Third Publication of Proposed Means of Compliance with the Special Condition VTOL

The document at hand, Doc. No. MOC-3 SC-VTOL, contains the third publication of MOCs with the Special Condition VTOL. It proposes a new MOC that adds to the ones already published with Docs. No. MOC SC-VTOL and MOC-2 SC-VTOL. Following completion of this public consultation process, it is planned to collect all final MOCs in an upcoming issue of Doc. No. MOC SC-VTOL, for general convenience.

Public consultation on the EASA Comment-Response Tool (CRT) at http://hub.easa.europa.eu/crt/
Deadline to submit comments: 12 August 2022

Statement of Issue

Substantial progress has been made in the development and integration of rechargeable lithium batteries in aviation. However, they still represent a significant fire hazard when used as power supply for systems in traditional aircraft due to their susceptibility to failures leading to self-sustaining increases in temperature and pressure (thermal runaway).

The recent use of lithium batteries as propulsion energy storage devices in electric and hybrid aircraft increases the importance of properly addressing this hazard, due to their novel function, higher capacity, higher specific energy, and higher voltage and the lack of significant service experience in this context.

Some of the most common root causes that could lead to a thermal runaway are (non-exhaustive list):

- Design and manufacturing issues
- Installation or maintenance issues
- Internal fault conditions (cell manufacturing quality issues, dendrites…)
- External abuse conditions (external short-circuit, overcharge…)
- Physical damage during storage, transportation, service, or swapping
- Heat sources (poor electrical connections, corrosion, short-circuits, arcs…)

Some of them can be prevented with proper design, manufacturing, installation, operation, and maintenance, while others cannot be completely avoided (i.e., cell internal short-circuit due to latent manufacturing defects), therefore, their effect should be properly mitigated.

Furthermore, the batteries and their protective layers/measures in propulsion battery systems represent a considerable part of the weight of the aircraft. Therefore, it is essential to define test requirements that ensure the adequate level of safety of the product for the intended operational conditions in a feasible way. This may include considerations on the time-to-land following the detection of a critical thermal runaway.

Log of issues

Issue	Issue date	Change description
1	29/06/2022	First Issue for Public Consultation

Proposed Means of Compliance with the Special Condition VTOL

Contents

MOC – SUBPART E – LIFT/TRHUST SYSTEM INSTALLATION

MOC VTOL.2440 Propulsion Batteries Thermal Runaway

1. Introduction

Compliance with VTOL.2440, but also with VTOL.2330, VTOL. 2400(d), VTOL.2425(a), VTOL.2430 (a)(1)(2)(5)(6)(7), (b)(2)(3), (c)(3), (d), VTOL.2510, and VTOL.2525 requires demonstrating that the hazards from a fire in the propulsion battery system will be appropriately mitigated.

The latest lithium battery systems safety standard RTCA DO-311A is a useful baseline for developing and testing propulsion battery systems. However, its "Thermal runaway containment test" in section 2.4.5.5, was developed for lithium batteries that provide power to other aircraft systems or equipment, without considering the particularities of very large propulsion battery systems needed in electric and hybrid aircraft.

That containment test, when applied to propulsion battery systems, may lead to decrease their energy/weight ratio unduly and substantially, because of placing the focus on the containment of an extreme thermal runaway event instead of considering the implementation of different protection layers and the containment of a realistic worst-case thermal runaway event. While this test could be accepted as means of compliance, provided that other requisites are met, it should not alleviate the implementation of protective layers/measures.

In this Means of Compliance, EASA proposes an alternative method for propulsion lithium batteries, to promote best industry practices, robust designs, and protection layers strategies for the entire propulsion battery system. Moreover, this alternative intends to foster innovation and development of new solutions for these battery system protection layers, instead of relying only on containment mitigations.

The main reasons for this alternative method to RTCA DO-311A section 2.4.5.5. "Thermal Runaway Containment Test" are:

(a) The amount of additional external energy put into the battery system for this test is far in excess of energies used in service, which are limited by fail-safe protection layers and proper design, manufacturing, installation, operation, and maintenance.

  (1) Depending upon the chemistry, rechargeable lithium battery can accept overcharging levels that lead to double the normal energy before reaching a point of chemical and thermal instability.

  (2) Heating the whole battery could compromise the validity of the test results due to mechanical and thermal effects created by pre-heating the whole battery structure, materials, and components to high temperatures.

(b) In most of the cases, overcharging (if feasible) or overheating the whole battery will normally drive a near-simultaneous failure of all cells in the battery which does not represent a realistic in-service field failure, but an extreme condition not encountered in service, even in batteries where reliable and tested protection layers were not implemented.

(c) However, in other cases, this test may lead to undertest the propulsion battery containment, since:

  (1) Only one test article is tested.

(2) There is no characterisation of thermal runaway behaviour at cell level for different parameters.

(3) The variability in the characteristics of the cells, or the possibility of having defective cells within the battery system, may lead to trigger very few cells at temperatures lower than the thermal runaway initiation temperature of most of the cells.

(4) As the heating device power may be removed once initiated the thermal runaway, it could lead to have only those very few cells into thermal runaway.

(5) If a thermal runaway occurs in at least two cells, the objective of the test is already met.

(6) Degradation of the propulsion battery containment due to aging and environmental conditions during operation is not considered.

(d) The design of electronics for critical aviation applications has been practiced for decades in the industry and demonstrated as highly effective for the safe operation of aircraft when consistent with appropriate industry practices. Therefore, as for any other system in the aircraft, if designed protections are shown to be reliable, the overall risk testing should consider these protections and their reliability.

Considering this, two acceptable approaches are proposed in this Means of Compliance to address the demonstration of an adequate mitigation of battery system thermal runaway conditions.

This Means of Compliance is not addressing neither superseding other tests needed for the certification of propulsion battery systems (i.e. external short circuit, available system capacity and energy, protections testing, battery system crashworthiness tests…).

2. Definitions

For the purpose of this MOC:

(a) "Battery" means a stand-alone battery or to a battery that is part of a battery system.

(b) "Battery system" means a battery plus any protective, monitoring, alerting circuitry or hardware inside or outside of the battery, its packaging, and the designed venting provisions.

(c) "Propulsion battery" means a battery or battery system used for propulsion applications.

(d) "Battery Module" means a group of interconnected cells in series and/or parallel arrangement contained in a single enclosure that ensures that no fluids, flames, gasses, smoke, or fragments enter other modules during normal operation or failure conditions.

3. Prerequisites

(a) General considerations

(1) Propulsion battery systems should follow the design, manufacturing, installation, operation, and maintenance guidance provided in RTCA DO-311A section 2.1 "General Requirements" and section 3 "Installation Considerations". They should successfully implement multiple layers of mitigation mechanisms against unsafe conditions, such as thermal runaway, by providing the following:

(i) Evidence that RTCA DO-311A section 2.1 and section 3 requirements have been considered and are successfully implemented.

(ii) Evidence that critical functions including control and protective functions that include software have been designed and validated, as per the applicable revision of EASA AMC 20-115, to appropriate design assurance level.
(iii) Evidence that critical functions including control and protective functions that include airborne electronic hardware have been designed and validated, as per the applicable revision of EASA AMC 20-152, to appropriate design assurance level.

Note: Demonstrating compliance with one of the test approaches defined in this MOC does not alleviate the classification of the failure condition "battery thermal runaway" (i.e. the thermal runaway of two or more cells within a battery) considered catastrophic.

(iv) Evidence that a propulsion battery System Safety Assessment (SSA) has been performed as per the applicable revision of SAE ARP 4761, addressing the hazards leading to thermal runaway, including:

(A) Functional Hazard Assessment (FHA)
(B) Quantitative analysis of the failure condition Fault Tree Analysis (FTA/DD/MA)
(C) Failure Modes and Effects Analysis (FMEA)
(D) Common Cause Analysis (CMA, PRA, ZSA…)

(v) The System Safety Assessment (SSA) should demonstrate that the safety objectives associated to identified failure conditions are fulfilled. In particular, any catastrophic failure condition should be extremely improbable and not result from a single failure of the critical functions of the propulsion battery system, including control and protective functions inside or outside of the battery
(vi) Performing thermal runaway non-propagation tests following the guidelines described in the following section (b) to demonstrate that propagation prevention mechanisms are successfully implemented during the whole operation and life of the propulsion battery system.

(b) Thermal Runaway Non-Propagation Tests:

(1) Latent manufacturing cell defects should be minimized, as stated in RTCA DO-311A section 2.1.7 "Mitigation of cells failures". However, even using the most reliable cells from the most robust suppliers, and applying proper incoming inspection and testing, these manufacturing defects cannot be totally prevented. Due to this, having an internal short circuit at cell level in propulsion battery systems with thousands of cells becomes the most likely scenario for a thermal runaway. Therefore, propagation to adjacent cells in the battery should be properly prevented to avoid a chain reaction.
(2) The applicant should define, in coordination with EASA, a set of tests at battery system level to demonstrate that the propagation prevention mechanisms described in RTCA DO-311A section 2.1 "General requirements", have been successfully implemented.
(3) The following guidelines should be considered for the development of Thermal Runaway Non-Propagation tests:
(i) Aging and environmental conditions during operation may result in degradation of the protection layers. Therefore, to test the worst-case condition during the life of the propulsion battery system, these tests should also be performed with batteries that have experienced loading that could lead to such degradation, i.e. vibrations, thermal

cycling and electrical cycling, either on separate test articles or sequentially on the same test articles. Batteries used for RTCA DO-160/EUROCAE ED-14 environmental tests or aging cycle tests can be used as test samples. Alternatively, batteries that have gone through equivalent accelerated life tests can be used.

(ii) A full characterisation of thermal runaway behaviour at cell level should be performed by the applicant to identify and include at battery system level tests, the following variabilities:

(A) Thermal Runaway Trigger Method. When overcharging the cell to force a thermal runaway is possible (no internal cell protections), cell thermal runaway behaviour between overcharging and overheating leads to different outcomes. These differences should be well understood and considered at battery system level testing.

(B) Different State of Charges (SOC). Normally, low SOC lead to more material remaining in the cell hence increasing the probability of cell-to-cell propagation. However higher SOC lead to a thermal runaway more explosive and energetic with more material expelled outside the cell. These differences should be well understood and considered at battery system level testing.

(C) Different positions of the internal short-circuit relative to the cell venting mechanism lead to different outcomes in the way the cell is venting or even cause side or bottom ruptures of the cell case. These differences should be well understood and considered at battery system level testing (i.e. different positions of the heater on the cell).

(D) Different heating rates (i.e. between 5°C/min to 20°C/min) have demonstrated different behaviour of the thermal runaway at cell level, with flames or smoke development depending on the heating rate. These differences should be well understood and considered at battery system level testing.

(E) For this characterization, at least the following parameters should be determined:

(a) Maximum temperature
(b) Average total energy release
(c) Initiation temperature
(d) Temperature rise rate
(e) Quantification of mass ejected

(F) Due to the high variability in cell level tests, the applicant should define, in coordination with EASA, an appropriate number of replicates to provide a representative sample for the cell thermal runaway characterization.

(iii) A thermal runaway in at least a pair of adjacent cells in the Propulsion Battery should be caused by overheating and/or overcharging as determined by the previous cell characterisation.

(iv) Triggered cells should be selected as follows:

(A) The pairing of cells should consider spacing and heat transfer characteristics to maximize the potential for propagation to other cells.

(B) The battery system configuration and installation location should be assessed to justify the selection of cells that have potential to become worst cases (e.g. centre, wide face, narrow face, corner, edge…).

(v) The tested battery system should be representative of the in-use application, and should include cooling, configuration into the aircraft, designated venting provision, and any other design configuration or variable that could impact the test outcome.

(vi) In case there are battery systems with different installations within the aircraft that could impact the test outcome, these different installations should be tested, or if properly justified, at least the worst-case installation.

(vii) The tested battery system should not be modified to such an extent that the method of propagation can be significantly different than in a non-modified battery system.

(viii) The cells should not be modified in any way that changes the composition or mechanical properties of the cell itself (including the external cell can).

(ix) The temperature of the battery system before triggering the cells should be always stabilized at 55°C or the maximum operating high temperature, whichever is higher.

(x) The trigger mechanism may be deactivated once a thermal runaway has been initiated in both cells.

(xi) It should be proven for each test that:

(A) The trigger method setup aims to trigger both cells at the same time.
(B) The two triggered cells have entered thermal runaway within 30 seconds of each other.

(xii) If a thermal runaway in the two targeted cells does not occur, the objective of the test has not been met.

(xiii) The following parameters should be recorded during the test:

(A) The voltages of at least the cells being triggered.
(B) The temperatures of the cells being triggered.
(C) The temperatures of the cells nearest to the cells being triggered.
(D) The temperatures of the external surface of the battery system (including the venting provisions).
(E) The temperatures of the gases that exit the battery system.

(xiv) The battery system tested should be monitored for 8 hours after the initial thermal runaway event, and during this time comply with the following:

(A) No propagation to other cells.
(B) No rupture of the battery system.
(C) No release of fragments outside the battery system.
(D) No escape of flames outside of the battery system.
(E) No escape of emissions outside the battery system, except through the designed venting provisions.

(F) No compromise of warning signals and safety functions (e.g., battery automatic disconnect function).

4. Approach #1: RTCA DO-311A Section 2.4.5.5. Battery Thermal Runaway Containment Test

(a) Propulsion Battery Systems are considered to properly fulfil verification aspects of propulsion battery system thermal runaway conditions when compliance is demonstrated with:

(1) Section 3. "Prerequisites" of this document, and
(2) Requirements of RTCA DO-311A section 2.2.2.4 when tested in accordance with section 2.4.5.5 Battery Thermal Runaway Containment Test, and
(3) Evidence that at least 20% of the cells achieved thermal runaway. This percentage could be reduced (not below 15%) with the concurrence of EASA, based on the design, protection layers, installation and testing robustness proposed by the applicant.

5. Approach #2: Battery Thermal Runaway Containment for Continued Safe Flight and Landing (CSFL) time Tests

(a) Propulsion Battery Systems are considered to properly fulfil verification aspects of propulsion battery system thermal runaway conditions when compliance is demonstrated with:

(1) Section 3. "Prerequisites" of this document, and
(2) The test guidelines defined in the following section (b).

(b) Thermal Runaway Containment for CSFL time Tests

(1) Experience has demonstrated that, although very unlikely, it cannot be fully discarded that more than 2 cells could go into thermal runaway due to an unforeseen failure mode. Therefore, the applicant should define in coordination with EASA, a set of tests to demonstrate that a realistic worst-case of thermal runaway in more than 2 cells can be safely managed at propulsion battery system level or installation level (Battery Explosive Fire Zone) for a time that covers at least the detection of the fire at the most adverse operation condition and an ensuing continued safe flight and landing in accordance with EASA MOC VTOL.2330 Fire Protection in designated fire zones.

(2) The following guidelines should be considered for the development of Thermal Runaway Containment for CSFL time Tests:

(i) Aging and environmental conditions during operation may result in degradation of the protection layers, therefore, to test the worst-case condition during the life of the propulsion battery system, these tests should also be performed with batteries that have experienced loading that could lead to such degradation, i.e. vibrations, thermal cycling and electrical cycling either on separate test articles or sequentially on the same test articles. Batteries used for RTCA DO-160/EUROCAE ED-14 environmental tests or aging cycle tests can be used as test samples. Alternatively, batteries that have gone through equivalent accelerated life tests can be used.

(ii) All the variabilities identified in the full characterisation of thermal runaway behaviour at cell level in the guidelines for development of Thermal Runaway Non-Propagation Tests (section 3.(b)(ii)) should also be included.

(iii) A thermal runaway in at least 20% of the cells in the propulsion battery system should be caused by overheating and/or overcharging as determined by the previous cell characterisation. This percentage could be reduced (not below 15%) with the concurrence of EASA, based on the design, protection layers, installation and testing robustness proposed by the applicant.

(iv) Triggered cells should be selected as follows:

(A) The cells should consider spacing and heat transfer characteristics to maximize the potential for propagation to other cells.
(B) The battery system configuration and installation location should be assessed to justify the selection of cells that have potential to be worst cases to be tested (e.g. centre, wide face, narrow face, corner, edge, subgroup of triggered cells in different sides, …)

(v) The tested battery system should be representative of the in-use application, and should include cooling, configuration into the aircraft, designated venting provision, and any other design configuration or variable that could impact the test outcome.

(vi) In case there are battery systems with different installations within the aircraft that could impact the test outcome, these different installations should be tested, or if properly justified, at least the worst-case installation.

(vii) The tested battery system should not be modified to such an extent that the method of propagation can be significantly different than in a non-modified battery system.

(viii) The cells should not be modified in any way that changes the composition or mechanical properties of the cell itself (including the external cell can).

(ix) The temperature of the battery before triggering the cells, should be always stabilized at 55°C or the maximum operating temperature, whichever is higher.

(x) The trigger mechanism may be deactivated once a thermal runaway has been initiated in all the targeted cells.

(xi) It should be proven for each test that:

(A) The trigger method setup aims to trigger all targeted cells at the same time
(B) All triggered cells have entered into thermal runaway within 1 minute.

(xii) If a thermal runaway in the targeted cells does not occur, the objective of the test has not been met.

(xiii) If propagation to all cells is prevented, the number and locations of cells that entered thermal runaway should be reported.

(xiv) The following parameters should be recorded during the test:

(A) The voltages of at least the cells being triggered.
(B) The temperatures of the cells being triggered.
(C) The temperatures of the cells nearest to the cells being triggered.
(D) The temperatures of the external surface of the battery system and/or Explosive Fire Zone.
(E) The temperatures of the gases that exit the battery system and/or Explosive Fire Zone.

(xv) During the test it should be demonstrated that the thermal runaway can be safely managed at propulsion battery system level or installation level (Battery Explosive Fire Zone) for a time that covers at least the detection of the fire at the most adverse operation condition and an ensuing continued safe flight and landing in accordance with EASA MOC VTOL.2330 Fire Protection in designated fire zones.

Note: Since propulsion batteries have much higher capacity and size than conventional systems batteries, it may not be feasible to design a battery system that complies with the previous test approaches with a reasonable weight penalty. The applicant may propose a properly modularized battery system design with smaller modules, to comply at module level with any of the test approaches defined in this document.