

ED-312

GUIDANCE ON DETERMINING FAILURE MODES IN LITHIUM-ION CELLS FOR EVTOL APPLICATIONS

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CHAPTER 1

PURPOSE AND SCOPE

1.1 INTRODUCTION AND PURPOSE OF DOCUMENT

This document contains guidance on the definition of lithium-ion cell failures, cell failure causes and materials level failure modes. It also informs on interdependencies between failure causes that may be considered when defining a verification and validation strategy for the cell, as defined in other cell related EUROCAE documents.

NOTE: *Specific qualification testing is out of scope of this guidance.*

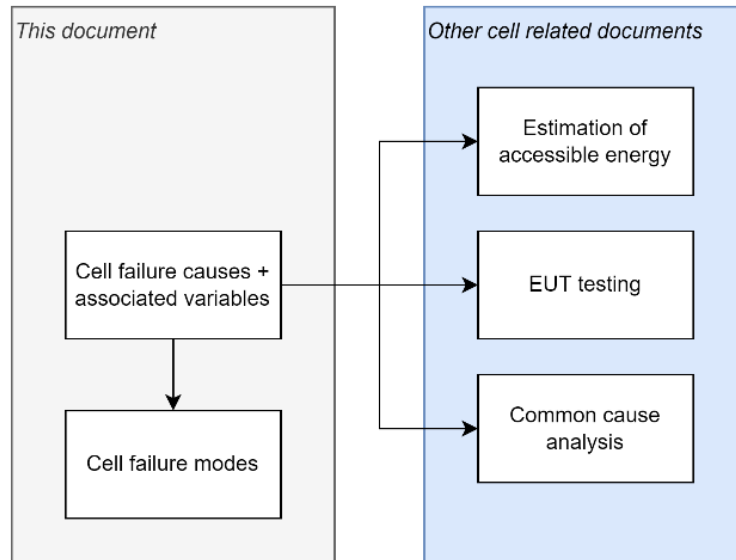


FIGURE 1-1: SCHEMATIC SHOWING RELATIONSHIP BETWEEN THIS DOCUMENTS AND OTHER CELL RELATED DOCUMENTS

1.1.1 How to use this document

The information provided in this document may be used by the applicant to support the different stages of a Safety Assessment, as per ED-79A/ARP4754A and ARP4761. Accordingly, a specific safety objective commensurate to the aircraft category must be met to ensure an acceptable level of safety for the Systems, Components and Equipment installed on the aircraft.

As such, each applicant must select and justify an allowable Qualitative Probability of failure for their installed equipment, i.e. the probability of more than one lithium-ion cell being unable to provide the required power/energy or entering thermal runaway within one flight as a result of the same failure mode. An example is provided in Figure 1-2. The system must be designed to meet the venting and failure containment requirements specific to the certification category.

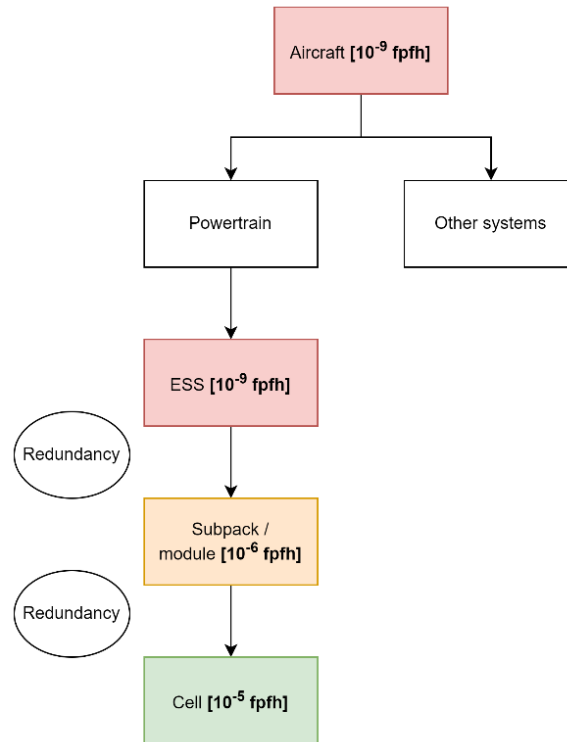


FIGURE 1-2: EXAMPLE FAULT TREE ANALYSIS FOR THE AIRCRAFT DEMONSTRATING HOW THE AIRCRAFT FAILURE RATE CASCADES TO THE CELL

This document contains considerations that may be made by the applicant when determining and evidencing a failure rate for the cell.

CHAPTER 2 describes failure causes by defining different types of limits for the cell that should be adhered to, to reduce the risk of initiating the associated failure modes. This Chapter also describes common interdependencies between different failure causes.

CHAPTER 3 describes cell failure modes, describes the effects that they have on the function of the cell and categorises each failure mode by failure condition, which is the worst-case failure type for the cell. This gives the applicant an indication of the level of risk that the failure mode poses to a cell upon exposure to a failure cause.

CHAPTER 4 describes how the failure effects described in CHAPTER 3 may progress. An example is given in Figure 1-3 alongside a general overview of the contents of the document.

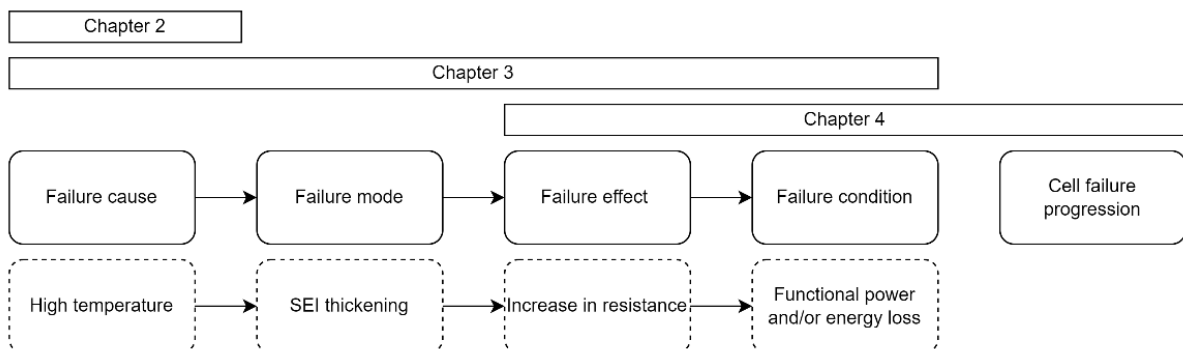


FIGURE 1-3: FLOW CHART DEMONSTRATING THE FORM OF THIS DOCUMENT

The cell failure progression flow diagram in CHAPTER 4 also contains advisory information on the interdependencies between failure effects.

1.2 ASSUMPTIONS

This document is largely agnostic to cell form factor (pouch, prismatic, cylindrical), chemistry and battery architecture, however the failure cases described here are based on current technology and research, therefore may not apply to or capture all failure modes for future technologies.

Abuse-based failures are omitted as they are out of scope. These external factors may be managed through pack design.

1.3 ABBREVIATIONS

TABLE 1-1: LIST OF ABBREVIATIONS

Abbreviation	Description
AC	Alternating Current
ACC	Anode Current Collector
ACIR	Alternating Current Internal Resistance
ARP	Aerospace Recommended Practice
BMS	Battery Management System
CCC	Cathode Current Collector
CCUL	Charge Current Upper Limit
CID	Current Interrupt Device
CS	Certification Specifications
CTLL	Charge Temperature Lower Limit
CTUL	Charge Temperature Upper Limit
DC	Direct Current
DCIR	Direct Current Internal Resistance
DCUL	Discharge Current Upper Limit
DTLL	Discharge Temperature Lower Limit
DTUL	Discharge Temperature Upper Limit
EASA	European Union Aviation Safety Agency
EIS	Electrochemical Impedance Spectroscopy
ESS	Energy Storage System
ETSO	European Technical Standard Order
EUT	Equipment Under Test
IEC	International Electrotechnical Commission
MOC	Means of Compliance
N/A	Not applicable
OCV	Open Circuit Voltage
OVLL	Operating Voltage Lower Limit
OVUL	Operating Voltage Upper Limit
PPE	Personal Protective Equipment
PTC	Positive Thermal Coefficient
RTCA	Radio Technical Commission for Aeronautics

SC	Special Condition
SEI	Solid Electrolyte Interphase
SOC	State of charge
SOH	State of health
SOHc	State of health (capacity loss)
SOHr	State of health (resistance increase)
STSL	Storage SOC (state of charge) Lower Limit
STSUL	Storage SOC (state of charge) Upper Limit
STTLL	Storage Temperature Lower Limit
STTUL	Storage Temperature Upper Limit
TLSL	Temperature Lower Safety Limit
TUSL	Temperature Upper Safety Limit
VLSL	Voltage Lower Safety Limit
VTOL	Vertical Take Off and Landing
VUSL	Voltage Upper Safety Limit

1.4

GENERAL DEFINITIONS

1.4.1

Cell

'Cell' in this document refers to a technologically mature lithium-ion cell supplied by a cell manufacturer. 'Mature' in this instance refers to a cell that is in full scale production and is no longer in a prototyping phase.

Figure 1-4 describes the basic format, components and function of a lithium-ion cell (format and chemistry agnostic.)

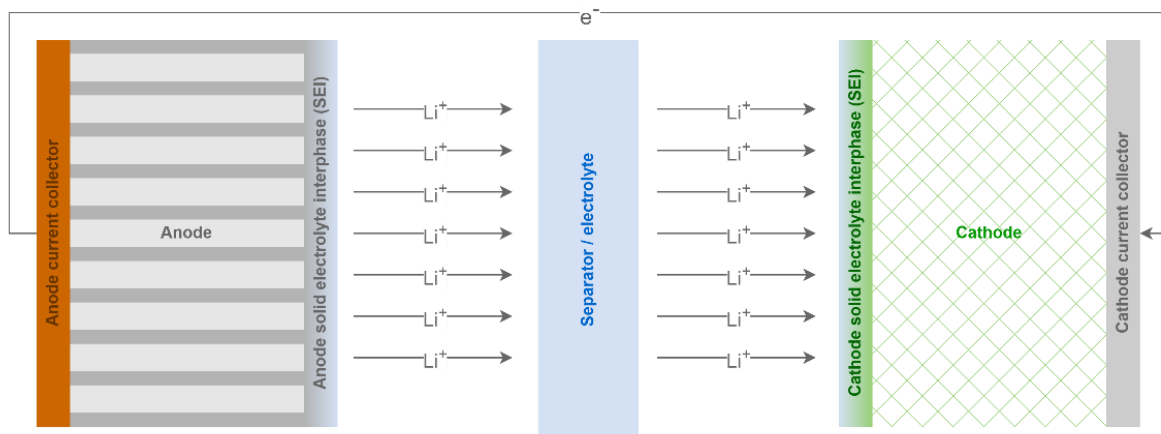


FIGURE 1-4: BASIC LITHIUM-ION CELL STRUCTURE AND FUNCTION DURING DISCHARGE

A traditional lithium-ion cell is comprised of anodic and cathodic current collectors, anode material, cathode material, separator and electrolyte. The current collectors connect the active cell materials to an external electrical circuit, enabling the transfer of electrons to the device that the cell is connected to. In traditional lithium-ion cells, the electrodes are electrically insulated from each other using a separator; a porous membrane saturated with electrolyte. Novel technologies such as solid-state cells do not contain a separator; instead a solid ceramic electrolyte material is electrically insulating but facilitates lithium ion transport. The anode and cathode are ionically connected through the electrolyte which allows lithium ions to travel between the electrodes during charge and discharge.

During charging of a Li-ion cell, lithium ions are driven out of the cathode active material, travel through the electrolyte (and separator if present) and intercalate into the anode active material. During discharge, lithium ions move out of the anode active material and back to the cathode active material, releasing electrons into the external circuit through the anodic current collector to power the device that it is connected to. It is important that the charge and discharge processes occur at rates that are compliant with thermodynamics and kinetics of the system, which is defined by the cell chemistry. This document is cell chemistry agnostic; chemistry specific failures are to be managed by the applicant.

1.4.2 Energy Storage System (battery system)

A number of modules and/or packs connected in series and/or parallel and any protective, monitoring, alerting circuitry or hardware, its packaging and the designed venting provisions.

NOTE: This aligns with the definition of 'battery system' in MOC-3 SC-VTOL

1.4.3 Cell failure

Loss of functional power or energy of the cell as per Section 0.

1.4.4 Failure cause

A failure cause in this document refers to a condition, environment or process which may cause or catalyze cell level failure modes.

1.4.5 Failure mode

A failure mode is defined in ARP 4761 as 'The way in which the failure of an item occurs.' Further to this, this document refers to the process and/or specific materials change that occurs within the affected cell as a result of the failure cause. Each of these lead to one or more of the failure effects defined in Section 4.1.

1.4.6 Failure effect

A failure effect is defined as per ED-79A/ARP 4754A and ARP 4761 as 'A description of the operation of a system or item as the result of a failure; i.e., the consequence(s) a failure mode has on the operation, function or status of a system or an item.' This is the effect that the failure mode has on the function of a cell. These effects can progress along a failure pathway, defined in CHAPTER 4, resulting (at worst case) in loss of functional power and/or energy or thermal runaway of a cell, defined as failure conditions.

1.4.7 Failure condition

A failure condition refers to the worst-case failure type at a cell level, which describes whether during cell failure, the cell loses the ability to deliver functional power/energy and remains inert or whether there is a risk of thermal runaway.

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1.6 RELATIONSHIP TO SC-VTOL

Whilst this standard was developed with a particular view to the European legal framework, namely the EASA Special Condition VTOL.2430, it may be applied to support other regulatory frames.

1.7 RELATIONSHIP TO OTHER DOCUMENTS

EUROCAE documents:

- ED-289: Guidance on determination of accessible energy in battery systems for eVTOL applications
This document describes the considerations that must be made when carrying out the tests and predictions that are described in ED-289. E.g. cell limits to apply when considering a load profile or carrying out tests/simulations to ensure that the cell does not degrade at an unexpected rate.
- ED-79A/ARP 4754A: Guidelines for Development of Civil Aircraft and Systems
Definition of failure effects.

The following external (non-EUROCAE) documents have been used in the development of this document:

- EASA MOC-3 SC-VTOL: Third Publication of Proposed Means of Compliance with the Special Condition VTOL
Used in the definition of energy storage system.

- ARP 4761: Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
Definition of failure modes and failure effects.
- RTCA DO311A: Minimum Operational Performance Standards for Rechargeable Lithium Batteries and Battery Systems
Definition of thermal runaway.
- IEEE 1725: Standard for Rechargeable Batteries for Mobile Phones, Revision 2.5
Section 2.1.3 provides a reference for the types of testing and monitoring that may be carried out during cell manufacture to minimise introduction of cell defects from the manufacturing process.

CHAPTER 2

GUIDANCE ON CELL FAILURE CAUSES

This chapter describes the conditions, environments or processes that may exacerbate or cause onset of cell level failure modes. These are described as **Failure Causes** for the purpose of this document and are defined in Section 1.4.4.

Each failure cause is described in section 2.1 by defining limits that may be applied to the cell during its operation or storage to ensure that cell failure is controlled:

- Safety limits: Limit that should never be breached during any operational condition. Breach of this limit is likely to result in cell failure as per the failure modes described in CHAPTER 3.
- Operational limits: Limit applied during normal operation of the cell. If the cell is operated within these limits, cell failure should not occur within the expected degradation as qualified by the applicant is expected.
- Lifetime limits: A sub-category of operational limits, used to prolong the lifetime of the cell by minimizing degradation effects – this is a smaller window within the operational window. This is informed by testing and stress factor analysis based on the applicant's specific use case.

Figure 2-1 demonstrates how these limits apply to the cell, how they impact cell degradation and the likelihood of occurrence of the failure modes in CHAPTER 3.

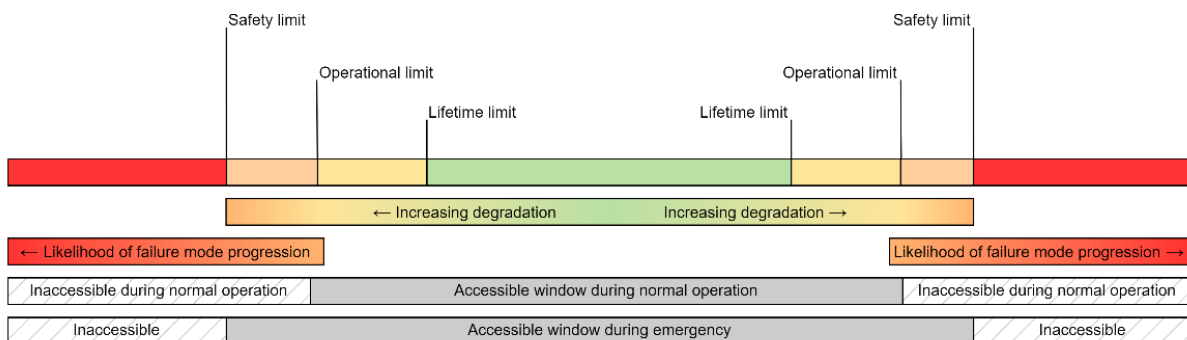


FIGURE 2-1: SCHEMATIC ILLUSTRATING HOW CELL LIMITS RELATE TO FAILURE MODE PROGRESSION

These limits are used by the applicant and are defined by one of the following:

- The cell manufacturer
- A common agreement between the cell manufacturer and the applicant
- The applicant, where sufficient evidence is provided to support the definition of the limit and considering the technical specification(s) provided by the cell manufacturer

NOTE: The applicant is defined as the party which applies for airworthiness certification

2.1 FAILURE CAUSES

2.1.1 Operational considerations

This section covers failure causes that the cell may experience during operation. These should be considered during design of the Energy Storage System (ESS) and definition of load profiles and use cases for the vehicle.

The failure causes defined here are commonly interlinked and this may be considered when setting the limits described in each section. For example, some of the cell failure modes associated with low temperature operation of a cell are most commonly