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Subject Abuse testing procedure on Li and SC cells and modules			Dissem. Level **PU**

Deliverable 3100.4
Abuse Test Plan for Li Batteries and SC

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Summary

This deliverable deals with abuse tests available for electric energy storage systems EES in electrically propelled vehicles (EV and HEV), which are in this case lithium secondary batteries (Li) and super capacitors (SC). This report is part of the Work Package 3100 “Storage System Specifications & Test planning (Battery and Supercaps)” in which the dedicated Task 3120 ”Abuse test procedure definition” had the scope to investigate and propose existingt esting procedures with attention to extreme mechanical, thermal and electrical conditions, tailored on the heavy duty vehicles. The work has been done mostly by AIT with contribution from ENEA, car makers, Magna and Dimac. A test matrix is also proposed for cells and modules.

The document starts with an introduction and then continues with the demands on measurement and test facility equipment. Initial cycles and conditions suited to obtain comparable results are given. Finally the tests are explained in detail and the method to evaluate and document the results is stated.

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Table of contents

Introduction

Scope

This deliverable is prepared for the Milestone 3300.1 of WP3300 using parts of WP 3100.

The DOW programme for this task was as follows:

Abuse testing is aimed at characterizing energy storage systems Li and SC cells in the WP during off- normal or in severe operating conditions/environments. The test program of abuse testing has the main objective to identify through controlled simulation testing all the possible risks conditions. These conditions will be then analyzed to clearly define mitigation measures to be used in design, control and usage of such storage systems. The work carried out on cells in this WP 3300 is complementary and parallel to that on modules (WP3400). Failure pathways will be proposed based on the abuse testing results (and not on post-mortem analysis), so as to eventually propose novel parameters for the provision

Task 3310 + 3320 Abuse testing of Li and SC cells
Using abuse test plans developed in WP3100, AIT, ENEA and Volvo, with the contribution and approval of Magna (for Li) or Dimac (for SC), will carry out abuse testing and safety analysis, concentrating on:

1. Mechanical (vibration)
2. Thermal
3. Electrical
4. Mixed (for example mechanical and electrical together)

The preliminary cell testing matrix, based on key influencing parameters, will clearly identify the needed cells (3 at least used for each test for acceptable statistics). Magna (for Li) or Dimac (for SC) will also assist data analysis and reporting.

Applied Methods

The manual *"Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicles Applications"* [2] from FreedomCAR is a widely accepted abuse test manual for commercial (H)EV tests as well as for research purposes. Another benefit is that the manual can be applied to both Li and SC. Therefore it serves as a basis for this document. The tests are adapted to fulfil the demands concerning costs, standards, the specific EES type to investigate and the testing facilities of the participants.

General

Measurements and Documentation

For the different tests different measurements will be necessary. Mandatory measurements are stated in the according test section. Additional logging of other parameters may be useful.
The documentation should include the measurement results in a format that allows comparison of various EES designs [2]. A short interpretation of the tests result should be included as well as a classification of the tests according to Tab. 1.

Abuse and Hazard Levels

Abuse Levels

The tests are classified in terms of their harm to the cell according to [2]:

Level 1: The EES is expected to remain essentially intact
Level 2: The EES may become inoperable but should not expose humans to known health risks
Level 3: The EES is exposed to destructive situations

The abuse level is indicated in brackets in the header of the section.

Hazard Levels

The response of the cell, module or package is classified according to:

Tab. 1. Hazard levels [4]

Hazard Level	Description	Classification Criteria & Effect
0	No effect	No effect. No loss of functionality.
1	Passive protection activated	No defect; no leakage; no venting; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.
2	Defect/Damage	No leakage; no venting, fire or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.
3	Leakage Δ mass < 50%	No venting, fire or flame*; no rupture; no explosion. Weight loss < 50% of electrolyte weight (electrolyte = solvent + salt).
4	Venting Δ mass ≥ 50%	No fire or flame*; no rupture; no explosion. Weight loss ≥ 50% of electrolyte weight (electrolyte = solvent +salt).
5	Fire or Flame	No rupture; no explosion (i.e., no flying parts):
6	Rupture	No explosion, but flying parts of the active mass.
7	Explosion	Explosion (i.e., disintegration of the cell)

*The presence of a flame requires an ignition source in combination with fuel and oxidizer in concentrations that will support combustion.

EES Data

The parameters of the cells and modules used for this project are stated below. All test procedures are referred to these values.

Battery Type

Li Cell

The Li to investigate is a **32113** cell (generation 2) from **A123 systems** with following parameters:

Capacity	4.4Ah
Nominal Voltage	3.3V
Mass (average)	205g
Diameter	32mm
Length	113mm
Energy	14.5Wh
Specific Energy	75Wh/kg
Power (25C, 50%SOC, 10sec)	578W
Specific Power (25C, 50%SOC, 10sec)	2979W/kg
DCR (25C, 50%SOC, 10sec)	4.5mΩ

Li Module

The module to investigate is a **2p18s** combination of **32113 cells from A123 systems** with following parameters:

Capacity	8.5Ah
Nominal Voltage	59.4V
Mass (average)	10kg
Length	436mm
Width	293mm
Height	83mm
Energy	505Wh
Specific Energy	50.5Wh/kg
Power (23℃, 56%SOC, 2sec)	11.25kW

Supercap Type

SC Cell

The SC to investigate is a **BCAP3000 P270** cell from **Maxwell** with following parameters:

Capacitance	3000F
Nominal Voltage	2.7V
Mass (average)	510g
Diameter	60.7mm
Length	138mm
Energy	3.04Wh
Specific Energy	5.96Wh/kg
Power	3020W
Specific Power	12300W/kg
DCR	0.29mΩ

SC Module

The SC module to investigate is a **BMOD0063 P125** cell from **Maxwell** with following parameters:

Capacitance	63F
Nominal Voltage	125V
Mass (average)	59.5kg
Length	762mm
Width	425mm
Height	265mm
Energy	101.7Wh
Specific Energy	2.53Wh/kg
DCR (25C, 50%SOC, 10sec)	18mΩ

The test plan for SC cells is designed according to these values.

Conditioning and Initial SOC

Conditioning

Fabric new cells are not mature and show different behaviour than they will show under subsequent cycles. They develop full capacity and power capability after some initial cycles [1]. For useful results the cell should experience a few forming cycles before being tested. Thus the Li cell and module should undergo 10 full cycles according to Tab. 2 and Tab. 3. While the SC cell and module should undergo 50 full cycles according to Tab. 4 and Tab. 5.

Initial SOC

If not stated otherwise the tests are done at SOC = 100%. To ensure full charged state and comparable initial conditions this section provides a guideline for adequate charging.

Li charging procedure

The device has to be discharged with a rate of 1C to the lower voltage limit. Then a rest time of 30min has to be given followed by a charging cycle where the current is limited to a rate of 1C and the voltage is limited to the upper voltage limit. The termination condition is when the current falls below a level of 0.05C. Before starting another cycle or a test a rest time of 30min should be given.

Tab. 2. Li Cell Charging Procedure (full cycle)

Mode	Current	Voltage	Breaking Condition
CC	-4.4A		Voltage ≤ 2.0V
Break			Time ≥ 30min
CC	4.4A		Voltage ≥ 3.6V
CV		3.3V	Current ≤ 0.2A
Break			Time ≥ 60min

Tab. 3. Li Module Charging Procedure (full cycle)

Mode	Current	Voltage	Breaking Condition
CC	-8.5A		Voltage ≤ 46.8V
Break			Time ≥ 30min
CC	8.5A		Voltage ≥ 65.7V
CV		65.7V	Current ≤ 0.4A
Break			Time ≥ 60min

SC charging procedure

The device has to be discharged with a rate of 5mA/F down to a lower voltage limit of V=0.3*Nominal Voltage. Then a rest time of 5min has to be given followed by a 15 min charging cycle where the current is limited to 50mA/Farad and the voltage is limited to the nominal voltage. Before starting another cycle or a test a rest time of 30min should be given [6].

Tab. 4. SC Cell Charging Procedure (full cycle)

Mode	Current	Voltage	Breaking Condition
CC	-15A		Voltage ≤ 0.81V
Break			Time ≥ 30min
CC	150A		Voltage ≥ 2.7V
CV		2.7V	Current ≤ 5A
Break			Time ≥ 60min

Tab. 5. SC Module Charging Procedure (full cycle)

Mode	Current	Voltage	Breaking Condition
CC	-0.32A		Voltage ≤ 50V
Break			Time ≥ 30min
CC	3.2A		Voltage ≥ 125V
CV		125V	Current ≤ 5A
Break			Time ≥ 60min

Sample Number and Schedule

Sample Number for Each Test

To get reliable results each test should be conducted using several test units finding a balance between statistical relevance and expense. Tab. 6 shows the number of cells and modules to be checked in each test.

Tab. 6. Definition of samples to be used in each test.

Test	# Li Cells	# Li Modules	# SC Cells	# SC Modules
Overcharge / Overvoltage	3	1	3	1
Short Circuit	3	1	0	0
Overdischarge / Voltage reversal	3	1	3	1
Thermal Stability	3	0	3	0
Elevated Temperature Storage	9	0	9	0
Rapid Charge	0	1	0	1
Controlled Crush	6	0	6	0
Penetration	3	1	3	1
Immersion	0	1	0	1
Total	*30*	*6*	*27*	*5*

Test Schedule

Tab. 7. Schedule for Tests

	Okt. 10	Nov. 10	Dez. 10	Jän. 11	Feb. 11	Mär. 11	Apr. 11	Mai. 11	Jun. 11	Jul .11	Aug. 11	Sep. 11	Okt. 11	Nov. 11	Dez. 11	Jän. 12	Feb. 12	Mär. 12	Apr. 12	Mai. 12
Overcharge / Overvoltage																				
Short Circuit																				
Overdischarge / Voltage reversal																				
Thermal Stability																				
Elevated Temperature Storage																				
Rapid Charge																				
Controlled Crush																				
Penetration																				
Immersion																				

Tests

Electrical

Overcharge / Overvoltage (Abuse Level 2)

According to [5] Chap. 5.1.1 and [2] Chap. 5.1. Both tests are adapted and combined. Measurements have to be taken according to Tab. 8.

Tab. 8. Measurements for mechanical tests

Measurement	Apply (rate)
Current	Li=1s; SC=0.2s
Cell Voltage	Li=1s; SC=0.2s
Surface temperature	Li=1s; SC=0.2s
Video	Yes
Pictures	Yes
Gas analyses	Yes (for cell)

Assembly Level

Cell and Module

Description

Cell (without protection circuit):
The cell is charged with the standard charging current (see Tab. 2 to Tab. 5) until the device vents, explodes, reaches 200% SOC or the surface temperature returns to ambient temperature again. If the cell is damaged it has to be observed for two more hours and then be discharged safely.

Module (with passive protection circuit):
The module is charged with the standard charging current (see Tab. 2 to Tab. 5) until the overcharge protection circuit is activated. When a charge greater than 1.2 times the maximum allowed charge according to manufacturer is reached the test has to be stopped.

Battery Parameters

Tab. 9. Li Overcharging Procedure (full cycle)

	Mode	Current	Voltage	Breaking Condition
Cell	CC	4.4A		Venting, Explosion, 200% SOC (8.8Ah in total)
	Observation			2h
Module	CC	8.5A		Activation of protection circuit, SOC 120% (10.2Ah in total)
	Observation			3h

Supercap Parameters

Tab. 10. SC Overcharging Procedure (full cycle)

	Mode	Current	Voltage	Breaking Condition
Cell	CC	150A		Venting, Explosion, 200% SOC (5.5Ah in total)
	Observation			2h
Module	CC	3.2A		Activation of protection circuit, SOC 120% (2.625Ah in total)
	Observation			3h

Short Circuit (Abuse Level 3)

According to [2] Chap. 5.2. Measurements have to be taken according to Tab. 11.

Tab. 11. Measurements for short circuit tests

Measurement	Apply (rate)
Current	0.2s
Cell Voltage	0.2s
Surface temperature	0.2s
Video	Yes
Pictures	Yes
Gas analyses	No

Assembly Level

Module (mandatory) and cell (optional). Note: This test is mainly interesting concerning Li modules but can also be done with SC modules.

Description

The terminals of the module (with passive protection circuit) are short circuited in less than one second with a resistance smaller than 5mΩ for 10min.

Parameters

Tab. 12. Short circuit test plan

	Mode	Resistance	Breaking Condition
Module and Cell	Short Circuit	0.5mΩ	10min
	Observation		2h

Overdischarge / Voltage reversal (Abuse Level 2)

According to [2] Chap. 5.3. Measurements have to be taken according to Tab. 13.

Tab. 13. Measurements for short circuit tests

Measurement	Apply (rate)
Current	1s
Cell Voltage	1s
Surface temperature	1s
Video	Yes
Pictures	Yes
Gas analyses	No

Assembly Level

Module (mandatory) and cell (optional). Note: Overdischarge is an abuse scenario for Li while voltage reversal is an abuse scenario for SC.

Description

Overdischarge (for Li):
Discharge module (with passive protection circuit and cooling system) or cell with a current rate of 0.1C down to fully discharged state. After reaching this limit the test should be continued for 90min more or until 50% of the subassemblies have achieved voltage reversal for more than 15min.

Voltage Reversal (for SC):
Charge the module (with passive protection circuit and cooling system) or cell with a current rate of 5C to its nominal voltage. Reverse the polarity of the charge and charge the device to its negative nominal voltage with the current limited to a rate of 5C. After reaching the negative nominal voltage the test should be continued for 90min more or until 50% of the subassemblies have achieved voltage reversal for more than 15min.

Parameters

Tab. 14. Overdischarge procedure for Li

	Mode	Current	Voltage	Breaking Condition
Cell	CC	-0.44A	0V	Voltage ≤ 0V
	Hold		0V	90min
Module	CC	-0.85A	0V	Voltage ≤ 0V
	Hold		0V	90min

Tab. 15. Voltage Reversal Procedure for SC

	Mode	Current	Voltage	Breaking Condition
Cell	CC	+150A	+2.7V	Voltage = 2.7V
	CC	-150A	-2.7V	Voltage ≤ -2.7V
	Hold		-2.7V	90min
Module	CC	+16A	+125V	Voltage = 125V
	CC	-16A	-125V	Voltage ≤ -125V
	Hold		-125V	90min

Thermal

Thermal Stability (Abuse Level 3)

According to [2] Chap. 4.1. Measurements have to be taken according to Tab. 16.

Tab. 16. Measurements for thermal stability tests

Measurement	Apply (rate)
Current	No
Cell Voltage	1s
Surface temperature	1s
Video	Yes
Pictures	Yes
Gas analyses	No

Assembly Level

Cell

Description

The cell gets heated up from 30℃ to 200℃ above its operational temperature in steps of 5℃ and with brakes of 30min. If the cell vents, explodes or undergoes other major damage before the upper temperature is reached the test has to be stopped.
When self heating is detected hold the temperature level under the reaction becomes stable. Then proceed with increasing the temperature.

Parameters

This test is equal for both Li and SC and should be conducted like shown in Fig. 1.

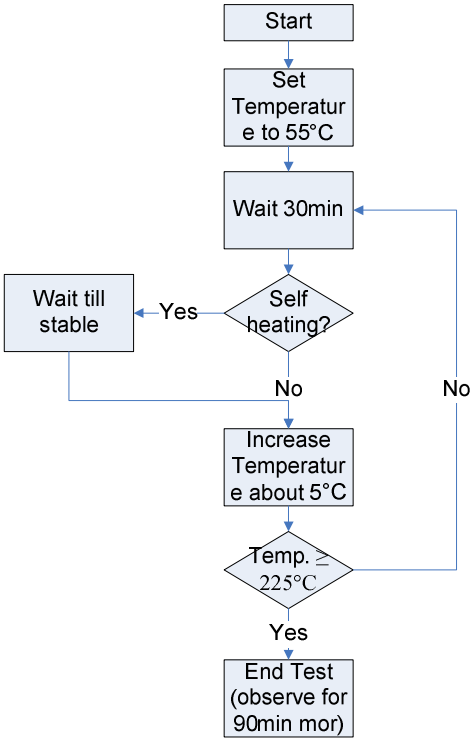

Fig. 1. Flow Diagram for Thermal Stability Test

Elevated Temperature Storage (Abuse Level 2)

According to [2] Chap. 4.3. During this test procedure no permanent monitoring of the device under test (DUT) is necessary.

Assembly Level

Cell

Description

The device under test is stored at several different temperature- and SOC levels (see Tabelle 17). At the beginning of the test and then weekly a capacity measurement has to be performed applying the standard charging cycle (Tab. 2 and Tab. 4) two times. After the capacity measurement the DUT has to be charged to its corresponding SOC level again. The test should be ended if the remaining capacity is less than 80% of the initial capacity or two months of testing time were exceeded.

Tabelle 17. Temperature- and SOC levels

	40 °C	**60 °C**	**80 °C**
100% SOC	X	X	X
50% SOC	X	X	X
20% SOC	X	X	X

Parameters

This test is equal for both Li and SC and should be conducted like shown in Fig. 1.

Rapid Charge / Rapid Discharge (Abuse Level 2)

According to [2] Chap. 4.4. Measurements have to be taken according to Tab. 18.

Tab. 18. Measurements for rapid charge / rapid discharge

Measurement	Apply (rate)
Current	0.2
Cell Voltage	0.2s
Surface temperature	1s
Video	Yes
Pictures	Yes
Gas analyses	No

Assembly Level

Module

Description

The cell gets heated up from 30℃ to 200℃ above its operational temperature in steps of 5℃ and with brakes of 30min. If the cell vents, explodes or undergoes other major damage before the upper temperature is reached the test has to be stopped.
When self heating is detected hold the temperature level under the reaction becomes stable. Then proceed with increasing the temperature.

Parameters

This test is equal for both Li and SC and should be conducted like shown in Fig. 1.

Tab. 19. Li Module Charging Procedure (full cycle)

Step	Mode	Current	Breaking Condition
1	CC	-25.5A	Voltage ≤ 46.8V
2	CC	25.5A	Voltage ≥ 65.7V
3	Loop		20 iterations or fault condition

Tab. 20. SC Module Charging Procedure (full cycle)

Step	Mode	Current	Breaking Condition
1	CC	-0.96A	Voltage ≤ 50V
2	CC	9.6A	Voltage ≥ 125V
3	Break		20 iterations or fault condition

Mechanical

The measurements which have to be taken according to Tab. 21 are equal for each test.

Tab. 21. Measurements for mechanical tests

Measurement	Apply (rate)
Current	No
Cell Voltage	0.1s
Surface temperature	1s
Video	Yes
Pictures	Yes
Gas analyses	No

Controlled Crush (Abuse Level 3)

According to [2] Chap. 3.1.

Assembly Level

Cell

Description

Crush the cell between two plates. One plate has a flat surface and one a textured surface.

Tab. 22. Li Cell Test Plan

	Type	Hold for
Stage 1	Displacement 4.8mm	5min
Stage 2	Displacement 16mm with limited force to 2010.4N (205kg)	5min

Tab. 23. SC Cell Test Plan

	Type	Hold for
Stage 1	Displacement 9.2mm	5min
Stage 2	Displacement 30.2mm with limited force to 4020.8N (510kg)	5min

Penetration (Abuse Level 3)

According to [2] Chap. 3.2. The tests stated in this section are equal for both Li and SC.

Assembly Level

Cell and module

Description

Press a mild steel pointed conductive rod with 3mm diameter through both the Li and the SC cell. The rod has to be electrical insulated from the test article.

Immersion (Abuse Level 2)

According to [2] Chap. 3.4.

Assembly Level

Module

Description

The modules are given in a standard composition of sea water at 25℃ (36g salt per litre water) for a minimum of two hours.
Additional measurement the resistance between the case and the positive and negative terminal before and after the test should be measured.

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