

ED-289

GUIDANCE ON DETERMINATION OF ACCESSIBLE ENERGY IN BATTERY SYSTEMS FOR EVTOL APPLICATIONS

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CHAPTER 1

INTRODUCTION

1.1 PURPOSE AND SCOPE

This document contains minimum requirements for ***state observer and state predictors of energy storage systems in eVTOL applications***.

Compliance with this standard is recommended as one means of assuring that the equipment will perform its intended function(s) satisfactorily under all conditions normally encountered in routine aeronautical operation.

The equipment may also have additional functions for which other MOPS or ETSOs may be applicable or, it may contain additional functions not defined by any MOPS or ETSO and, non ETSO function guidance may be applicable.

1.2 APPLICATIONS

Compliance with this standard by manufacturers, installers and users is recommended as a means of assuring that the equipment will satisfactorily perform its intended function(s) under all conditions normally encountered in routine aircraft operations.

Any regulatory application of this document in whole or in part is the sole responsibility of appropriate government agencies.

As the measured values of equipment performance characteristics may be a function of the method of measurement, standard test conditions and methods of test are recommended in this document.

1.3 DESCRIPTION OF EQUIPMENT/FUNCTION

This document assumes that the energy storage system (ESS) fulfils, among others, the function to provide an eVTOL with accessible energy for safe flight and landing. To fulfil this function, the ESS state(s) which limits the accessible energy, e.g. cell temperature or state of charge, shall be known to the operator. As some of these internal states are not directly measurable quantities, the ESS has to perform state observations. These are based on physical measurement data, including residual errors, and consisting of, but not limited to, terminal cell voltage, surface temperature or current. Furthermore, some of these state observers rely on ESS models or assumptions with finite accuracy. As the accessible energy of a battery is highly dependent on the flight profile, the ESS also has to perform a prediction of these battery states with regard to the planned flight profile for every given mission. This assures before and during flight, that the ESS can provide accessible energy until the eVTOL reaches safe landing.

The aim of this document is to provide guidance on the determination of the maximum error of that state prediction for a worst-case flight profile during the design phase of the ESS. This worst-case flight profile will be denoted later simply as "Load Profile" and defines an envelope of the consumed power over time and shall be selected in accordance with the operational requirements of the aircraft. The maximum error metric in state prediction for the complete lifetime of the ESS when performing a state prediction for the Load Profile shall then be considered for a safety margin. This assures that the expected residual errors in state observation and state prediction do not critically influence the utilization of the ESS within its known physical limits.

Therefore, the state predictor can assure that a planned profile does not violate any safety boundary until safe landing has been reached and thus allows the operator to confirm the useable energy and range for a given mission.

System failures, e.g. failed sensor read-outs or run-time violations of processors, are not considered in this context as contributors for an erroneous state observation or state prediction, as they are considered in ED-79A / ARP-4754A [1]. Only normal ageing of ESS components (battery cells, etc.) is considered. Foreseeable emergency scenarios,

that require an increased power demand from the ESS, are considered when specifying the Load Profile.

1.4

DEFINITIONS AND ABBREVIATIONS

TABLE 1-1: LIST OF ABBREVIATIONS

BMS	Battery Management System
BOL	Beginning of Life
EMC	Electromagnetic Compatibility
EOL	End of Life
EPC	End Point Condition
ESS	Energy Storage System
ETSO	European Technical Standard Order
EUT	Equipment under Test
eVTOL	Electric vertical take-off and landing aircraft
OCV	Open Circuit Voltage
MOPS	Minimum Operational Performance Standard
RTCA	Radio Technical Commission for Aeronautics
SEI	Solid Electrolyte Interface
SOC	State of Charge
SOF	State of Function
SOH	State of Health
SOP	State of Power

1.4.1

Definition of the Equipment under Test (EUT)

The performance of the state observer and state predictor on the ESS is evaluated during the design validation phase against a testbench setup. Therefore, the battery management system (BMS), and all required sub-systems, operates together with a representative set of battery cells according to the blue area in [FIGURE 1-1](#), and composes the EUT. Due to the huge variety in design and specification of ESS for eVTOL applications, this document will not pre-define the EUT but provide requirements for deriving the EUT from the later ESS. The selected EUT shall be confirmed by the certifying authority.

Requirements on selecting this EUT are described in the following section and utilised in the evaluation procedure which is detailed in [CHAPTER 3](#).

NOTE: *EUT requirements are currently being drafted in EUROCAE WG-112 VTOL [3].*

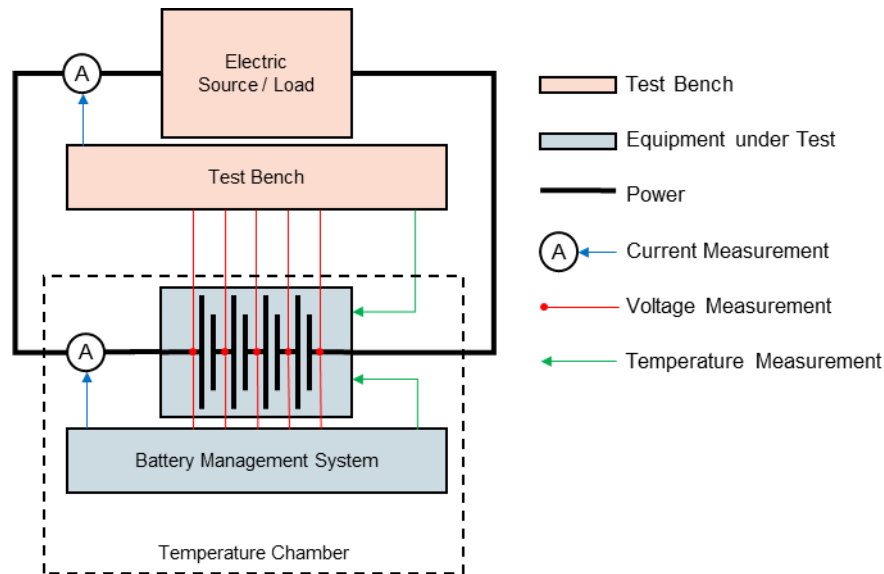


FIGURE 1-1: THE EUT (BLUE AREA), WHICH COMPRISES OF A REPRESENTATIVE SET OF BATTERY CELLS AND THE BMS IS VALIDATED AGAINST A TEST BENCH SETUP (RED AREA).

Req. EUT.1: Definition of an EUT

The EUT shall be derived from the ESS operating in the eVTOL application, including the BMS) and all required sub-systems that hosts the state observation and prediction. Furthermore, all system components which states are identified as a Physical Limit of the ESS (see [SECTION 2.1.1](#)) shall be represented in the EUT.

NOTE: Relevant system components can be, but are not limited to, battery cells, electrical wiring, contactors, and interconnectors.

NOTE: One option is to define the ESS as the EUT.

Req. EUT.2: Thermal interface

The EUT shall reflect the thermal interface of the ESS. Especially, thermal gradients over the EUT surface shall be taken into account.

NOTE: This includes heating, cooling, or isolation capabilities of the ESS to represent the thermal inhomogeneity during an eVTOL operation.

Req. EUT.3: Mechanical interface

The EUT shall reflect the mechanical interface of the ESS. Especially, mechanical stress gradients over the EUT surface shall be taken into account.

NOTE: This includes all mechanical loads, e.g. clamping force or weight, and transient loads, e.g. vibration during flight and ground operation, of the ESS to represent the mechanical inhomogeneity during an eVTOL operation.

Req. EUT.4: Electrical interface

The EUT shall reflect the electrical interface of the ESS. Especially, harmonic distortions of electrical loads and sources shall be taken into account.

NOTE: The harmonic distortions of testbench loads, e.g. based on the operation of inverters or superimposed waveform generators, shall represent potential electric disturbance during an eVTOL operation.

Req. EUT.5: Inhomogeneous ageing

The EUT shall comprise of an appropriate number of battery cells that represents the ESS architecture and the inhomogeneous ageing of individual cells.

NOTE: This includes the inhomogeneous calendar or cyclic ageing of cells and the feedback of this inhomogeneous ageing due to an inhomogeneous current, temperature and SOC distribution during an eVTOL operation.

Req. EUT.6: Inhomogeneity due to maintenance

If the maintenance procedure in the eVTOL application allows the replacement of a subset of cells within an aged ESS with new cells of identical chemistry, the EUT shall reflect such an inhomogeneity.

NOTE: *It is acceptable to scale down the maintenance measures of the eVTOL application to the EUT scope, i.e. reflecting the replacements of whole battery modules of an eVTOL by replacing single cells of the EUT.*

Req. EUT.7: Electronic and Electric interface

The EUT shall utilize the complete electronic and electric architecture as used in the eVTOL application.

NOTE: *This represents potential receiver of disturbance, e.g. measurement circuits for physical cell properties. Also, the impact of electronic-based actuators, e.g. cell balancing, or switching ON / OFF cycles shall be considered as sources of disturbance.*

1.4.2

Definition of the Load Profile

The test bench in [FIGURE 1-1](#) comprises of, but is not limited to, an accurate measurement equipment, an electric load and electric source. The aim of the electric load and source is to synthesize the electric operation of the ESS. For eVTOL application, this shall be a set of multiple worst case load profiles in different environmental and starting conditions with intermediate charging sessions. In short, the load profile shall represent an envelope of all foreseeable conditions in which the eVTOL has to provide a state observation and state prediction later. The load profile(s) shall be signed off by the certification authority.

For a reproducible electric operation of the EUT, this document defines requirements on such a load profile which shall be defined by the applicant in alignment to the future eVTOL operation. The result shall be an electric power over time profile that can be read out by the electric load and source of the test bench.

NOTE: *This document will not pre-define a reference load profile for all eVTOL applications as each load profile differs significantly among different eVTOL configurations.*

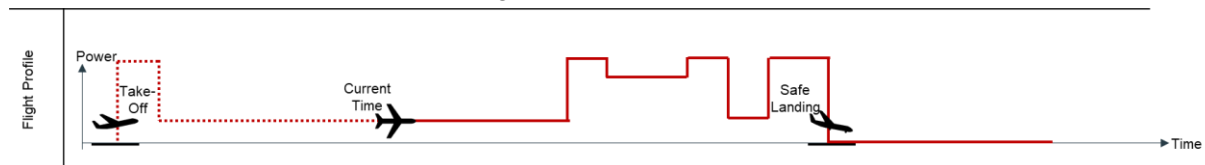


FIGURE 1-2: EXAMPLE OF THE DISCHARGING PHASE OF AN EVTOL LOAD PROFILE AS POWER (Y-AXIS) OVER TIME (X-AXIS) DIAGRAM.

Req. Load Profile.1: Definition of a Load Profile

A Load Profile shall be defined, that represents the time profile of the electric charging and discharging power of the ESS in the eVTOL application.

Req. Load Profile.2: Start Condition

The Load Profile shall start after the EUT has reached a pre-defined reset condition.

NOTE: *This allows for a reproducible operation of the profile and thus a comparison of its results.*

NOTE: *Reset conditions for the EUT are defined in [SECTION 2.1](#).*

Req. Load Profile.3: Start Temperature

The stabilized cell temperature of the EUT shall be a parameter to the starting condition of the Load Profile. At least the upper and lower boundary of valid ESS temperatures shall be evaluated as a starting temperature.

NOTE: *The variation of the starting temperature is introduced in order to reach all possible temperature ranges during operation.*

Req. Load Profile.4: Current Magnitude

The Load Profile shall reflect the maximum current magnitudes in charging and discharging direction.

Req. Load Profile.5: Current Dynamics

The Load Profile shall reflect the in-use power dynamics of the eVTOL application.

NOTE: *For this reason, the intended loads of the eVTOL (e.g. Motor inverter or DC/DC converter) shall be synthesized, either by operation of inverters or superimposed waveform generators.*

Req. Load Profile.6: SOC Swing

The Load Profile shall reach the minimum and maximum operational SOC of the ESS.

Req. Load Profile. 7: Physical Limits

The Load Profile shall meet all specified physical limits of the EUT individually and in various different operating states.

NOTE: *The definition of physical limits can be found in [SECTION 2.1](#).*

NOTE: *For example, if three physical limits of the EUT are defined, the Load Profile shall meet each of them individually. Furthermore, the relevant worst-case combinations of multiple physical limits shall be identified, and a rationale shall be given, why the identified sub-set of combinations is sufficient to demonstrate that the state observer and state predictors are independent of interference from these combinations.*

Req. Load Profile.8: Reset Conditions

The Load Profile shall not meet any explicit reset conditions during operation unless the specified reset interval t_{reset} is reached.

NOTE: *The definition of reset conditions can be found in [SECTION 2.1](#).*

Req. Load Profile.9. Electronic operation cycles

If applicable, the Load Profile shall include ON and OFF cycles of all utilized electronic components of the EUT.

NOTE: *Potential error sources due to ON and OFF cycles of electronic components shall be represented by the Load Profile.*

Req. Load Profile.10: Representation of emergency conditions

The Load Profile shall include foreseeable emergency flight and landing scenarios, with higher power demands immediately before physical limits of the EUT are reached.

NOTE: *Higher power demands can be a result of, but are not limited to, partial ESS failures, partial propulsion failures or abnormal behaviour of control systems.*

1.4.3**Definition of an Ageing Profile**

The accuracy of the state observer and state predictor shall be evaluated for all phases of the ESS operation from Beginning of Life (BOL) till End of Life (EOL). This includes the degradation of battery cells and auxiliary equipment, which normally occurs over months in a conventional ESS operation, due to calendar and cyclic ageing mechanisms. Thus, after every completed evaluation step of the state predictor the EUT shall perform an Ageing Profile that transfers the system to a further aged state until it reaches its EOL condition. The aim of the Ageing Profile is not to evaluate the ESS total lifetime but to reach all foreseeable stages of degradation. Therefore, an artificial

acceleration of this ageing process with a deliberate expansion of the operational limits within the limits of safe operation and consistent ageing modes is acceptable.

Accelerated ageing due to detrimental environmental effects (e.g. air pressure, altitude, humidity and condensation) are not scope of the Ageing Profile, as the life cycle validation is covered in ED-14G / DO-160G [2] .

As the individual degradation of an ESS is dependent on the eVTOL application, this document defines requirements on the Ageing Profile which shall be specified individually by the applicant. The result shall be an electric power over time profile that can be read out by the electric load and source of the test bench.

Req. Ageing Profile.1: Definition of an Ageing Profile

An Ageing Profile shall be defined, that reflects the time profile of the electric charging and discharging power of the ESS in the eVTOL application.

NOTE: *The alignment to the electric charging and discharging profile in the eVTOL application is required in order to cover expectable ageing mechanisms of the ESS.*

Req. Ageing Profile.2: Temperature Swing

The Ageing Profile shall reflect the lower and upper operational temperature limits as well as the rate of temperature change of the EUT.

NOTE: *In order to accelerate the ageing procedure, it is valid to expand the temperature swing within the limits of safe operation and consistent ageing modes.*

Req. Ageing Profile.3: SOC Swing

The Ageing Profile shall reflect the lower and upper operational SOC limits of the EUT.

NOTE: *In order to accelerate the ageing procedure, it is valid to expand the SOC swing within the limits of safe operation and consistent ageing modes.*

Req. Ageing Profile.4: Current

The Ageing Profile shall reflect the operational current limits in charging and discharging direction as well as current dynamics of the EUT.

NOTE: *In order to accelerate the ageing procedure, it is valid to increase the current within the limits of safe operation and consistent ageing modes.*

Req. Ageing Profile.5: Environment

If applicable, the Ageing Profile shall reflect the environmental conditions of the EUT.

NOTE: *In order to accelerate the ageing procedure, it is valid to implement more harsh environmental conditions within the limits of safe operation and consistent ageing modes.*

1.5

ASSUMPTIONS

N/A

1.6

REFERENCES

TABLE 1-2: TABLE OF REFERENCES

Reference	Name	Title
[1]	ED-79A / ARP-4754A	Guidelines For Development Of Civil Aircraft and Systems
[2]	ED-14G / DO-160G	Environmental Conditions and Test Procedures for Airborne Equipment
[3]	Draft ED-XXX	Technical Standard on Rechargeable Lithium Batteries in eVTOL applications (Currently in development in EUROCAE WG-112 VTOL)
[4]	Draft ED-XXX	Compliance methodologies for VTOL energy level information to the crew (Currently in development in EUROCAE WG-112 VTOL)