BATTERY PASSIVATION

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Battery Passivation
D7 – Executive Summary Report

ESA Ref. AO/1-8325/15/NL/LvH

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Introduction

Airbus Defence and Space (France), in partnership with CEA (France) and the two main European battery manufacturers for space Saft (France) and ABSL (England), is pleased to present this document in the frame of the study for the European Space Agency (ESA): **Battery Passivation (Ref: AO/1-8325/15/NL/LvH)**.

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1. REFERENCE DOCUMENTS & ACRONYMS

1.1 Reference documents

RD NO.	TITLE	REFERENCE	ISSUE /REV	DATE
RD 1	Environmental Impact on Power Systems After End-Of-Life	CDF-TN-069	01/00	04/09/2014
RD 2	Spacecraft Power System Passivation - D8 Phase1 Final Report	SPSP.PATRI.RP. 61318	02/00	12/10/2015
RD 3	Battery Passivation - Proposal in response to ESA Invitation to Tender: AO/1-325/15/NL/LvH	TSPES81.PC.PT.7 32476.15	01/00	July 2015
RD 4	D1 - Test specification requirements	2125.NT.SB.16.214 3.ASTR	01/00	24/02/2016
RD 5	D2 – Test plan-procedure	2125.PE.SB.16.220 6.ASTR	03/00	13/03/2017
RD 6	D3 – Test Report	ELEC.ENG.RP.201 8.1000061264.ADS	01/00	10/2018
RD 7	D4 - Degradation investigation report	ELEC.ENG.NT.201 8.1000061265.ADS	01/00	11/2018
RD 8	D5 - Final report	ELEC.ENG.NT.201 8.1000070244.ADS	01/00	11/2018

1.2 Acronyms

ABSL	AEA Battery Systems, Ltd.
ARC	Accelerated Rate Calorimetry
BOL	Beginning of Life
CCCV	Constant Current Constant Voltage
CEA	Commissariat à l’énergie atomique et aux énergies alternatives
EOCV	End of Charge Voltage
EOL	End of Life
ESA	European Space Agency
EGSE	Electrical Ground Support Equipment
GSTP	General Support Technology Programme
RD	Reference Document
RUAG	Rüstungs Unternehmen Aktiengesellschaft
SAFT	Société des Accumulateurs Fixes & de Traction
SOC	State of Charge
SPSP	Spacecraft Power System Passivation
WBS	Work Breakdown Structure

2. BACKGROUND AND SCOPE OF THE STUDY

Sustainability of future missions relies on current design decisions in order to avoid future satellite collisions or interferences among them. One of the key sub-systems to correctly dispose and secure the satellite is the Electrical and Power System, since it contains electrochemical devices like Li-ion batteries that can suffer from unknown behaviours after several years in orbit, due to radiation and uncontrolled temperature ranges or unregulated power control leading to potential overcharge and even in-orbit explosions.

Current initiatives like ESA's Clean Space are developing new methods and processes in order to avoid as much as possible the generation of space debris. In order to decide the best way to make safe or completely deplete a spacecraft's battery, it is of primary importance to be aware of the risks posed by the battery itself: which temperatures or radiation doses can be withstood, what is the probability of a thermal runaway leading to a cell explosion…

This study was part of the Clean Space's Power Passivation Roadmap. In order to be coherent, it took into account the main outputs from the preliminary studies:

- The ESA internal activity "Environmental Impact on power systems after EOL", see [RD 1].
- The GSTP study "Spacecraft Power System Passivation" led by RUAG Finland and more precisely the output from phase 1, see [RD 2].

The objective of the activity was "**to test Li-Ion battery cells and modules under extreme conditions encountered after spacecraft disposal in order to assess their safety".**

The scope was therefore:

- Limited to Li-Ion technology (other technologies like Ag-Zn, Ni-Cd… can be quoted but will not be part of the study).
- Limited to European battery models. As requested by ESA, only batteries usually offered by the main European manufacturers will be used, in this case Saft and ABSL.
- Limited to realistic extreme conditions after spacecraft disposal (or be defined during the study).

3. APPROACH TO THE STUDY

To reach the main technical objective, analysed in depth in the previous section, the following approach was proposed:

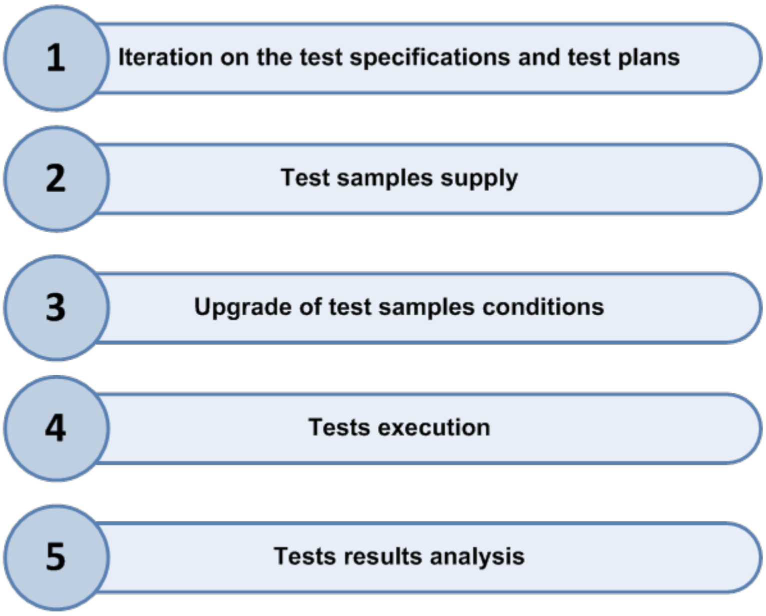

Figure 3-1 Proposed approach to reach the technical objective

1. **<u>Iteration on the test specifications and test plan:</u>** following the different options listed for spacecraft disposal as well as the extreme conditions, a list of suggested tests was specified in the proposal (see [RD 3]).
2. **<u>Test samples supply:</u>** To cover all the cells specified in the SoW, the two European space battery manufacturers have been associated to this study. The supply of samples was therefore guaranteed.
3. **<u>Upgrade of test samples conditions:</u>** available aged cells came from different sources and were either irradiated or not. More recently released cell models were artificially aged by cycling and/or irradiated. The aging impact needed to be proven as major on battery safety.
4. **<u>Tests execution:</u>** once all the samples were upgraded, the tests specified could be started. CEA has all the facilities required to perform the abusive and destructive tests.
5. **<u>Tests results analysis:</u>** degradation and failures were investigated by all the four partners of the study.
6. **<u>Final conclusions:</u>** once all the test results have been deeply understood, analysed, and summarized, a set of final conclusions was established in order to propose the best passivation strategy or strategies concerning the battery safety. A series of recommendations were provided for updating current hypotheses, existing rules and list some guidelines for current and future missions.

4. ACHIEVEMENTS

This section **summarises the findings of the study**.

The conclusions included in this document are based on the investigations done on all the t**ests performed by ABSL and SAFT prior to this study** and **by CEA in the frame of the study** on all the cells listed in RD 5.

Tests have been performed on more than 200 battery cells, both fresh and aged/irradiated. The tests performed in this TRP include External short-circuit, Internal short-circuit, Over-charge, Over-discharge, Accelerating Rate Calorimetry (ARC) test, Over-temperature test and Micrometeoroids. Cells and modules from the two main battery manufacturers in Europe, ABSL and SAFT, are used for testing including ABSL18650-HC, 18650-HCM, 18650-NL and SAFT VES16, VES140, VES180.

Some tests were performed in inert atmosphere for flight representativeness, at cell level and module level. In general each test was performed on at least 2 samples. If test results were not conclusive, one or more samples were added to be able to draw conclusions.

Be aware that all the conclusions are based on a limited number of samples and provide a good trend on the overall behaviour; that is, one cannot generalize from these findings. Besides, extrapolation of the obtained results on other cells or modules arrangement shall be assessed carefully and preferably by conducting specific abusive test.

Recommendations related to the battery safety after end of mission and electrical passivation are provided in §5, as well as more detailed guidelines to update existing passivation rules.

A proposition for future steps to follow and perspectives is also included.

Refer to RD 7 for a detailed comparison, analysis and understanding of the results of the abusive and destructive tests done on the entire battery cell and module samples. The conditions and the results are described for each test, with a risk level assessment to explain the danger of that kind of event if it occurs on board a satellite.

Refer to RD 8 for a summary of the main findings for each type of test, the conditions, their suitability and limitations.

Figure 4-1: Pictures of two VES140 battery cells after external short-circuit test

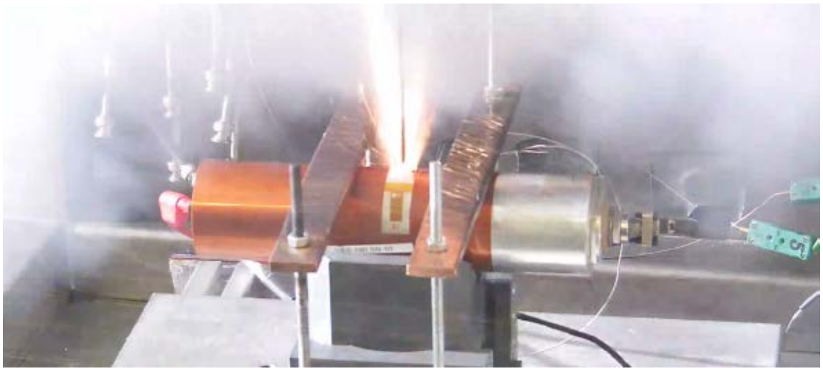

Figure 5-2: Picture of a VES180 battery cell before, during and after internal short-circuit

Figure 6-3: Picture of two different ABSL battery modules during overcharge

5. CONCLUSION

Recommendations for passivation at end of mission

In order to ensure a good passivation at the end of spacecraft mission, it is recommended to r**emove all on-board sources of energy:**

- First fluidic passivation for exhaustion of the propellants and depressurization of the tank,
- Electrical and RF passivation to **inactivate the power sources** and avoid any spurious RF emission.

For the electrical passivation, it is recommended to **isolate the battery from the solar arrays** (for example by disconnecting the solar arrays from the main power bus) so that the battery **cannot be recharged or even worse overcharged.**

In order to ensure battery safety in extreme conditions, it is recommended, when possible, to **fully discharge the battery** through the power sub-system (Power Conditioning and Distributing Unit or Power Supply Regulator) and to **over-discharge it down to 0V or below thanks to a resistive load or any other mean**.

It is recommended to perform a **thermal analysis at spacecraft level at end of mission** (with worst case assumptions with regard to thermo-optical properties and spacecraft attitude) and make sure that the battery temperature will not exceed the onset point (with 10°C margin) to protect the battery from thermal runaway.

The prevention from the other risks is summarized hereafter.

External short-circuit:

A first recommendation is to apply **double insulation rules** in order to avoid as much as possible the external short-circuit event.

Besides, it has been proven than cells internal protection devices can be very efficient at cell level but can also fail in a module configuration. Therefore, prevention of external short-circuit at battery level is also recommended:

- Use of safe power connectors (keying system, scoop proof),
- Use of protective devices (fuses, circuit breakers, thermal switches)

Internal short-circuit and micrometeoroids:

A **thermal isolation of the cells (individually) inside the battery module** can be imagined in order to prevent failure propagation, but the impact on the mass and cost would need to be assessed.

The use of a strong **external battery casing** can also be imagined to prevent debris generation and failure propagation to the surrounding equipment, especially to other power sources such as propulsion tanks. This could be a good option, especially for small batteries.

Overcharge:

Test conclusions highlight that **cells internal protections are an asset** but might not be sufficient in all cases, especially at module level. Extrapolation of cell abusive testing at module level shall be assessed carefully and preferably by conducting specific abusive test on modules, on top of cell abusive tests.

Overcharge can lead to thermal runaway and have catastrophic consequences. Therefore, protections against overcharge through system level design are prescribed to ensure battery safety:

- At the end of mission, it is highly recommended to **isolate the battery from the Solar Array** in order to prevent any undesired and uncontrolled recharge of the battery.

High Temperature & ARC (Accelerated Rate Calorimetry):

The aim of the ARC test is to analyse the thermal behaviour of the cells under adiabatic conditions in order to identify the non-self-heating, self-heating and thermal runaway regions for each cell model by gradually increasing the chamber temperature. ARC test conclusions highlight that **onset and thermal runaway temperatures are fully correlated with the cell stored energy**, i.e. the SOC and to a lesser extent the ageing loss.

Besides, the over-discharged tested cells (at 0V) showed a safer response to ARC test than cells at 0% SOC (some cells at 0V could go up to 150°C without going into thermal runaway but it isn't the case at 0% SOC)

Therefore, **for battery passivation at end of life**, **it is recommended to over-discharge cells down to 0 Volts** in order to limit the risk of thermal runaway.

Besides, it is recommended to do a **thermal analysis at spacecraft level at end of mission** and make sure that the battery temperature will not exceed the onset point (with 10°C margin) to protect the battery from thermal runaway (no exothermic reaction).

It is therefore proposed to include systematically additional tests for new cells qualification, in order to know the onset and thermal runaway temperatures of the cells (today tested up to 60°C only) as well as other abusive tests. Besides, the passivation scenario at the end of the mission should be assessed **at battery and system levels** with additional simulations and analysis at thermal and electrical system levels to help mitigation of the risk linked to the energy storage systems.