Electronic Systems against the indirect effects of lightning [10].

E.5 International Standards Organisation (ISO)

ISO 7137 (2001): Aircraft - Environmental conditions and test procedures for airborne equipment [11].

E.6 Equivalences in FAA and EUROCAE

During the early draft development of AC 20-155, the Federal Aviation Administration (FAA) had intended to recognize the fact that EUROCAE document ED-84, *Aircraft Lightning Environment and Related Test Waveforms*, was technically equivalent to SAE Aerospace Recommended Practice (ARP) document 5412 (same title), and that EUROCAE document ED-91, *Aircraft Lightning Zoning*, was technically equivalent to SAE ARP document 5414 (same title).

However, prior to the release of AC 20-155, it was recognized that SAE ARP 5412 and ARP 5414 had both been revised to ARP 5412A and 5414A, respectively, whereas the same revisions had not been incorporated into the corresponding EUROCAE documents. Because of this, the EUROCAE documents were no longer considered “technically” equivalent, and their references were subsequently removed from the initial release of AC 20-155.

EUROCAE has since updated documents ED-84 and ED-91, through amendment changes. The SAE AE-2 Lightning Committee has reviewed these amendment changes to EUROCAE documents ED-84 and ED-91 in light of the revisions that were made to SAE ARP 5412A and ARP 5414A.

The SAE AE2 committee has concluded that:

- EUROCAE ED-84, *Aircraft Lightning Environment and Related Test Waveforms,* when accompanied by Amendments 1, 2, and 3, is technically equivalent to SAE ARP 5412A, *Aircraft Lightning Environment and Related Test Waveforms*.
- EUROCAE ED-91, *Aircraft Lightning Zoning*, when accompanied by Amendments 1 and 2, is technically equivalent to SAE ARP 5414A, *Aircraft Lightning Zoning*.

This review was documented in an SAE AE-2 Lightning Committee Correspondence to the FAA dated June 8, 2007. The FAA concurs with this position, and agrees that the EUROCAE documents, with the applicable Amendments, are interchangeable with their corresponding SAE ARP. [12]

E.7 Standard comparison

All the standards are not the same. It depends on the manufacturer, but they have to be in accordance with the regulating law (see Table E.7.1). [13]

Table E.7.1 Standard Comparison [13]

Standard	Parameter	MS Pattern	MB Pattern (Bx)	MB Pattern (Ax)
DO 160D	No of transients	14 strokes	20 of (WF3)	3 bursts of (B1)
	Distribution	random	random	random
	Impulse spacing	10 - 200ms	50 - 1000µs	30ms - 300ms
	Event duration	1.5s		3s
	Test time			5min
NH90	No of transients	24 strokes	20 of (WF2 & 3)	24
	Distribution	random	random	random
	Impulse spacing	N/D	N/D	N/D
	Event duration	2s	1ms	2s
Airbus A380	No of transients	24		500
	Distribution	random		random
	Impulse spacing	10 - 200ms		10µs - 10ms
	Event duration	2s		2s
SAE-ARP5412	No of transients	14 strokes	20 of (WF3)	3 bursts of (B1)
	Distribution	random	random	random
	Impulse spacing	10 - 200ms	50µs - 1000µs	30ms - 300ms
	Event duration	1.5s		3s
	Test time			5min.
Boeing D6	No of transients		20 of (WF3)	24
	Distribution		random	random
	Impulse spacing		20µs - 50µs	10ms - 200ms
	Event duration			
	Test time			0.5 - 2s

E.8 References

[1] *Lightning and Surge,* G&M Compliance, Inc. [Electronically accessed 12 March 2010], <http://gmcompliance.thomasnet.com/item/all-categories/lightning-surge-2/item-1007?&forward=1>

[2] *The American Association for Laboratory Accreditation,* A2LA, The American Association for Laboratory Accreditation, [Electronically accessed 11 March 2010], <http://www.a2la.org/scopepdf/1719-02.pdf>

[3] *Lightning Effects on Aircraft of the composite material,* Metallum, [Electronically accessed 12 March 2010], <http://www.metallum.com.br/17cbecimat/resumos/17cbecimat-205-004.pdf>

[4] *Lightning Protection of Aircraft,* IEEE, [Electronically accessed 15 Marchg 2010], <http://eeeic.eu/proc/papers/84.pdf>

[5] *Federal Aviation Regulations,* Flight Sim Aviation, [Electronically accessed 16 March 2010], <http://www.flightsimaviation.com/data/FARS/part_25.html>

[6] *DO-160,* Wikipedia, the free encyclopedia, Updated 23/03/2010, [Electronically accessed 23 March 2010], <http://en.wikipedia.org/wiki/DO-160>

[7] *DOD-160,* CELAB, your solution in certification, [Electronically accessed 3 April 2010], <http://www.ceinfo.eu/DOD160.htm>

[8] *Updates on RTCA DO-160,* IEEE, [Electronically accessed 02 March 2010], <http://www.google.es/url?sa=t&source=web&ct=res&cd=1&ved=0CAYQFjAA&url=http%3A%2F%2Fewh.ieee.org%2Fr6%2Focs%2Femc%2Fimages%2Fpdf%2Fupdates%2520on%2520rtca%2520do-160%2520lightning%2520testing%25202.ppt&rct=j&q=and+F+are+driven+by+the+use+of+composite+materials+used+for+airframe+construction.+Many+composites+do+not+conduct+lightning+currents+the+way+metal+airframes+do%3B+hence%2C+the+possibility+of+higher+voltages+and+currents+getting+into+cables+and+equipment+of+the+aircraft.&ei=rBvHS5_uA5P9_AaNu4TYDA&usg=AFQjCNGLAVrocNjamt67J1Aby9WBec9B3Q>

[9] EUROCAE Annual Report (2005-2006), EUROCAE, [Electronically accessed 03 March 2010], <http://www.eurocae.net/annualreport.pdf>

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[12] Updates to Advisory Circular (AC) 20-155*, SAE Documents to Support Aircraft Lightning Protection Certification*, Updated 4/28/2006, [Electronically accessed 23 March 2010], <http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgAdvisoryCircular.nsf/list/AC%2020-155/$FILE/AC%2020-155_update.pdf>

[13] *Explanation and Experiences with RTCA/DO160 Level 5 avionics testing,* EMC Partner, [Electronically accessed 24 March 2010], < http://www.emc-partner.com/resource/pdf/a_do-160_level5.pdf>

APPENDIX F. FAA REGULATIONS

FAA Federal Aviation regulations (FARS, 14 CFR) Part 33 Section 5. Instruction manual for installing and operating the engine. [1]

Each applicant must prepare and make available to the Administrator prior to the issuance of the type certificate and to the owner at the time of delivery of the engine, approved instructions for installing and operating the engine. The instructions must include at least the following:

(a) *Installation instructions*
  1. The location of engine mounting attachments, the method of attaching the engine to the aircraft, and the maximum allowable load for the mounting attachments and related structure.
  2. The location and description of engine connections to be attached to accessories, pipes, wires, cables, ducts, and cowling.
  3. An outline drawing of the engine including overall dimensions.

(b) *Operating instructions*:
  1. The operating limitations established by the Administrator.
  2. The power or thrust ratings and procedures for correcting for nonstandard atmosphere.
  3. The recommended procedure, under normal and extreme ambient conditions for:
    (i) Starting;
    (ii) Operating on the ground; and
    (iii) Operating during flight.

F.1 Reference

[1] *Regulations,* Flight Sim Regulations, [Electronically accessed 15 April 2010], <http://www.flightsimaviation.com/data/FARS/part_33-5.html>

APPENDIX G. TESTS

G.1 Carbon Fibre

Measures of the material: 232 x 26.18 x 2.24 mm

1. Values

   V = 24 V

   R = 3.3 Ω

The value of the resistance is very small. The carbon fibre conducts electricity a little bit, so with R = 3.3 Ω it is a short circuit.

2. Values

   V =24 V

R = 220 Ω

$\rho = 10^{-9}$ Ω·m

The current in the circuit (see Figure G.1.1) should be (theoretically): I = 0.109 A

The results obtained (see Table G.1.1):

Table G.1.1 Carbon Fibre Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0.639	0.612	0.611	0.599	0.589	0.591	0.592	0.567	0.589	0.584
I (A)	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.2	0.2
V_R (V)	23	23	23	23	23	23	23	23	23	23

Figure G.1.1 Carbon Fibre Test

Note: The temperature in the resistance increases. The amperimeter fluctuates, when the current is a little bit over 0.1 it changes into 0.2.

G.2 Galvanized carbon steel

Values

Measures of the material: 91.21x19.12x0.97 mm

V =24 V

R = 220 Ω

The current in the circuit (see Figure G.2.1) should be (theoretically): I = 0.109 A

The results obtained (see Table G.2.1):

Table G.2.1 Galvanized Carbon Steel Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0	0	0	0	0	0	0	0	0	0
I (A)	0.1	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.1
V_R (V)	24	24	24	24	24	24	24	24	24	24

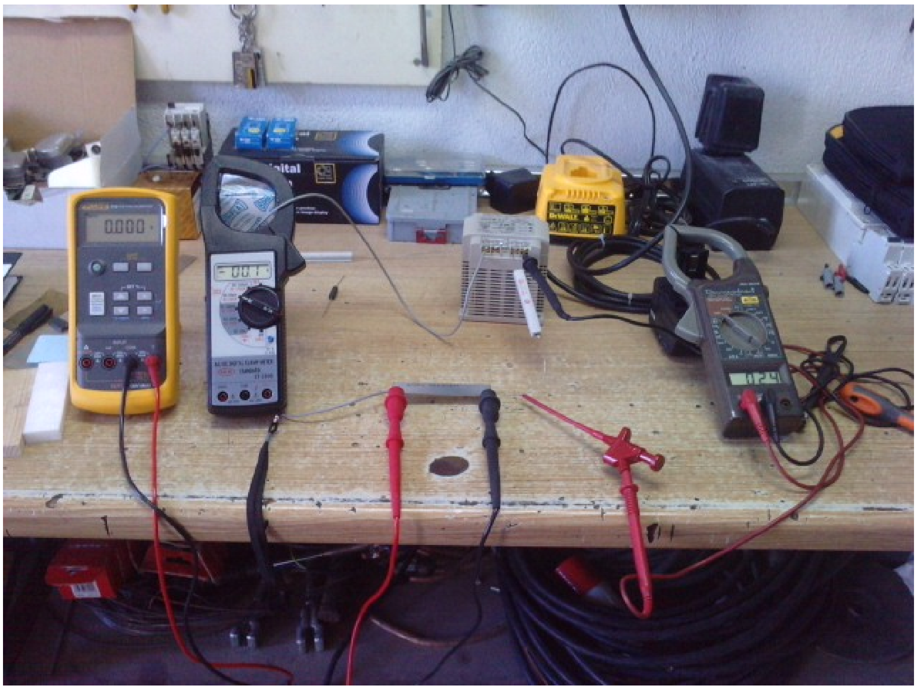

Figure G.2.1 Galvanized Carbon Steel Test

G.3 Stainless steel 304

Stainless steel type 1.4301 is also known as grade 304 respectively (see Table G.3.1). Type 304 is the most versatile and widely used stainless steel. It is still sometimes referred to by its old name 18/8 which is derived from the nominal composition of type 304 being 18% chromium and 8% nickel [1].

Table G.3.1 Typical chemical composition for 304 stainless steel alloys

%	304	304L	304H
Carbon (C)	0.08 max	0.03 max	0.10 max
Manganese (Mn)	2.0	2.0	2.0
Silicon (Si)	0.75	0.75	0.75
Phosphorus (P)	0.045	0.045	0.045
Sulphur (S)	0.03	0.03	0.03
Chromium (Cr)	18-20	18-20	18-20
Nickel (Ni)	10.5	12	10.5
Nitrogen (N)	0.1	0.1	-

Values

Measures of the material: 80.48x41.33x1.04 mm

V =24 V

R = 220 Ω

$\rho = 0.072 \times 10^{-6}\ \Omega.m$

The current in the circuit (see Figure G.3.1) should be (theoretically): I = 0.109 A

The results obtained (see Table G.3.2):

Table G.3.2 Stainless Steel 304 Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0.005	0.004	0.005	0.006	0.010	0.008	0.010	0.010	0.010	0.012
I (A)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
V_R (V	24	24	24	24	24	24	24	24	24	24

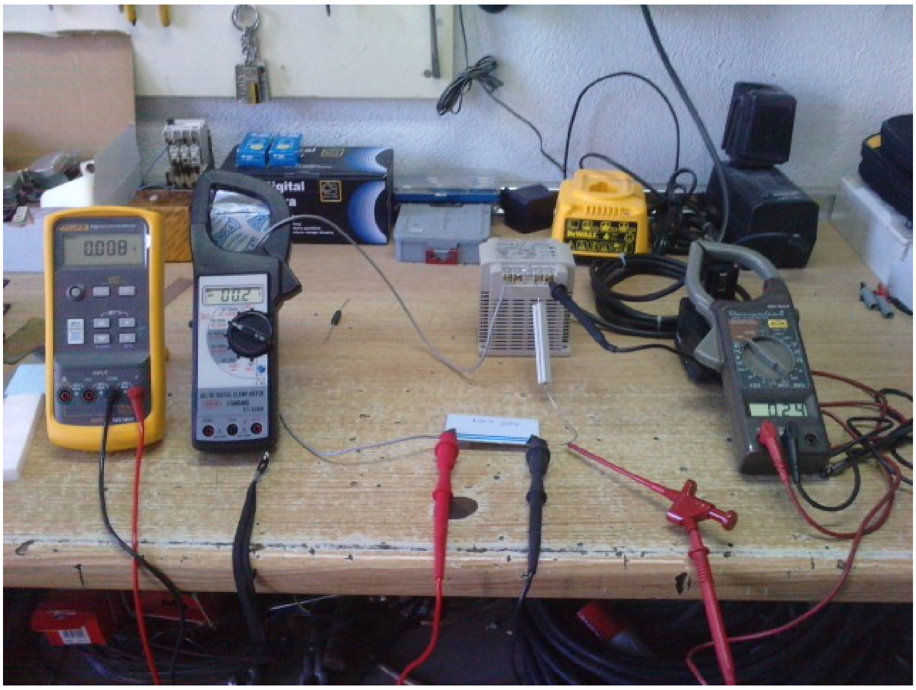

Figure G.3.1 Stainless Steel 304 Test

G.4 Aluminium

Values

Measures of the material: 139.56x40x1.06mm

V =24 V

R = 220 Ω

ρ = 2.65 ~ 8.21 × 10^{-8} Ω·m

The current in the circuit (see Figure G.4.1) should be (theoretically): I = 0.109 A

The results obtained (see Table G.4.1):

Table G.4.1 Aluminium Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0	0	0	0	0	0	0	0	0	0
I (A)	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2
V_R (V)	24	24	24	24	24	24	24	24	24	24

Figure G.4.1 Aluminium Test

G.5 Bronze

Values

Measures of the material: 75.91x39.80x0.09mm

V =24 V

R = 220 Ω

$\rho = 1.232 \cdot 10^{-8}\ \Omega \cdot m$

The current in the circuit (see Figure G.5.1) should be (theoretically): I = 0.109 A

The results obtained (see Table G.5.1):

Table G.5.1 Bronze Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
I (A)	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2
V_R (V)	24	24	24	24	24	24	24	24	24	24

Figure G.5.1 Bronze Test

G.6 Ungalvanized carbon steel

Values

Measures of the material: 24.81x12.01x3.51mm

V =24 V

R = 220 Ω

$\rho = 1.611 \cdot 10^{-7}\ \Omega \cdot m$

The current in the circuit (see Figure G.6.1) should be (theoretically): I = 0.109 A

The results obtained (see Table G.6.1):

Table G.6.1 Ungalvanized Carbon Steel Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
I (A)	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2
V_R (V)	24	24	24	24	24	24	24	24	24	24

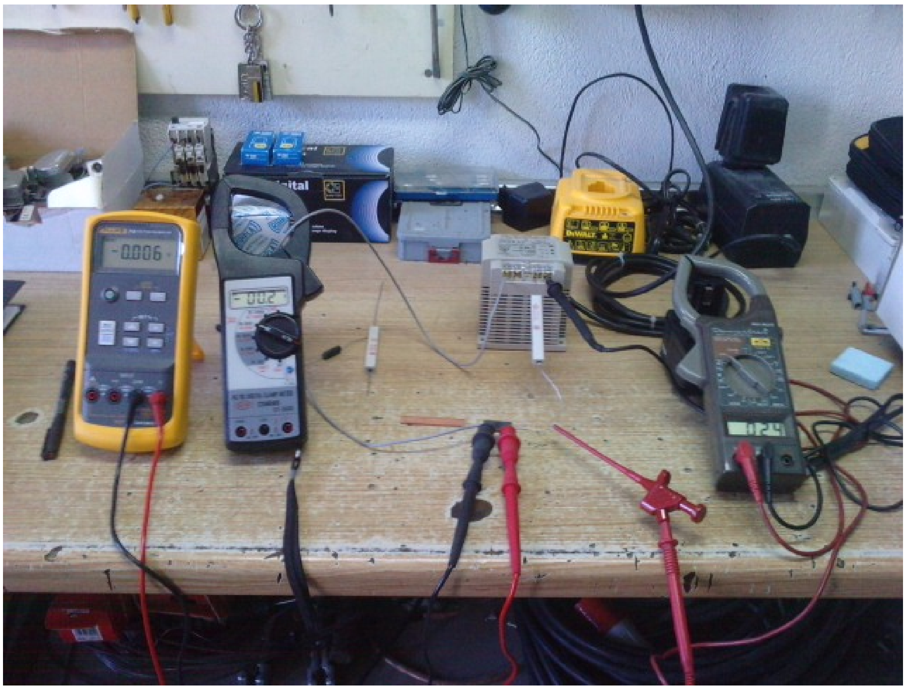

Figure G.6.1 Ungalvanized Carbon Steel Test

G.7 Copper

Values

Measures of the material: 56.89x10.04x1.42mm

V =24 V

R = 220 Ω

$\rho = 16.78 \cdot 10^{-9}\ \Omega \cdot m$

The current in the circuit (see Figure G.7.1) should be (theoretically): I = 0.109 A

The results obtained (see Table G.7.1):

Table G.7.1 Copper Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	0	0	0	0	0	0	0	0	0	0
I (A)	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.2
V_R (V	24	24	24	24	24	24	24	24	24	24

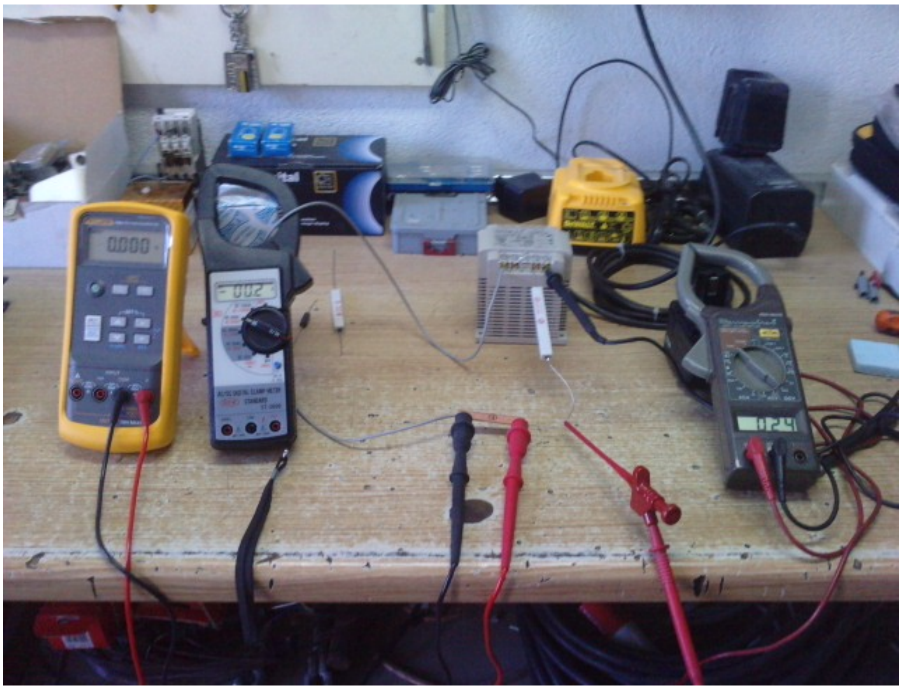

Figure G.7.1 Copper Test

G.8 Glass fibre 1

Values

Measures of the material: 64.13x10.36x0.31mm

V =24 V

R = 120 Ω

The current in the circuit (see Figures G.8.1 and G.8.2) should be (theoretically): I = 0.2 A

The results obtained (see Table G.8.1):

Table G.8.1 Glass Fibre 1 Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A	0	0	0	0	0	0	0	0	0	0
V_R (V	0	0	0	0	0	0	0	0	0	0

Figure G.8.1 Glass Fibre 1 Test (V_M)

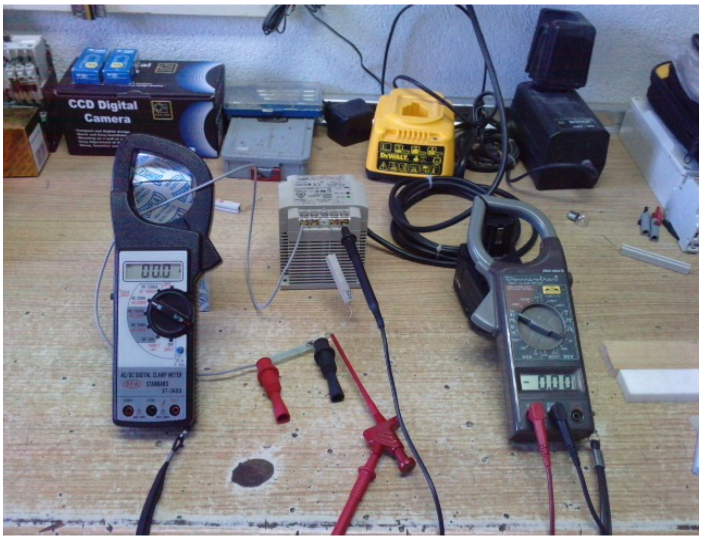

Figure G.8.2 Glass Fibre 1 Test (V_R)

G.9 Wood

Values

Measures of the material: 118.48x35.90x11.95mm

V =24 V

R = 120

The current in the circuit (see Figures G.9.1 and G.9.2) should be (theoretically): I = 0.2 A

The results obtained (see Table G.9.1):

Table G.9.1 Wood Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
V_R (V)	0	0	0	0	0	0	0	0	0	0

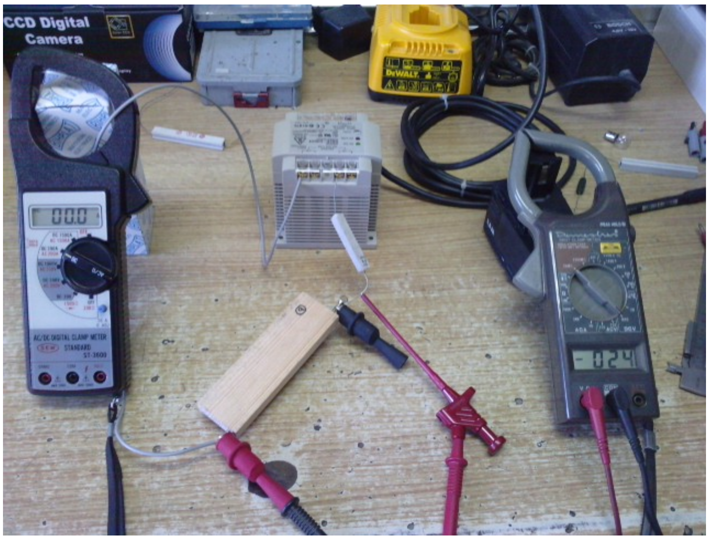

Figure G.9.1 Wood Test (V_M)

Figure G.9.2 Wood Test (V_R)

G.10 Polyethylene

Values

Measures of the material: 109.46x28.66x12.34mm

V =24 V

R = 120

The current in the circuit (see Figures G.10.1 and G.10.2) should be (theoretically): I = 0.2 A

The results obtained (see Table G.10.1):

Table G.10.1 Polyethylene Test Results

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
V_R (V	0	0	0	0	0	0	0	0	0	0

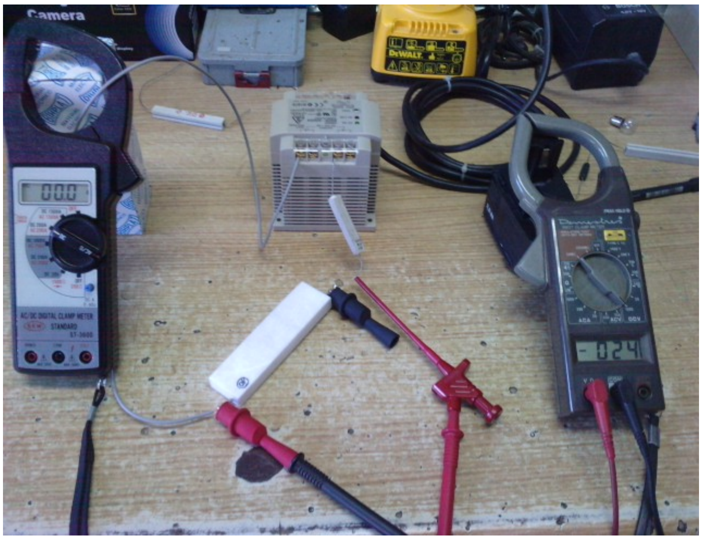

Figure G.10.1 Polyethylene Test (V_M)

Figure G.10.2 Polyethylene Test (V_R)

G.11 Foam

Values

Measures of the material: 45.26x45.08x9.43mm

V =24 V

R = 120

The current in the circuit (see Figures G.11.1 and G.11.2) should be (theoretically): I = 0.2 A

The results obtained (see Table G.11.1):

Table G.11.1 Foam Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
V_R (V)	0	0	0	0	0	0	0	0	0	0

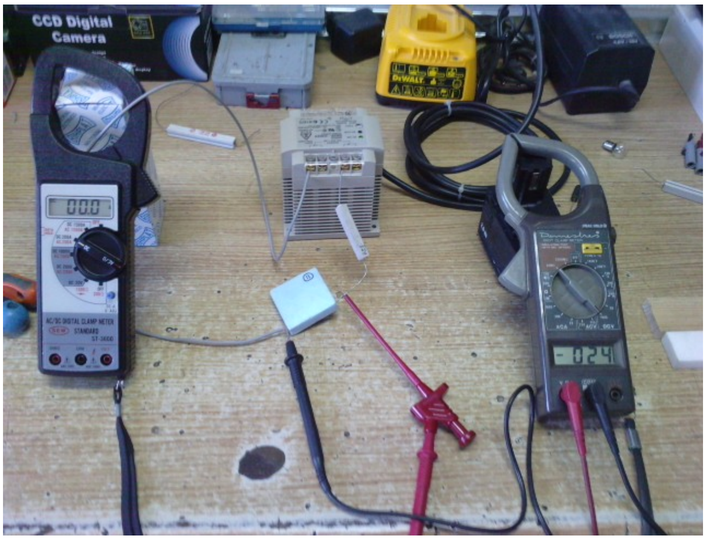

Figure G.11.1 Foam Test (V_M)

Figure G.11.2 Foam Test (V_R)

<u>G.12 Epoxy resin</u>

Values

Measures of the material: 55.71x22.43x1.46mm

V =24 V

R = 120

The current in the circuit (see Figures G.12.1 and G.12.2) should be (theoretically): I = 0.2 A

The results obtained (see Table G.12.1):

Table G.12.1 Epoxy resin Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
V_R (V)	0	0	0	0	0	0	0	0	0	0

Figure G.12.1 Epoxy resin Test (V_M)

Figure G.12.2 Epoxy resin Test (V_R)

G.13 Semi-conducting self-fusing tape

Values

Measures of the material: 119.67x18.90x0.8mm

V =24 V

R = 220

The current in the circuit (see Figure G.13.1) should be (theoretically): I = 0.109 A

The results obtained (see Table G.13.1):

Table 7.2.13.1 Semi-conducting self-fusing tape Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	21	21	21	21	21	21	21	21	21	21
I (A)	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
V_R (V)	2.98	3.03	3.03	3.04	3.04	3.05	3.04	3.04	3.04	3.05

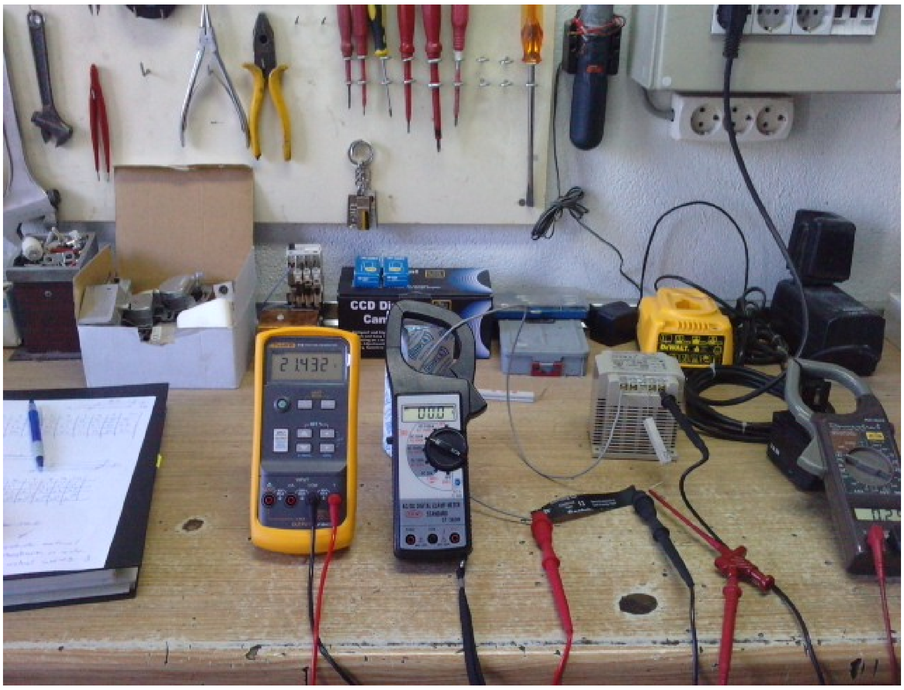

Figure G.13.1 Semi-conducting self-fusing tape Test

G.14 Glass fibre 2

Values

Measures of the material: 60x18.57x0.01mm

V =24 V

R = 120

The current in the circuit (see Figures G.14.1 and G.14.2) should be (theoretically): I = 0.2 A

The results obtained (see Table G.14.1):

Table G.14.1 Glass Fibre 2 Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
V_R (V)	0	0	0	0	0	0	0	0	0	0

Figure G.14.1 Glass Fibre 2 Test (V_M)

Figure G.14.2 Glass Fibre 2 Test (V_R)

G.15 Plastic

Values

Measures of the material: L=82.02mm Ø=25.26mm

V =24 V

R = 220

The current in the circuit (see Figures G.15.1 and G.15.2) should be (theoretically): I = 0.109 A

The results obtained (see Table G.15.1):

Table G.15.1 Plastic Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
V_R (V)	0	0	0	0	0	0	0	0	0	0

Figure G.15.1 Plastic Test (V_M)

Figure G.15.2 Plastic Test (V_R)

G.16 Glass

Values

Measures of the material: 69x63x2mm

V =24 V

R = 220

The current in the circuit (see Figures G.16.1 and G.16.2) should be (theoretically):

I = 0.109 A

The results obtained (see Table G.16.1):

Table G.16.1 Glass Test Results

	1	2	3	4	5	6	7	8	9	10
V_M (V)	24	24	24	24	24	24	24	24	24	24
I (A)	0	0	0	0	0	0	0	0	0	0
V_R (V)	0	0	0	0	0	0	0	0	0	0

Figure G.16.1 Glass Test (V_M)

Figure G.16.2 Glass Test (V_R)

Note: The following tests could have been done with the resistance of 3.3 Ω, since they do not conduct electricity:

- 8 (Glass Fibre 1),
- 9 (Wood),
- 11 (Foam),
- 12 (Epoxy Resin),
- 13 (Glass Fibre 2),
- 14 (Plastic)
- 15 (Glass)

G.17 Appendix

[1] *Stainless Steels - Stainless 304 Properties, Fabrication and Applications,* AzoM Materials, [Electronically accessed 23 April 2010], <http://www.cabot-corp.com/wcm/download/en-us/sb/ESD-Test-Sp1.pdf>

APPENDIX H. AVIONICS TESTS SYSTEM

[1] *Avionics Test System,* EMC Partner, [Electronically accessed 12 March 2010], <http://www.emc-partner.com/resource/pdf/e-aircraft.pdf>