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An introduction to a new aerospace lightning direct effects research programme and the significance of Zone 2A waveform components on sparking joints

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***Abstract*—PROTEST is the name of a new UK based aerospace lightning direct effects research program with the principal purpose of researching the lightning direct effects of structural aircraft fuel tank joints. It is particularly focused on understanding the out-gassing phenomena and its relationship with the various design parameters of composite structures. Early activity within the project investigated the waveform components that are of most relevance to future studies. The paper documents the findings of this early activity. It was found that the D-component is the only aerospace standard lightning current component relevant to the generation of out-gassing phenomena in Zone 2A. Lightning direct effects tests where the C-component was used in isolation did not produce any out-gassing when there was a total deposited charge of both 100 and 200 Coulombs. Combined waveform sequences of D, DB and DBC all produced similar results; and it was found that out-gassing is sensitive to scaled versions of the D-component.**

Keywords- sparking joints; CFRP; lightning direct effects, out-gassing, PROTEST

I. INTRODUCTION

Fuel ignition threats from direct effects of lightning strikes to aircraft are a major concern to aircraft manufacturers. Multiple layers of protection are commonly implemented in order to address this threat. However, the development of such protection measures within the constraints of modern aircraft development objectives is challenging.

A particular lightning direct effect (LDE) that creates a fuel ignition hazard is caused by lightning current transfer between metallic fasteners and the surrounding structure within the fuel tank region of the aircraft. Such high current transfer can create thermal sparks, generating molten debris that is ejected by hot pressurized gas. This event is commonly referred to as 'out-gassing' within the aerospace industry.

The industry has been aware of this threat for many years. Protection measures and certification guidelines have been developed alongside advancements in fuel tank structural materials. The design of such protection methods would greatly benefit from further understanding of the physics of the phenomenon which is currently not fully understood. In particular, the relationship between the physical mechanisms of out-gassing and certain design parameters can lead to efficiencies in both the protection technologies and the entire development process by reducing the necessity to rely on physical tests.

The Protection of Structures from Lightning Strike (PROTEST) is a collaborative research effort supported by the UK's Aerospace Technology Institute. Project partners include Airbus Group Innovations, Airbus Operations, Cardiff University, Hexcel Composites and the National Composites Centre (UK). The project addresses the understanding of out-gassing phenomenon and its relationship to key design parameters of fuel tank structural joints, particularly those consisting of carbon fiber reinforced plastic (CFRP).

A necessity early in the program was the identification of the aerospace lightning current components that are of most relevance and significance to the generation of out-gassing.

The paper first introduces the aims and objectives of PROTEST alongside a recall of the out-gassing phenomenon that was discussed in a previous paper [1]. The investigation of the most significant aerospace standard lightning current components to the generation of out-gassing is then presented. The outcome of the investigation has led to the identification of a single lightning test current waveform that shall be used for future out-gassing studies.

II. Overview of the PROTEST Research Program

The PROTEST project followed the work of an internal Airbus Group research project. The test results discussed later were generated during this earlier work and not specifically under the framework of PROTEST.

A. Aims and objectives

The principal objective of PROTEST is to advance the understanding of the physical phenomena related to a particular lightning direct effect, commonly referred to by the aerospace industry as *pressure sparking* or *out-gassing*. Understanding the physical phenomenon and its relationship to aircraft design parameters enables a design with considerable appreciation of the margin to hazardous levels. This leads to the creation of efficiencies (weight and cost) in future lightning strike protection schemes at reduced development time and expense.

Other objectives are to collate test data into a centralized system for performing design rationalization, creating future test methods that capitalize on knowledge/techniques developed during the program and the dissemination of information to the wider community.

B. Basics of the out-gassing phenomenon

Out-gassing (or pressure sparking) is a particular lightning direct effect that may occur from structural joints located in the fuel laden volume of an aircraft. When metallic fasteners located in such joints carry and exchange lightning currents with the surrounding structure, it is possible for thermal sparks to be emitted from the joint. These sparks may consist of hot pressurized gas, molten metallic debris and perhaps ionized particles. If uncontrolled, the event is extremely hazardous due to its potential to cause fuel vapor ignition. A photograph of a typical out-gassing event taken during a lightning direct effects test is shown in Figure 1.

Figure 1. Open shutter photograph of an intense out-gassing event taken during an LDE test

Fisher and Plumer describe the basic understanding of the phenomenon in the lightning protection of aircraft handbook [2]. The later work of Pryzby and Plumer [3] led to the inclusion of an approximate guideline for the threshold current per fastener in a structural joint in a revision of the original handbook [4]. Since then there have been many publications regarding the phenomenon. The authors of this paper more recently provided a review of current understanding, certification requirements and suggested future direction for the development of protection techniques [1].

The material used for primary structure of aircraft fuel tanks has developed since Fisher and Plumer’s 1977 publication. Aircraft such as the Airbus A350 and A400M now use a large percentage of carbon fiber reinforced plastic (CFRP) as primary fuel tank structure, replacing traditional metallic components. However, the means of joining primary structural components by way of bolted joints has remained.

Although there has been many references to out-gassing in the literature [5][6][7], few have attempted to provide understanding of the fundamental mechanisms that drive the phenomenon [8][9] and there has been no attempt to completely capture how variations in particular design parameters relate to the out-gassing threat. For instance, the rough guideline limit of 5 kA per fastener [4] is true for certain joint designs whereas it is incredibly conservative for others. There is evidence that utilizing particular fastener technologies [10] can increase the current threshold for the occurrence of out-gassing due to the effectiveness of the fastener-to-structure contact that these provide. However, there are many other factors of the joint design that also affect this threshold.

The PROTEST program focuses on understanding how structural joint design parameters influence out-gassing. Previous Airbus Group research led to the establishment of a number of key protection functions such as:

- maximizing skin conductance
- maximizing contact between the fastener and the structure
- improving electrical isolation between the nut and sub-structure

This high level functional approach to the protection of the joint is used as a starting point for the identification of design parameters that are likely to influence each function. These design parameters are then varied in bespoke lightning direct effects tests to understand their influence on metrics that can be used to identify the electrical behavior within the joint and characterize the out-gassing intensity. Further diagnostic capability that may provide these metrics were discussed in [1].

III. Significance of Aerospace Standard Lightning Waveform Components on Out-gassing Phenomenon

The lightning direct effects tests conducted in PROTEST are specifically defined to isolate a chosen design parameter to be used as a controlled variable. However, out-gassing is not only influenced by the condition of the test sample, it is also dependent on the characteristics of the simulated lightning current that is injected into the test sample. Therefore, there may potentially be multiple tests for a single attribute of a

The PROTEST project is supported by the UK’s Aerospace Technology Institute

particular design variable due to the range of lightning test waveforms that are recommended in the aerospace standards.

For this reason, the identification of the most significant waveform of interest was an essential task early in the PROTEST test program.

A. Determining the applicable lightning waveform components of concern

The requirements and guidelines to prevent hazards associated with ignition sources are provided by the Federal Aviation Administration, Code of Federal Regulations (Part 25) [11][12][13], the EASA certification standards and other equivalent national standards. The test methods and associated lightning strike waveforms that should be used in order to demonstrate flight worthiness are provided in the aerospace standards and guidance material. These are jointly produced by the Society of Automobile Engineers (SAE) AE2 committee and European Organization for Civil Aviation Equipment (EUROCAE) working group 31. An introduction to aerospace lightning testing can be found in [14].

The lightning zone that is applicable to a particular aircraft component or sub-assembly is first determined by reference to SAE ARP 5414 [15]/EUROCAE ED-91 [16]. The lightning waveforms for each zone are specified in SAE ARP 5412B [17]/EUROCAE ED-84A [18].

On large commercial aircraft, the fuel tank is commonly in the outer wing box (OWB) and on some occasions the center wing box (CWB). The majority of the OWB on the Airbus A350 is assigned as lightning Zone 3 but there are also small sections assigned as Zone 2A.

According to the zoning standards, Zone 3 includes surfaces of the aircraft that are unlikely to be subject to a lightning attachment. In this zone, the structural joints are largely at threat from current that is conducted through the structure and happens to conduct via the joint. However, a section of SAE ARP 5414 [15]/EUROCAE ED-91 [16] states that new or novel design features located in Zone 3 must be shown to withstand a nominal lightning attachment, without catastrophic failure.

Areas in Zone 2A are those of the aircraft surface where a subsequent return stroke is likely to be swept with a low expectation of hang on. In this zone, fasteners of a structural joint between a wing skin and a rib or a wing skin and a spar, could be subjected to a direct attachment.

Of the two zones, Zone 2A is the most severe threat and, for this reason, the Zone 2A threat was the most applicable for the PROTEST project. The Zone 2A threat effectively envelopes the scenario of new or novel design features that is stated above.

The lightning current components for the zone according to the waveform standards are D, B and C. The characteristics of each component are recalled in TABLE I.

The D component is an impulse with very high peak current and high rate of change. Whereas the B component is a transition at a much lower current that leads into the C component that is of significantly longer duration with a high charge transfer at relatively low peak current.

A test campaign was defined in order to determine the significance of each waveform component on out-gassing.

TABLE I. IDEALIZED LIGHTNING CURRENT COMPONENTS FOR ZONE 2A [18]

	Lightning Current Component		
	B	**C**	**D**
Peak current (kA)	4.2	0.2-0.8	100
Time to peak (µs)	813	N/A	3.18
Time to half-value (µs)	2340	N/A	34.5
Charge (C)	10.5	200	4.8
Action integral (A^2s)	2.85×10^4	6.4×10^5 max.	2.5×10^5
Time duration	≤ 5 ms	0.25 to 1 s	≤ 500 µs

B. Test method

The test matrix was defined with the intention of producing three repeat tests per waveform component. The following waveform sequences were tested:

- D component
- Scaled D components (D/2 and D/10)
- D component plus B component
- D component plus B component plus C component
- C component only at both 100C and 200C

Scaled D-components are where the peak current has been reduced. For example, D/2 has a nominal peak current of 50 kA and action integral of 0.63×10^5 A^2s. C-200C represents the full C-component as specified in TABLE I. Whereas C-100C represents a modified C-component with half the charge deposition as the full C-component. The modified C-component has the same current amplitude as C but has a shorter duration.

The test matrix is designed to investigate the following:

- The significance of the peak impulse component (D-component) and/or the significance of the action integral of the impulse component
- The significance of the amount of charge deposited by the continuing current component (C-component)
- The significance of the combined waveform sequences (D, D/B, D/B/C)

A photograph of one of the test samples is shown in Figure 2. The test sample consisted of 12 test fasteners, each with its own dedicated current return connection. The interface between the test sample and the test rig for a test to a particular fastener is shown in Figure 3. The close proximity of the dedicated current return connection to each test fastener limits the current distribution to neighboring test fasteners and thus reduces the amount of pre-conditioning of subsequent tests. This is a result of a trade-off between the cost effectiveness of the test and an ideal test arrangement.

The test sample consisted of a single CFRP laminate with 34 unidirectional plies laid in multiple directions. All fasteners were aerospace grade EN6114 fasteners with a sulfuric acid anodized surface. The interface between the test fastener and the CFRP was via the shank area of the fastener only. The fasteners were installed in a clearance fit with a mean clearance of 21 µm and standard deviation of 0.8 µm.

A diagram of the test fastener interface is shown in Figure 4. There were non-conductive spacers positioned at both the head side and nut side of the fastener to ensure that current exchange was only at the shank-to-structure interface. A metallic bracket was positioned at the head of the fastener to provide a fixed connection for current injection. The clamping of the joint provided partly by the nut of the fastener usually provides a layer of protection against out-gassing by securing a small containment volume. This was specifically disabled in the test assembly by utilizing a metallic washer with a grooved section that provides an escape path for any build-up of pressure within the containment volume.

This test assembly is a much simplified version of a true structural joint interface where typically there is a CFRP wing skin with countersink, joined to substructure such as a CFRP spar. The simplification was to specifically reduce the complexity of the interface to enable further understanding. Throughout the PROTEST test campaign, the complexity of the joint will be enhanced until a full representative joint is attained.

Measurements were taken of the injection current and the potential difference between the test fastener and the current return connection of the adjacent test fastener. Evidence of out-gassing was recorded by means of a digital camera. The camera was set so that light was captured during the full duration of the strike. A FLIR ThermoVision A320 thermal camera was also used to capture the temperature change at the underside of the test sample.

A hollow plastic cap was bonded to the underside of the test sample that enclosed the nut of the test fastener. This meant that any out-gassing from the joint was contained by the cap. A pressure transducer was threaded into the cap to provide a time dependent measurement of out-gassing pressure from the joint. This enabled a comparative assessment of the out-gassing intensity by means of the peak dynamic gas pressure released by the event for each applied waveform component. The underside of the test sample with connected pressure sensor is shown in Figure 5.

Figure 2. Photograph of test sample

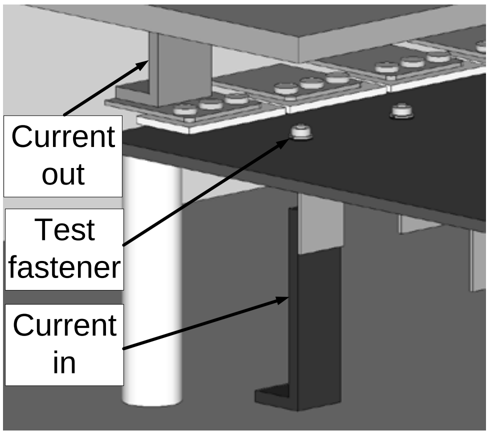

Figure 3. Diagram of test arrangement

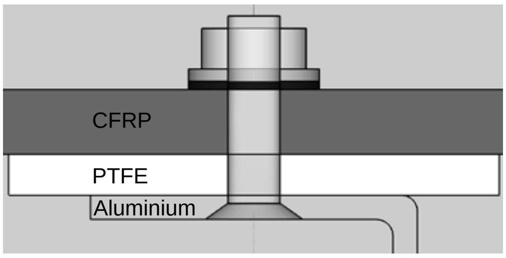

Figure 4. Diagram of test fastener interface

Figure 5. Photograph of the underside of the test sample

C. Test results

The measured current waveforms used for the tests are shown in Figure 6 and Figure 7. Photographs taken during scaled D-component strikes are shown in Figure 8. A voltage measurement and an out-gassing pressure measurement for a full D-component strike is shown in Figure 9. A summary of the test results is provided in TABLE II. The table provides the measured peak current, peak voltage and peak pressure for each test. Also, an indication is given on detected light during the test. In some cases, due to experimental reasons, measurements were not taken.

A comparison of the measured peak pressure for waveform sequences containing variants of the D-component is provided in Figure 10.

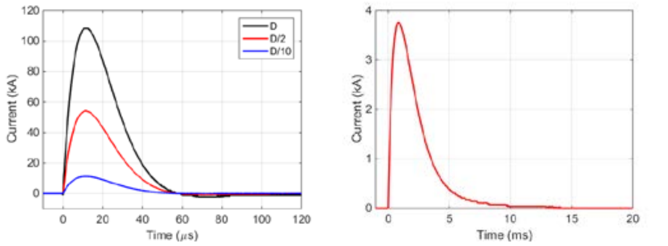

Figure 6. Typical test waveforms (D-component – left, B-component – right)

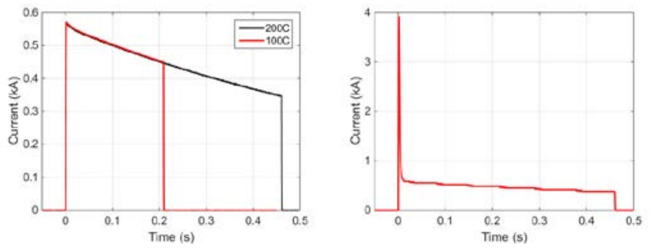

Figure 7. Typical test waveforms (C-component – left, combined B-C, right)

Figure 8. Photographs taken during scaled D-component strikes (Full D-component – top, D/2 – middle, D/10 – bottom)

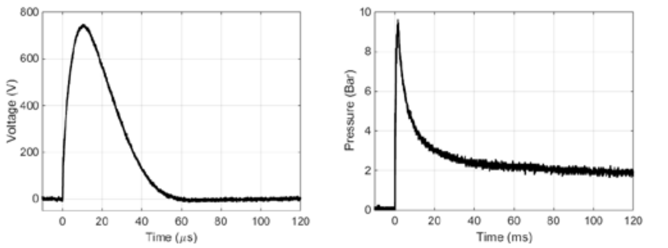

Figure 9. Voltage measurement for a full D-component strike

TABLE II. SUMMARY OF TEST RESULTS

Test type waveform	Test ID	Peak current (kA)	Peak voltage across test terminals (V)	Peak pressure (Bar)	Light
D	4	108	720	10.3	Y
	5	108	750	9.5	Y
	6	108	712	9.5	Y
D/2	1	58	447	7.7	Y
	13	54	-	-	Y
	14	54	384	1.5	Y
	15	54	383	7.7	Y
D/10	2	11	112	0	N
	3	11	120	0	N
D,B	7	108	624	8.7	Y
	8	108	667	8.8	Y
	9	108	631	-	Y
D,B,C 200	10	109	690	8.6	Y
	11	108	735	8.8	Y
	12	108	701	10.2	Y
C100	16	0.57	-	0	N
	17	0.57	-	0	N
	18	0.57	10	0	N
C200	19	0.57	10	0	N
	20	0.57	11	0	N
	21	0.57	11	0	N

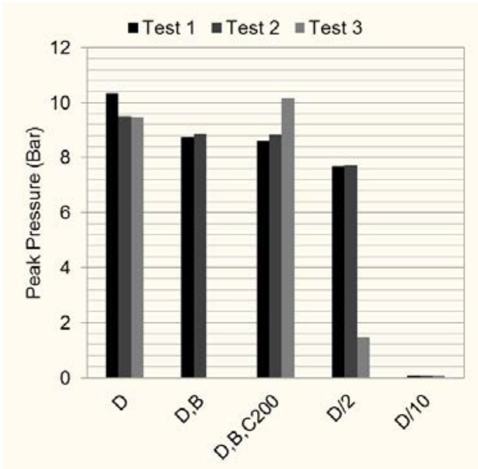

Figure 10. Measured peak pressure for waveform sequences containing variants of the D-component

D. Discussion

Based on the measurements taken, all waveform sequences that included the full D-component behaved similarly. All of these waveforms produced out-gassing from the joint with a peak pressure in the nut-cap within a range of 8.6 to 10.3 Bar. The D/2 strikes also produced out-gassing but with a reduced peak pressure. For two of these strikes, the peak pressure was approximately 7.7 Bar, whereas one strike was significantly reduced at a peak pressure of 1.5 Bar. This suggests that the current level was near a transition point in the event. The reduced peak pressure compared to the full D-component strikes suggests a less intense event occurs when a reduced amplitude D-component is used. This is reinforced by the fact that the two D/10 strikes produced no out-gassing.

No out-gassing was observed when the C-component was used with no impulse component. For this reason, it cannot be said that the full C-component is any more significant than the modified C-component in terms of out-gassing.

The fact that the C-component alone produced no out-gassing coupled by the fact that there is no significant difference between the D-component alone and the full Zone 2A sequence is important. It suggests that out-gassing is dependent on the D-component alone and there is no significant influence from the other components. For this reason, it was decided to use only scaled versions of the D-component in the PROTEST project.

It must be highlighted here that these findings have been made for a simplified joint where only a single current path exists between the test fastener and the CFRP laminate. There is not yet any evidence to suggest that this is also the case for a fully representative structural joint.

IV. CONCLUSIONS

The paper introduces a new aerospace lightning direct effects research project that aims to understand 'out-gassing' phenomena. A process of down-selection was undertaken as part of this project that aimed to identify the most significant aerospace standard lightning waveform component that will be used for the remainder of the program.

Following an assessment to determine the applicable zone of interest (Zone 2A), it was found by a number of practical lightning experiments that only the D-component is influential in developing out-gassing in this particular test configuration. No out-gassing was observed when only the C-component was used at both 100C and 200C.

V. FUTURE WORK

The specific reasons for why the D-component is the most influential waveform for generating out-gassing was not investigated as part of this work. However, the characteristics of the impulse and its influence on out-gassing will be further understood during the remainder of the PROTEST project.

The waveform has a very high rate of change of current early in the strike. This causes a rapid increase in the reactive component of the voltage drop across the test sample which could be specifically influential to any electrical discharge activity within the joint. The D-component deposits a large amount of energy, particularly over a very short time period. The materials ability to react to this may be of importance.

The understanding of the significance of the different aspects of the D-waveform will be addressed in PROTEST in parallel to understanding the influence of particular design parameters.

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REFERENCES

[1] S. Evans, I. Revel, M. Cole, R. Mills, "Lightning strike protection of aircraft structural joints" , International conference on lightning protection, Shanghai, 2014

[2] F. A. Fisher and J.A. Plumer, "Lightning protection of aircraft", 1st ed., NASA reference publication 1008, Oct. 1977, pp. 165-167

[3] J. E. Pryzby and J.A. Plumer, "Lightning protection guidelines and test data for adhesively bonded aircraft structures", NASA contractor report 3762, Jan. 1984

[4] F. A. Fisher and J.A. Plumer, "Aircraft lightning protection handbook", DOT/FAA/CF-89/22, Federal Aviation Adminstration, Sept. 1989, pp. 196

[5] J. H. Morrill, "Effect of fastener installation fit and finish on sparking damage a componeits joints", Interational conference on lightning and static electricity, USA, 2005

[6] D. Morgan, C. J. Hardwick, S. J. Haigh and A. J. Meakins, "The interatction of lightning with aircraft and the challenges of lightning testing", Lightning hazards to aircraft and launchers, Journal aerospace lab, AL (2012): 05-11

[7] L. Chemartin, P. Lalande and F. Tristant, "Modeling and simulation of sparking in fastening assemblies", International Conference on Lightning and Static Electricity, Seattle, 2013.

[8] I. Revel, G. Peres, B. Lepetit, L. Andrivet and F. Flourens, "Understanding of sparking phenomenon in CFRP assemblies", International conference on lightning and static electricity, France, 2007.

[9] B. Lepetit, I. Revel, G. Peres, L. Andrivet and F. Flourens, "In-strike dynamical measurements of contact resistances", 30th International Conference on Lightning Protection, Cagliari, 2010.

[10] H. Mulazimoglu and L. Haylock, "Recent developments in techniques to minimize lightning current arcing between fasteners and composite structure", International Conference on Lightning and Static Electricity, Oxford, 2011.

[11] Federal Aviation Administration, "CFR 25.581 – Lightning protection", January 2002.

[12] Federal Aviation Administration, "CFR 25.594 – Fuel system lightning protection, January 2002.

[13] Federal Aviation Administration, "CFR 25.981 – Fuel tank ignition prevention", July 2008.

[14] D. Morgan, C. J. Hardwick, S. J. Haigh and A.J. Meakins, "The interaction of lightning with aircraft and the challenges of lightning testing." Lightning Hazards to Aircraft and Launchers, Journal Aerospace Lab, AL (2012): 05-11.

[15] "Aircraft lightning zoning", Aerospace recommended practice (ARP) 5414, SAE International, Warrendale, PA, 1999

[16] "Aircraft lightning zoning", EUROCAE ED-91, July 1998.

[17] "Aircraft lightning environment and related test waveforms", Aerospace recommended practice (ARP) 5412B, SAE International, Warrendale, PA, 2013

[18] "Aircraft lightning environment and related test waveforms", EUROCAE ED-84A, July 2013.