Definitions of Test Conditions for High Voltage Aerospace Systems Using the IAGOS Atmospheric Dataset

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Abstract

Aerospace electrical systems are continuing to increase their voltage levels to meet the on-board power demands of more-electric aircraft (MEA) where hydraulic and pneumatic systems are replaced with electrical equivalents. This trend will only continue as hybrid and all-electric aircraft are developed. These higher power demands require the use of higher voltages and as such it is essential to explore the behaviour of the insulation system in the aerospace environment. This insulation must operate in an environment where the operating and ambient temperatures range from 250°C to -65°C, the air pressure is around one tenth of that at ground level and where the levels of humidity and ozone vary rapidly. Understanding the impact of these variables on aircraft high voltage insulation systems is crucial in predicting their behaviour and lifetime. Our work with the IAGOS atmospheric dataset presents worst-case and typical flight environments for higher than expected cruising altitudes, and uses the findings to compare the relative rates of degradation of insulating materials at ground and cruising altitudes.

Introduction

Future aircraft systems are pushing to higher voltages to deliver the power densities required of more-electric aircraft (MEA) and the benefits they promise. This is done by replacing the hydraulic and pneumatic systems with electrical equivalents which aim to lower carbon emissions through lower fuel consumption, improved safety and reliability as a result of more integrated propulsion and distribution systems [1]. For instance, in the hybrid-electric project between Airbus, Siemens and Rolls-Royce due 2020, the E-fan X is expected to replace one of four gas turbines with a 2 MW electric motor [2]. For these revolutionary technologies to be implementable for future aircraft, an increase in the peak levels of current or voltage is clearly required. If higher currents are used, the conductor size required to keep the operating temperature of the power system at a satisfactory level would not be acceptable from a weight perspective [3]. Therefore, the most suitable method is to increase the operating voltages to minimise any risk of overheating the electrical systems and to manage the challenges associated with voltage drop.

The use of high voltages (HV) is already present in-service Airbus A350 and Boeing 787 which have double the operating voltages of previous commercial aircraft at 230 V AC. However, higher voltages raise the risk of damaging partial discharges (PD) and result in an increased rate of electrical ageing of equipment on board [4]. This is only exacerbated under lower air pressures where PD onset can occur at lower voltages due to the changes in the discharge process associated with low pressure. If a system is operated under HV under low atmospheric pressures, greater electrical ageing is bound to accelerate any chemical and / or mechanical ageing mechanisms expected in the system [5]. The way that aerospace equipment ages in comparison to ground level equipment is likely to be different as a result of spending a majority of its flight in the environmental conditions experienced during cruise.

This paper provides an example of how environmental data is essential for the design and qualification of high voltage electric systems used onboard aircraft. A specific example relating to insulation ageing is used. To understand how electrical insulation ages, theoretical models, such as the inverse power law, the relationship between life as a result of the voltage, and the Arrhenius equation, the relationship between chemical reaction rate as a function of temperature, have been widely used to predict lifetime; this study uses the operating temperature of the insulation to determine the rate of ageing using the latter. Although real cases will evidently involve a combination of stressors that complicate ageing mechanisms, the aerospace environment in which the electrical systems operate in must first be understood.

Importance of Mapping the Aerospace Environment

Aircraft systems are expected to operate at ground-level, switched on at the gate and taxi on the runway before take-off, to high altitudes of around 11 km during the cruise stage. Cruising altitudes are equivalent to air pressures of 22 kPa, with some systems qualified to operate up to 15 km (11.6 kPa) [6]. The temperature typically ranges from ground ambient temperatures to -55°C expected for cruise altitudes. There is also variable oxygen and water concentrations which influence the irregularity and unpredictability of humidity levels during flight. Finally, ozone concentrations peak at altitudes above 10 km, with higher probabilities of aircraft entering the ozone layer on routes away from the equator and during summer months where boundaries drop by 1–2 km [7].

The departure and destination airport location and the flight route influence the environment surrounding insulating systems used on an aircraft. This has an impact on the material ageing processes as a result of varying temperatures and voltage levels at which partial discharge takes place [8] and, if a certain combination of circumstances arise, can result in the need to manage issues such as high thermal build-up and condensation being deposited onto insulated surfaces. Knowledge of the aerospace environment must therefore influence the way HV systems for aerospace applications are designed and tested. Systems must be safe to fly and components suitable for use on the ground must be carefully assessed to see if they would be suitable for use at altitude.

Existing Environmental Standards

In the most widely used standard for environmental testing of aerospace equipment, RTCA DO-160, the standard specifies ambient ground-level temperatures of 15 – 35°C and ambient air pressures of 84 – 107 kPa, and for an average cruise altitude of 10.7 km, a
minimum operating temperature of -55°C and a minimum air pressure of 23.8 kPa [6]. This is in close agreement with the International Standard Atmosphere (ISA) that provides separate equations that define temperature and pressure for a given altitude, which in this case is a temperature of -56.5°C and pressure of 22.7 kPa for an altitude of 11 km [9]. Aside from defining ambient ground and operating temperatures, the standard also includes information on ground survival temperatures and short-time operating temperatures. Ground survival high and low temperatures signify the extreme conditions that equipment located at ground-level must be tested, and for the equipment to withstand if it is to qualify. Although it is important to highlight that the equipment does not have to be operating under the ground survival conditions, the temperature will ultimately influence heat transfer if the equipment is then switched on. The short-time operating temperature is maximum temperature that the equipment is expected to endure while operating at ground-level, prior to take-off. This is typically the same as the operating temperatures given for all equipment categories in the RTCA standard, except for category A3; this category specifies pressurisation, above 57 kPa, or maximum altitude for sea-level, with partial or full temperature control surrounding the system stated in the standard.

It is therefore important to not only include the operating conditions but also the ground survival temperatures in test specifications; whether that is thermal endurance testing of systems placed in an constant extreme environment and/or high load and the time-to-failure is measure, or in a step test where temperature and/or load is gradually increased to find the maximum withstand environment. It is not clear that these existing standards will provide adequate atmospheric definitions for all forms of testing required for HV systems to be used on future hybrid and all-electric aircraft.

**IAGOS Environmental Dataset**

Aerospace environmental data for over 24 years is contained within the In-service Aircraft for a Global Observing System (IAGOS) database. IAGOS has been set-up by European research institutes as a successor of the Water Vapour on Airbus In-service Aircraft (MOZAIC) program. The aim of this project has been to observe, record and track the atmospheric composition within a changing climate for weather prediction and metrological applications, and the effect of a growing population on air quality and levels of carbon emissions released into the atmosphere [11].

This database holds information such as aircraft altitude, air temperature, pressure, relative humidity, water and trace gas concentrations for over 54,000 flight profiles of a modified fleet of Airbus A330 and A340 across 148 airports in the world. In this paper we will be using the data available to determine the flight environment a typical aircraft may experience, in terms of both average and extreme temperatures, altitudes and pressures and to be able to conclude with an insight into better testing conditions with set environmental parameters for future testing of HV equipment.

**Method**

**IAGOS Data Processing**

As of June 2018, there were 56,432 flights in the database that can be found at [http://iagos.sedoo.fr/][12]. In our work, a total of 54,200 flight data files for the years 1994 - 2017 were obtained from the IAGOS website. This included data from all airports regardless of flight duration, departure or arrival geographical location, flight path and seasonal variances. The parameters of interest included in the database are: altitude (m), air pressure (pa), air temperature (K), water vapour volume (ppm), ozone concentration (ppb), relative humidity of liquid water (0-100%) as well as geographic index for each flight.

From the raw data files, a new database was created which included new additions, such as flight duration, calculated from frequency of observations within data files, as well as ascent and descent durations for each profile determined from the ascent and descent index. Individual maximum, mean and minimum values of each parameters were also added. Finally, error processing (where data was clearly incorrect due to sensor and calibration issues) removed selected files to give a total of 46,185 flights for analysis.

**Results and Discussion**

**Environmental Analysis**

Ground level temperatures were previously discussed as important for systems that are electrically loaded on the ground and their temperatures can rise quickly if surrounded by high environmental conditions and thereby increasing the rate of insulation ageing. The ground air temperature of airports visited in the IAGOS program can be seen in Figure 1 below.

The distribution shows a multi-banded pattern, which could be due to seasonal effects if the base is a handful of similarly located airports, or possibly the resolution of the instruments used. Two key peaks are observed, the first peak seen at 17°C, and the second peak, also the mode, is at 28°C. An 11°C difference between the peaks is substantial for the onset of material ageing in HV systems, as discussed in the lifetime prediction section later in the paper. The temperature ranges from -12°C and reaches as high as 40°C. This range shows that if an aircraft is taxiing at the departure airport for 30 minutes at an ambient of 30°C, while a second aircraft taxiing for 10 minutes at an ambient of 0°C, the temperature of the equipment will vary considerably depending on airport ambient air temperature. The cooler atmosphere will cool the initial start of the system, while the warmer ambient temperatures for a longer duration of taxi will cause engine and primary controls to warm up to higher temperatures than expected by researchers and manufacturers.
Air temperature during cruise can be seen in Figure 2 to have an even distribution. The majority of the data lies between the temperatures of -35°C and -65°C with a mean cruise temperature of -51°C. The distribution is slightly uneven on the right-hand side due to flights with shorter durations which skew the distribution towards warmer temperatures as they do not reach altitudes as high as those for long-haul flights. Nevertheless, the minimum, mean and maximum values can be used to set environmental test chamber temperatures, while the normal distribution means that it can be easily incorporated within testing plans of ageing aerospace equipment such as cabling, wires or component either HV or not.

A similar distribution can be seen for cruise air pressures in Figure 3 which ranges from 18 to 26 kPa, while a substantial number of long-haul aircraft are found to operate at 21.6 kPa. The distribution shows clear bands observed for particular cruising altitudes that may have been defined by air traffic control or general standards. These pressure increments could potentially be used within testing methodologies for simulated environments, where ageing rates at particular cruising pressures can be compared alongside one another to determine a ‘typical’ pressure.

The relationship between altitude and air temperature can be seen in Figure 4 which shows the percentiles of temperatures for each particular altitude. The dash-dot (red) and dash (blue) lines show the 99.5% and 95.0% percentiles respectively, while the solid (black) line is the mean temperature at a given altitude. The aircraft is expected to operate in between temperatures of -65 and 40°C, with few aircrafts reaching as low as -74°C, but still a substantial difference than that stated in the RTCA standard for environmental testing of aerospace equipment. The nature of the distribution is symmetrical for ground and cruise altitudes, but this is skewed towards the warmer regions in the intermediate altitudes. The gaps between the 95.0% and 99.5% lines are closer together at temperatures above the mean, meaning the data is more concentrated, than those at colder temperatures of that below the mean. The regions with the greatest variance in temperature are at ground-level and at cruising altitudes. These could be worse in terms of thermal ageing of equipment due to less predictability.

A 3-dimensional visualisation of the temperature data in Figure 4 is shown in Figure 5, where the distribution can be seen more clearly (orientation of the axes are slight different as it best shows the peaks and troughs of the distribution). The concentration of the cruising temperatures above 12 km shows that the temperature of the air becomes much more stable and predictable from this altitude. Comparing the ground and cruise temperature values from RTCA with IAGOS in Table 1, show overall similar mean trends, with IAGOS having a greater range, especially at higher altitudes where RTCA data may be less representative of the aerospace environment. RTCA defines the environment at 10 km cruising altitude as -55°C, while IAGOS has observed temperatures anywhere from -35°C to -60°C; the operating low temperature in RTCA remains at -55°C regardless of whether equipment is operating at an altitude of 10.7 or 21.3 km.

Table 1. Comparison of RTCA and IAGOS Environmental Definitions

<table>
<thead>
<tr>
<th></th>
<th>RTCA</th>
<th>IAGOS</th>
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</thead>
<tbody>
<tr>
<td>Ground Ambient Temp.</td>
<td>15 to 35</td>
<td>-15 to 40</td>
</tr>
<tr>
<td>Ground Survival Temp.</td>
<td>-55 to 85</td>
<td>-50 to 105</td>
</tr>
<tr>
<td>Maximum Ground Alt.</td>
<td>1325</td>
<td>1680</td>
</tr>
<tr>
<td>Ground Ambient P.</td>
<td>84 to 107</td>
<td>83 to 102</td>
</tr>
<tr>
<td>Operating Low Temp.</td>
<td>-55</td>
<td>-55</td>
</tr>
<tr>
<td>Operating Altitude</td>
<td>10.68 (Cat.)</td>
<td>10.05 to 12.52</td>
</tr>
<tr>
<td>Operating Low P.</td>
<td>23.8</td>
<td>17.7 to 26.2</td>
</tr>
</tbody>
</table>
The key difference found between the IAGOS study and RTCA standard is higher than expected altitudes reached by commercial aircraft, which will subsequently affect any related environmental parameters such as cruise air pressure and temperature. This study of the IAGOS data therefore suggests that any aircraft systems that are exposed to the cruising environment during flight are experiencing lower than expected operating pressures and temperatures than that is stated in the RTCA standard. This is likely to influence the performance of HV equipment, as aircraft spend the majority of their operating life at high altitudes, where electrical and chemical ageing mechanisms and rates will be dependent on the environment. This will likely test the design of HV systems, for instance, clearance distances of electronic components, thermal expansion of connectors and PD damage prone materials in motor windings and cabling.

**Example Use of IAGOS Data in Lifetime Calculations**

In an aerospace system, the operating temperature will vary throughout the flight cycle. This could be due to changes in electrical loading and/or changes environmentally. In this analysis, a ‘typical’ representation of the aerospace environment is used within a thermal model for the lifetime assessment of an insulated cable. Taking an aerospace cable used in the C2 zone of the RTCA standard as an example, it is expected to operate in an unpressurised and uncontrolled temperature location during cruise at 10.7 km, and the operating temperature and short-term operating temperatures are both given as -55 to 70°C, with ground survival conditions given as -55 to 85°C [6]. If the equipment is said to be located on the wing, and the aircraft has sat idle at 40°C ground temperature long enough for all systems exposed to reach equilibrium with the ambient air, the short-term operating temperature will start at 40°C and continue to increase during the taxi stage. The colder air temperatures during ascent and cruise is expected to be beneficial for equipment cooling, especially if in direct contact with air outside of aircraft. Conversely, if the aircraft is flying at higher altitudes, a lower air density reduces the amount of heat transfer from loaded systems.

From a COMSOL model of a 00 AWG copper conductor with a single layer of ETFE insulation, the temperature of the conductor and insulation as a result of the environment can be found. The assessment of ageing is based on a purely thermal mechanism, taking into account both the air temperature of the environment and Joule heat conducted and radiated into the outer insulation layer. The results from the model are shown in Table 2, where ‘typical’ ground conditions corresponds to a cable temperature of 111°C, while a ‘typical’ cruise environment gives a cable temperature of 88°C. Both environments yield temperatures that are greater than the RTCA short-term operating ground survival temperatures, with ground-level environment surpassing the short term operating temperature of 85°C by 26°C.

The thermal output of the model can then be used in an Arrhenius model to establish a relationship between the aerospace environment and any ageing mechanisms that is thermally activated:

\[ k = Ae^{-E_a/RT} \]  

(1)

where \( k \) = rate (s⁻¹), \( A \) = pre-exponential factor, \( E_a \) = activation energy in (J mol⁻¹), \( R \) = gas constant (J mol⁻¹ K⁻¹) and \( T \) = temperature (K).
The activation energy and pre-exponential factor values are material dependent for cable with a 1 mm thick ETFE insulating layer and have been taken from Hondred et al. which state that the degradation mechanism of ETFE is not purely a single order mechanism [13].

Solving the Arrhenius equation for ground-level and moderate cruise conditions gives the ‘relative’ rate of degradation the cable insulation in the model. It is important to highlight that this does not give the lifetime but as a comparison of ageing rates and the gradual degradation that may occur in the two varying environments.

### Table 2. Lifetime Prediction of a 50 W/m Cable Modelled in COMSOL

<table>
<thead>
<tr>
<th>Temperature of Cable</th>
<th>Cruise-level (-60°C, 20 kPa)</th>
<th>Entire Flight Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-level (20°C, 100 kPa)</td>
<td>111°C</td>
<td>88°C</td>
</tr>
<tr>
<td>Relative Lifetime of Cable</td>
<td>100%</td>
<td>107%</td>
</tr>
</tbody>
</table>

Table 2 shows the relative lifetime results for an aerospace cable operating at 50 W/m that ages 7% slower when operating in an aerospace environment than the same cable that is under ground-level conditions. The lifetime of a cable experiencing an entire flight cycle has a slightly increased relative life compared to the cruise example. This could be due to the fact that an aircraft spends the majority of its operation at high altitudes, with the additional decrease in rate of reaction could be a result of the change in air density during ascent. This would improve heat transferred from the cable to the environment, thereby reducing the temperature gradient across the ageing material. A drawback from this model is that it is purely thermal and any electrical ageing that has a substantial impact at low air pressure has not been accounted for, and there is a great possibility that this will change the overall lifetime. In addition, the model only studies temperature and pressure effects on thermo-oxidative mechanisms and does not include any hydrolytic effects that could occur during descent.

Finally, it would be useful to investigate the heat transfer dynamics, where in the next stage of this work we would like to study the time-dependent thermal flow, such as the rate at which the conductor will reach a particular temperature, and the change of heat transfer to the environment would be under varying conditions. It is hoped that the IAGOS dataset can be directly fed into the model to assess how the environment during ascent and descent influence the ageing and lifetime of HV equipment.

### References


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