CELL-INTEGRATED SENSING FUNCTIONALITIES FOR SMART BATTERY SYSTEMS WITH IMPROVED PERFORMANCE AND SAFETY

GA 957273

D1.2 – TESTING PLAN FOR CELLS AND MODULES

LC-BAT-13-2020 - Sensing functionalities for smart battery cell chemistries

Deliverable No.	1.2	
Related WP	1	
Deliverable Title	Testing plan for cells and modules	
Deliverable Date	30-03-2021	
Deliverable Type	REPORT	
Dissemination level	Public (PU)	
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Status	FINAL	30-03-2021

Summary

The tests defined in this document, first, shall enable an in-depth evaluation of the influence of the integrated sensors on the operational parameters of the cell. These tests will be performed on baseline cells without sensors, and the same cell type with sensors added inside. Second, the aim is to show a proof of concept for Battery Management Systems (BMS) that, using additional sensor data, allows for operation of battery modules with an optimized strategy. These tests are performed on a battery module using cells with integrated level-1 (pressure and temperature) sensors.

Thus, this testing plan provides:

1.) Side-by-side comparative tests on baseline cells and cells with internal sensors, including:

- Performance tests
- Safety tests
- Accelerated ageing tests

These tests are kept basic (e.g. static charge/discharge profiles) in order to allow for a good comparison both within the project and to literature and standards. The impact of temperature is analysed by the cycling of cells at elevated temperature. Due to the limited number of available specimen cells, care will be taken to schedule testing such that the maximum amount of information and utility can be extracted from each cell, i.e., progressing from the least destructive to the most destructive cell tests (e.g., safety tests).

2.) On module level, the testing seeks to determine the effect of a smart operating strategy that is enabled by the data obtained from the sensors in the cells and actuated by the BMS. A comparison of module operation with and without data from integrated sensors will be undertaken to determine the impact of a smart, sensor-data-driven operating strategy on performance, ageing/degradation and safety on cell and module level, and the ability to detect defects early on. As these tests are designed to explore the potential for real-world applications, dynamic driving cycles are used for evaluation of the modules.

3.) All the tests are supported by post-mortem analysis of selected cells in order to identify and assign potential influences of the sensors on the inner cell components.

4.) To determine the long-term influences of the corrosive environment on the sensors, several points for recalibration of the sensors are scheduled.

All tests named above are based on the requirements defined in D1.1 ‘Requirement Specification (Use cases, KPIs and cell, module requirements)’. As the D1.1 was finished behind schedule, this also impacted the deliverable D1.2. The delay of the present document is unlikely to lead to further delays in the project, as testing starts with a sufficient buffer period. In addition, this deliverable and the related task does not include any deviation from the objectives planned in the Grant Agreement of the SENSIBAT project.

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Abbreviations

Symbol / Abbreviation	
AC	*Alternate Current*
BMS	*Battery Management System*
CC	*Constant Current*
CV	*Constant Voltage*
DC	*Direct Current*
DOD	*Depth Of Discharge*
EIS	*Electrochemical Impedance Spectroscopy*
EOL	*End Of Life*
OCV	*Open Circuit Voltage*
SOC	*State Of Charge*
SOH	*State Of Health*
SOS	*State Of Safety*
U_{max}	*Upper Voltage Limit*
U_{min}	*Lower Voltage Limit*

Terms and Definitions

Capacity:

Electric charge which a cell or battery can deliver under specified charge and discharge conditions.

NOTE - The SI unit for electric charge, or quantity of electricity, is the coulomb (1 C = 1 As) but in practice, capacity of batteries is usually expressed in ampere hours (Ah).

Calendar Life:

The timespan at reference temperature (or if specified at other temperatures), reference SOC value and zero load (open-circuit) until the EOL criteria is reached (corresponding to key-off/standby conditions in the vehicle).

Constant Current (CC):

CC is a type of direct current that does not change its intensity with time and is a parameter to be controlled in corresponding charge or discharge phase.

Cell:

Secondary lithium-based battery cell developed in this project.

C-Rate (C)

Is a factor which puts the discharge or charge current in A in relation to the nominal capacity C_n in Ah:

$$C = \frac{I}{C_n}$$

So, the C-rate in 1/h is the inverse of the expected discharge time of the cell at the given current. In case of a discharge time of 1 h for a cell with C_n = 1 Ah this means:

$$I_C = \frac{C_n(Ah)}{t(h)} = \frac{1Ah}{1h} = 1A$$

C_n is defined with the nominal capacity of the cell, regardless of the progress of this value.

Constant Voltage (CV):

CV refers to a type of direct current where output current fluctuates to maintain a set voltage. It is a parameter to be controlled in corresponding charge or discharge phase.

Cycle:

A discharge phase followed by a charge phase (both not necessarily full).

Depth of Discharge (DOD):

Ratio between withdrawn charge Q during discharge and the nominal capacity C_n. For a fully charged cell, DOD=0, and for an empty cell, DOD=1.

$$DOD = \frac{Q}{C_n} = \frac{\int_{t(SOC=1)}^{t} i\,dt}{C_n}$$

Direction of electric current:

For discharge the sign is positive.

For charge the sign is negative.

Lower voltage limit (U_{MIN}):

The lower voltage limit allowed for the device under test → U_{MIN}.

Electrochemical impedance spectroscopy (EIS)

Measurement of the impedance of the cell/module as function of frequency when excited with alternating current/potential.

End of life (EOL):

State of the energy storage system, which marks a point where its performance is no longer sufficient for the intended purpose for the application. It is reached when,

$$C_{actual} \leq C_n \cdot 0.8,$$

or,

$$Rd_{actual} \geq Rd_n \cdot 2.$$

With C_{actual} being the current capacity in Ah and Rd_{actual} and Rd_n being the current and the nominal series resistance in Ω of the battery. For measurement of these values, see section 3.12.1 and 3.12.2. As reference the values at 25°C must be taken.

Nominal capacity (C_n):

The capacity value in Ah provided from the manufacturer under nominal conditions.

Rated capacity (C_r):

The capacity removed from a fully charged cell evaluated through a standard discharge (see sec. 3.7). Normally, the C_r value will be close to C_n. If C_r is significantly lower than C_n, C_r will be used for the definition of C-rate values, as well as DOD and SOC calculations. C_r will be determined by the partner doing the preconditioning.

Room temperature (RT):

The room temperature is defined as RT=25 ± 2 °C.

Standard charge (SCH):

See Sec. 3.6.

Standard cycle (SC):

See Sec. 3.8.

Standard discharge (SDCH):

See Sec. 3.7.

State of Charge (SOC):

Difference between remaining charge in the battery to its nominal capacity C_n. SOC = 1 - DOD.
The extension of the boundary conditions enabled by the integration of the sensors and the according improved operational strategy does not allow a clear definition of the SOC for this project. Details can be found in D1.1 'Requirement Specification (Use cases, KPIs and cell, module requirements)'. For further specification see also sec. 7.3.1.

State of Health (SOH):

Ratio between initial capacity or resistance to actual capacity or resistance.

$$SOH_C = \frac{C_{actual}}{C_n}$$

$$SOH_R = \frac{R_{actual}}{R_n}$$

The extension of the boundary conditions enabled by the integration of the sensors and the according improved operational strategy does not allow a clear definition of the SOH for this project. Details can be found in D1.1 'Requirement Specification (Use cases, KPIs and cell, module requirements)'. For further specification see also sec. 7.3.2 .

SOC Adjustment:

See Sec. 3.9.

Upper voltage limit (U_{MAX}):

The upper voltage allowed for the device under test → U_{MAX}.

1 Introduction

This document handles the general testing of all types of cells and modules developed during the SENSIBAT project.

First, the terms and definitions for a better understanding of the further test procedures is presented. Then the general section gives an overview of which tests are performed in which order by which partner. Not all tests defined in this section are described later by a procedure, as some specific ones need to be developed in the course of the project. As those tests are not for comparison among cells but rather for finding operational strategies for sensor-based cells only, they do not need to be defined yet. All tests, which serve for comparison of the SENSIBAT development are included in the upcoming sections.

Second, the tests on cell level are defined including performance, ageing and abusive tests. Third, the performance measurements on module level are defined. These are mainly focused on real-world driving-cycles.

Finally, the definitions for 'state of' values are specified, as they differ for modules with and without sensors.

2 General

This section gives an overview of the number of cells to be used, which tests are performed in which order by which partner.

2.1 Number of Cells, Type and Abbreviation

In total 120 cells in 5 different combinations of capacity and sensors are produced for testing. Detailed listing is provided in Table 1.

Table 1. Cells for testing.

Quantity	Type	Abbreviation
20	1Ah baseline	BL-1AH
20	5Ah baseline	BL-5AH
30	1Ah integrated level-1 sensors	L1-1AH
20[1]	5Ah integrated level-1 sensors	L1-5AH
30	1Ah integrated level-2 sensors	L2-1AH

2.2 Test Schedule and Responsible Matrix

The test schedule is optimized in terms of usage of cells/modules and to minimize cell transport, while achieving a maximum outcome and taking into consideration the following partner activities (from DOW):

- AIT will focus on short-term cell/module testing under different ambient conditions as well as comparative post-mortem analyses on baseline cells and cells with sensors to study ageing and degradation in the cells.
- FM will focus on validating the state algorithms under realistic operating conditions and comparing to the baseline, as well as validating the BMS operating strategy in battery modules under realistic operating conditions.
- FHG will perform a functional safety analysis of the BMS and other battery system electronics on the module level, supported by NXP-FR.
- FM, TUE and NXP-NL will support the interpretation of test/measurement results.
- VAR will perform safety tests such as short circuit, overcharging, nail penetration, and thermal stability.
- IKE will focus on long term/degradation testing for cell/module under different conditions, as well as on the validation of the SOS algorithm in collaboration with VAR´s safety tests.
- ABEE will contribute to the performance and ageing testing.

In order to maximise the cell/module usage the tests are categorized in 3 groups according to Table 2.

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[1] Min. 12 pieces. needed for assembly of 2 modules

Table 2. Expected impact of tests on cells and modules.

Expected Impact	Classification	Test
None	No impact on cell/module performance. Cell can be reused for further testing still allowing for repeatable outcome	Characterization, electrochemical impedance spectroscopy, basic (driving) cycle
Marginal	The cells are altered in their performance characteristics (reduced capacity and/or increased impedance) that will not allow for repeatable outcome throughout further testing. The cell is safe for handling and can be used for abusive/safety tests	Cycle- and calendar life tests, extensive driving cycles
Significant	Cell/module is unusable after testing	Abusive/safety tests, post-mortem analysis

Initial inspection (see sec. 3.1) should be done at reception of the cells and preconditioning (see sec. 3.10) when it is required, so they are not included in the test matrices (Table 3 and Table 4). For post-mortem analysis random cells are picked from each test if no loss in performance was detected compared to the baseline cells. If there are samples which show reduced performance, those are to be examined instead of random samples.

2.2.1.1 Cells

This section gives the tests, the number of cells and the sequence for each cell type. Difference in number of cells used in Table 3 and produced according to Table 1 are spare cells to increase number of cells for specific tests if there is inconsistent outcome or to substitute faulty cells.

Table 3. Test matrix for cells.

Cell type	#	Test 1 & Partner	Test 2 & Partner	Test 3 & Partner	Test 4 & Partner
BL-1AH	3	Performance / IKE	Cycle Life / IKE	Post-mortem / AIT	
	3	Performance / ABEE	Calendar Life /ABEE	Post-mortem / AIT	
	3	Performance / AIT	EIS / AIT	Safety / VMI	
	3	Performance/ TUE	Safety / VMI		
	8	Spare Cells	Safety / VMI		
Total	20				
BL-5AH	3	Performance / IKE	Cycle Life / IKE	Post-mortem / AIT	
	3	Performance / ABEE	Calendar Life /ABEE	Post-mortem / AIT	
	3	Performance / AIT	EIS / AIT	Safety / VMI	
	3	Performance/ TUE	Safety / VMI		
	8	Spare Cells	Safety / VMI		
Total	20				
L1-1AH	3	Performance / IKE	Cycle Life / IKE	Post-mortem / AIT	
	3	Performance / ABEE	Calendar Life /ABEE	Post-mortem / AIT	
	3	Performance / AIT	EIS / AIT	Safety / VMI	
	3	Performance/ TUE	EIS/ TUE	Safety/VMI	
	18	Spare Cells	Safety/VMI		
Total	30				
L1-5AH	3	Performance / IKE	Cycle Life / IKE	Post-mortem / AIT	
	3	Performance / ABEE	Calendar Life /ABEE	Post-mortem / AIT	
	2	Performance / AIT	EIS / AIT	Safety / VMI	
	12	Tests for modelling and algorithm development / FM+TUE	Module Assembly		
Total	20[2]				
L2-1AH	3	Performance / IKE	Cycle Life / IKE	Post-mortem / AIT	
	3	Performance / ABEE	Calendar Life /ABEE	Post-mortem / AIT	
	3	Performance / AIT	EIS / AIT	Safety / VMI	
	3	EIS / TUE	Safety / VMI		
	3	Tests for modelling and algorithm development / FM	Tests (driving cycle) to validate state estimation algorithms based on level 2 sensors / FM		
	15	Spare Cells	Safety / VMI		
Total	30				

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[2] Maximum available number of cells for testing as 12 are needed for module assembly.

2.2.1.2 Modules

This section gives the tests, and the sequence for the two modules.

Table 4. Test matrix for modules.

Module type	Test 1 & Partner	Test 2 & Partner	Test 3 & Partner	Test 4 & Partner
Deactivated L1 sensors	Performance/AIT	Driving Cycle / AIT	Driving cycle tests baseline / FM	
Activated L1 sensors	Performance/AIT	Driving Cycle / AIT	Tests for modelling and algorithm development at module level / FM	Driving cycle tests to validate state estimation algorithms and BMS operating strategy / FM

3 Cell Tests

3.1 Inspection of the cell[3]

Description:

Reliable test results and safety during testing can only be guaranteed using completely faultless cells. Thus, a careful inspection of the cell before and after transport is important.

Procedure:

1.) Check for damages on the transport packaging.
2.) Visual inspection: Check if the cell is undamaged after the transport. Ensure that the casing and the cell tabs are unharmed, and no leakage of electrolyte took place.
3.) Transcript the manufacturer ID. If an own ID is assigned the correspondence between the IDs must be clearly indicated in the report.
4.) Check physical values (weight, dimensions and volume) according to Figure 1. Check thickness for each point indicated T_n (n=1…9). Compare to values provided by manufacturer.
5.) Measure OCV of cell and reference electrode(s) if applicable (L2 sensors only) at RT.
6.) Measure impedance of the cell at 1kHz.
7.) Take top and side view picture of the cells.

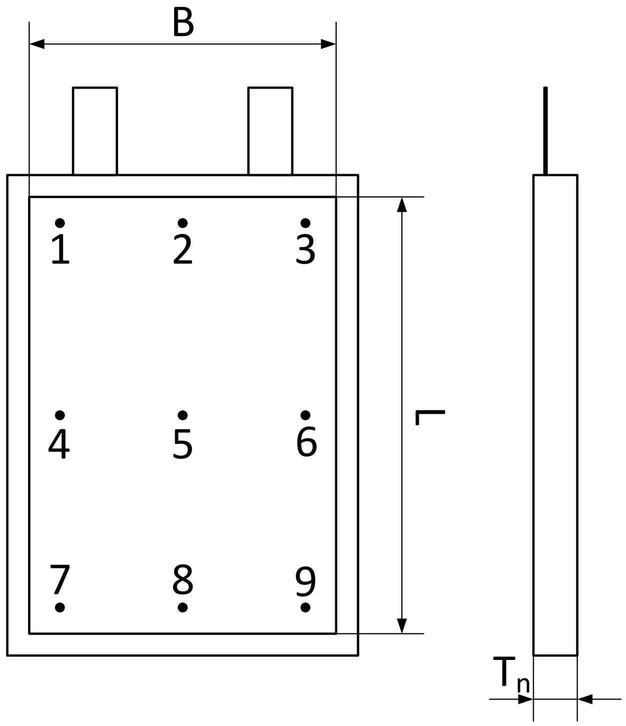

Figure 1. Dimensions of the cell and definition of measurement points for thickness measurement.

The cells with integrated sensors to be developed in the project (L1-1AH, L1-5AH and L2-1AH) will have a dedicated inspection process to be defined once they are designed in the WP3.

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[3] Before sending from manufacturer and upon reception (within 3 days) of cells.

Data Deliverables:

If the cell is damaged, a photograph with a description of the defect should be taken. The physical data must be reported for every cell and differences from manufacturer values should be highlighted. Moreover, OCV according to the above instructions should be reported, and its values should be highlighted if it is not within U_{MIN} and U_{MAX}. Re{Z} and if possible Im{Z} should be reported.

3.2 Thermal Measurements

Temperature sensors have to be placed in the middle of the surface area of the cell with good mechanical contact (according to Figure 2) and should be thermally insulated against the environment with wadding material or other thermally insulating material.

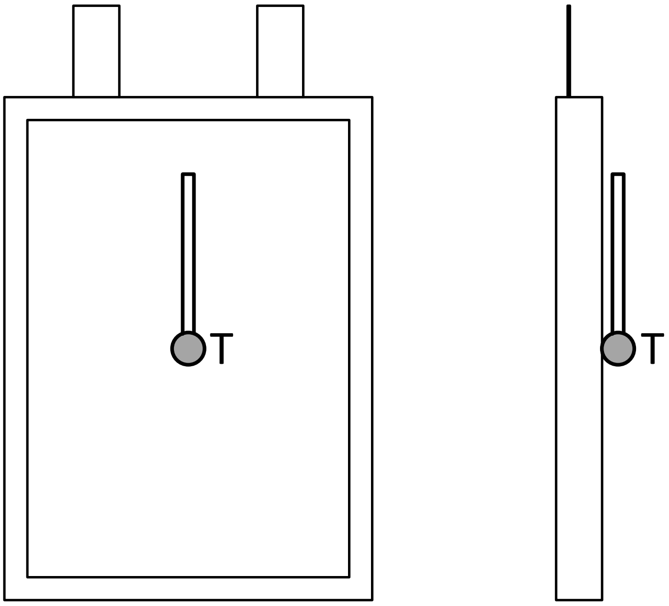

Figure 2. Position of the thermal sensors on the cell.

3.3 Thermal Stabilization

For thermal stabilization, the following steps should be performed: (1) Change to new temperature level, (2) wait until cell temperature has reached ±2°C of surrounding temperature, (3) wait for another 1h to establish thermal equilibrium.

3.4 Cells with Additional Sensors

For the cells which have additional sensors implemented, it is recommended to also log the data from the sensors during all tests if possible. If there is e.g. an internal reference electrode, the potential should be measured with an auxiliary input and recorded according to the other values.

3.5 Pressure on Cell Surface

A constant pressure load on the cells will be required to reach the full performance characteristics of the cells, especially for cycle life. The exact pressure value will be determined with the cell specification as part of deliverable D3.2. It is expected that the required pressure values will differ for the different cell designs and manufacturers in the project, therefore, it is necessary to refer to D3.2 for the correct value. Additionally, a suitable fixture has to be used to provide and control the surface pressure.

For cells with integrated L-1 pressure sensor, mechanical pressure on the cell surface is required in order to work correctly. The details are worked on in other WPs at the time of writing this deliverable. Upon availability the requirements will be added or referred to in this section.

3.6 Standard Charge

The Standard Charge (SCH) consists of a constant-current charge phase (CC), where the current is limited to 0.5 C, followed by a constant-voltage charge phase (CV), where the cell potential is held at U_{MAX} until I<0.05 C.

3.7 Standard Discharge

The SDCH consists of a CC discharge phase where the current is limited to 0.5 C. When the U_{MIN} is reached the discharge is completed as because a long-term low potential may harm the cell.

3.8 Standard Cycle

An Standard Cycle (SC) consists of a SDCH followed by a break of 900 s followed by a SCH followed by a break of minimum 900 s, where the next step is only started after $T_{CELL} \leq T_{AMB} + 2°C$ has been true for another 450 s.

3.9 SOC Adjustment

For impedance measurement several SOC levels are set. For the SOC levels to be comparable throughout the lifetime of the project those levels are assigned to a certain voltage (Table 5).

Table 5. Voltage level with corresponding SOC.

SOC (1)	Voltage (V)[4]
0.9	~4.0
0.5	~3.7
0.1	~3.4

Starting from fully charged state these SOC values should be approached by a discharge with 0.5C, once the SOC level is reached, the corresponding voltage must be held until I≤0.05C. Then there is a rest time of 1h followed by the actual measurement. The next SOC level is targeted by the same procedure as described above.

3.10 Preconditioning

Description:

To establish a comparable starting condition, the cells need to be cycled with a low C-rate after manufacturing prior to further testing.

Procedure:

The discharge and charge cycles are performed with a reduced current of 0.1C for charge and discharge. The formation values and procedure are stated in Table 6.

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[4] Exact value will be given when first cells are tested.

Table 6. Values for cell formation/preconditioning.

Step	Action	Comment
1	Rest 24h	
2	Charge with 0.1C until V=4.2V, Rest 15min	C_n used
3	Discharge with 0.1C until V=3.0V; Rest 15min	
4	Repeat step 2 and 3 for 2 times	
5	Charge with 0.3C for 1h	Charge SOC 0.3; Not needed if sequence is continued with check-up test (Table 8).
6	End	

An example procedure for the preconditioning on MACCOR- testing systems is listed in Table 7:

Table 7: Example Procedure for the preconditioning on MACCOR- testing systems.

Preconditioning

Formation steps + 30% SOC charging

Step	Type	Mode	Val	Limit	Val	End Type	Op	Val	Goto	Rpt Time	Val	Options	Step note
1	Rest					Step time	=	24:00:00	002	Step time	00:10:00	ANNN	
2	Charge	Current	0.1C			Voltage	>=	4.2V	003	Step time	00:10:00	ANNN	Formation charge
						StepTime	=	15:00:00	013	Voltage	0.02		
3	Rest					Step time	=	00:15:00	004	Step time	00:10:00	ANNN	
										Voltage	0.02		
4	Discharge	Current	0.1C			Voltage	<=	3.0V	005	Step time	00:10:00	ANNN	Formation discharge
						StepTime	=	15:00:00	013	Voltage	0.02		
5	Rest					Step time	=	00:15:00	006	Step time	00:10:00	ANNN	
										Voltage	0.02		
6	Do1												2 Cycles
7	Advance cycle												
8	Charge	Current	0.1C			Voltage	>=	4.2V	009	Step time	00:10:00	ANNN	
						StepTime	=	15:00:00	013	Voltage	0.02		
9	Rest					Step time	=	00:15:00	010	Step time	00:10:00	ANNN	
										Voltage	0.02		
10	Discharge	Current	0.1C			Voltage	<=	3.0V	011	Step time	00:10:00	ANNN	
						StepTime	=	15:00:00	013	Voltage	0.02		
11	Rest					Step time	=	00:15:00	012	Step time	00:10:00	ANNN	
										Voltage	0.02		
12	Loop1					Loop Cnt	=	2	013				
13	Charge	Current	0.3C			Voltage	>=	4.2V	014	Step time	00:10:00	ANNN	charge 30% SOC
						StepTime	=	01:00:00	014	Voltage	0.02		
14	End												

It is recommended that the preconditioning is followed by an initial check-up test in order to determine basic operational values. The sequence is given in Table 8.

Table 8. Recommended test sequence for initial check-up test.

Step	Action	Comment
0	Set temperature to RT	
1	Rest 60 min	
2	CC Charge with 0.5C, CV at 4.2V, Rest 15min	CV criteria current below 0.05C or 1h
3	Discharge with 0.5C; Rest 15min	
4	Repeat step 2 and 3	
5	CC Charge with 0.5C, CV at 4.2V, Rest 30min	CV criteria current below 0.05C or 1h; Achievable capacity is determined as C_n (or C_r respectively)
6	Discharge with 0.5C until 0.1* C_n reached;	SOC 0.9
7	Rest 30min	
8	Pulse 0.5C for 30 sec.	Pulse test at SOC 0.9
9	Rest 30min	
10	Discharge with 0.5C until 0.5* C_n reached;	SOC 0.5
11	Rest 30min	
12	Pulse 0.5C for 30 sec.	Pulse test at SOC 0.5
13	Rest 30min	
14	Discharge with 0.5C until 0.9* C_n reached;	SOC 0.1
15	Rest 30min	
16	Pulse 0.5C for 30 sec.	Pulse test at SOC 0.1
17	Rest 30min	
18	Discharge with 0.5C; Rest 15min	
19	CC Charge with 0.3C for 1h	Charge SOC 0.3
20	End	

An example procedure for check-up - Tests on MACCOR- testing systems is displayed in Table 9.

Table 9: Recommended test sequence for initial check-up test. Implementation on MACCOR- testing systems.

Checkup Cycles													
Step	Type	Mode	Val	Limit	Val	End Type	Op	Val	Goto	Rpt Time	Val	Options	Step note
1	Rest					Step time	=	01:00:00	002	Step time	00:10:00	ANNN	
2	Charge	Current	0.5C			Voltage	>=	4.2V	003	Step time	00:10:00	ANNN	0.5C charge
						StepTime	=	07:00:00	029	Voltage	0.02		
3	Charge	Voltage	4.2			Current	<=	0.05C	004	Step time	00:10:00	ANYN	CCC charging
						StepTime	=	01:00:00	004				
4	Rest					Step time	=	00:15:00	005	Step time	00:10:00	ANNN	
										Voltage	0.02		
5	Discharge	Current	0.5C			Voltage	<=	3.0V	006	Step time	00:10:00	ANNN	discharge
						StepTime	=	07:00:00	029	Voltage	0.02		
6	Rest					Step time	=	00:15:00	007	Step time	00:10:00	ANNN	
										Voltage	0.02		
7	Charge	Current	0.5C			Voltage	>=	4.2V	008	Step time	00:10:00	ANNN	0.5C charge
						StepTime	=	07:00:00	029	Voltage	0.02		
8	Charge	Voltage	4.2			Current	<=	0.05C	009	Step time	00:10:00	ANYN	CCC charging
						StepTime	=	01:00:00	009				
9	Rest					Step time	=	00:15:00	010	Step time	00:10:00	ANNN	
										Voltage	0.02		
10	Discharge	Current	0.5C			Voltage	<=	3.0V	011	Step time	00:10:00	ANNN	discharge
						StepTime	=	07:00:00	029	Voltage	0.02		
11	Rest					Step time	=	00:15:00	012	Step time	00:10:00	ANNN	
										Voltage	0.02		
12	Charge	Current	0.5C			Voltage	>=	4.2V	013	Step time	00:10:00	ANNN	0.5C charge
						Current	<=	0.05C	013	Voltage	0.02		
						StepTime	=	03:00:00	013	SetVar	atEnd: V		set Cr
13	Rest					Step time	=	00:30:00	014	Step time	00:01:00	ANNN	Rest 30 min
										Voltage	0.02		
14	Discharge	Current	0.5C			User Def	:	Capacity >0.1*Var	015	Step time	00:02:00	ANNN	discharge to 90%
						Voltage	<=	3.0V	015	Voltage	0.02		
15	Rest					Step time	=	00:30:00	016	Step time	00:01:00	ANYN	Rest 30 min
										Voltage	0.02		
16	Discharge	Current	0.5C			Step time	=	00:00:30	017	Step time	00:00:01	ANYN	30sec discharge
										Voltage	0.01		
17	Rest					Step time	=	00:30:00	018	Step time	00:01:00	ANYN	Rest 30 min
										Voltage	0.02		
18	Discharge	Current	0.5C			User Def	:	Capacity >0.5*Var	019	Step time	00:02:00	ANYN	discharge to 50%
						Voltage	<=	3.0V	019	Voltage	0.02		
19	Rest					Step time	=	00:30:00	020	Step time	00:01:00	ANYN	Rest 30 min
										Voltage	0.02		
20	Discharge	Current	0.5C			Step time	=	00:00:30	021	Step time	00:00:01	ANYN	30sec discharge
										Voltage	0.01		
21	Rest					Step time	=	00:30:00	022	Step time	00:01:00	ANYN	Rest 30 min
										Voltage	0.02		
22	Discharge	Current	0.5C			User Def	:	Capacity >0.9*Var	023	Step time	00:02:00	ANYN	discharge to 10%
						Voltage	<=	3.0V	023	Voltage	0.02		
23	Rest					Step time	=	00:30:00	024	Step time	00:01:00	ANYN	Rest 30 min
										Voltage	0.02		
24	Discharge	Current	0.5C			Step time	=	00:00:30	025	Step time	00:00:01	ANYN	30sec discharge
										Voltage	0.01		
25	Rest					Step time	=	00:30:00	026	Step time	00:01:00	ANYN	Rest 30 min
										Voltage	0.02		
26	Discharge	Current	0.5C			Voltage	<=	3.0V	027	Voltage	0.02		Final discharge
27	Rest					Step time	=	00:15:00	028	Step time	00:10:00	ANNN	
										Voltage	0.02		
28	Charge	Current	0.3C			Voltage	>=	4.2V	029	Step time	00:10:00	ANNN	charge 30% SOC
						StepTime	=	01:00:00	029	Voltage	0.02		
29	End												

Data Deliverables:

Capacity and capacity development for each charging and discharging cycle should be recorded. Cell showing anomalies should be highlighted in the data file.

3.11 Standard Impedance Spectroscopy (Full Cell Level)

Description:

Electrochemical Impedance Spectroscopy (EIS) examines the response characteristic of a cell to an excitation with a signal covering a frequency range of interest. E.g., for batteries this allows investigation of effects taking place in high frequency-regions like conductance, in middle-frequency regions like double-layer and charge-transfer behaviour, and in low-frequency ones regions mass transport can be depicted.

Procedure:

EIS measurements must be done at several SOC levels to capture all effects for the operation range of the battery. The SOC levels should be set according Sec. 3.9. The values for the EIS measurement can be seen in Table 10.

Table 10. Settings for standard EIS measurement.

Mode	**Potentiostatic, Mono Sine**
Voltage (Peak to Peak)	V_{PP} = 10 mV
Frequency range	10 kHz down to 10 mHz
Samples per frequency	$N \geq 3$
Break between each frequency	0.1 periods of previous frequency
Samples	≥6 samples per decade
Temperature	RT (25°C ±2°C)

Data Deliverables:

Impedance values for the different SOC levels in a Nyquist and a Bode plot and data logged in a file.

3.12 Performance - Tests[5]

These tests aim at determination of the main performance parameters throughout the lifetime of the cells. They are to be carried out on all types of cells and will be used for investigating the potential influences of the internal sensors on cell performance.

3.12.1 Capacity and Energy

Description:

This test aims to investigate the charge and discharge capacity and energy at different temperatures for different constant current rates. Capacity and energy are the main performance values of a battery as they determine the overall operating range of the vehicle.

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[5] Partially based on IEC 62660-1

Procedure:

For each current rate a discharge is performed. Between the cycles there is always a standard charge. The capacity is calculated during the second discharge phase. The capacity must be measured at RT for all current rates first.

Table 11. Sequence for capacity and energy determination.

Step	Action	Comment
1	Rest 60 min	
2	CC Charge with 0.5C, CV at U_{max}, Rest 15min	CV criteria current below 0.05C or 1h
3	Discharge with 0.5C; Rest 15min	
4	Loop: repeat step 2 and 3 for 2 times	
5	CC Charge with 0.5C, CV at U_{max}, Rest 15min	CV criteria current below 0.05C or 1h
6	Discharge with 0.33C; Rest 15min	Discharge Rate Cycle 0.33C
7	Repeat Step 2 and 3	
8	CC Charge with 0.5C, CV at U_{max}, Rest 15min	CV criteria current below 0.05C or 1h
9	Discharge with 1C; Rest 15min	Discharge Rate Cycle 1C
10	Repeat Step 2 and 3	
11	CC Charge with 0.5C, CV at U_{max}, Rest 15min	CV criteria current below 0.05C or 1h
12	Discharge with 3C; Rest 15min	Discharge Rate Cycle 3C
13	Repeat Step 2 and 3	
14	CC Charge with 0.33C, Rest 15min	Charge Rate Cycle 0.33C
15	Discharge with 0.5C; Rest 15min	
16	Repeat Step 2 and 3	
17	CC Charge with 1C, Rest 15min	Charge Rate Cycle 1C
18	Discharge with 0.5C; Rest 15min	
19	Repeat Step 2 and 3	
20	CC Charge with 3C, Rest 15min	Charge Rate Cycle 3C
21	Discharge with 0.5C; Rest 15min	
22	CC Charge with 0.5C, CV at U_{max}, Rest 15min	
23	Discharge with 0.5C; Rest 15min	
24	Loop: repeat step 22 and 23 for 2 times	
25	CC Charge with 0.05C to U_{max}, Rest 15min	Quasi OCV measurement
26	Discharge with 0.05C to U_{min}; Rest 15min	Quasi OCV measurement
27	End	

Data Deliverables:

Capacity and energy values for each charging and discharging cycle should be recorded. For quasi OCV measurement the voltage curve needs to be recorded.

3.12.2 Power and resistance

Procedure

The current/voltage characteristics must be determined by measuring the voltage at the end of the 10s current pulse, when a constant current during the 10s pulse is discharged and charged under the conditions specified below:

1. The SOC levels should be set according to Sec. 3.9.
2. The cell is charged or discharged at different C-rates (see Table 12 and Figure 3), and the voltage measured at the end of the 10s pulse is taken for further calculations. The standard measurement rate shall be 1Hz during the adjustment and the relaxation phases. For the pulse and the following initial 60 s of rest time the measurement interval must be reduced to 0.1s. If the voltage after or during the application of a 10-s current pulse exceeds the discharge U_{MIN} or U_{MAX}, the corresponding voltage limit shall be maintained for the duration of the pulse by reducing the current (CV mode).10-min rest time shall be provided between charge and discharge pulses as well as between discharge and charge pulses. However, if the cell temperature is not within 2 °C of the test temperature after 10 min, it shall be cooled further; alternatively, the rest time duration shall be extended, and it shall be inspected whether the cell temperature then settles within 2 °C. The next discharging or charging procedure is then proceeded with.

Table 12. Current pulses for BEV power test.

Charge and discharge current		
1/3 C	1 C	3 C

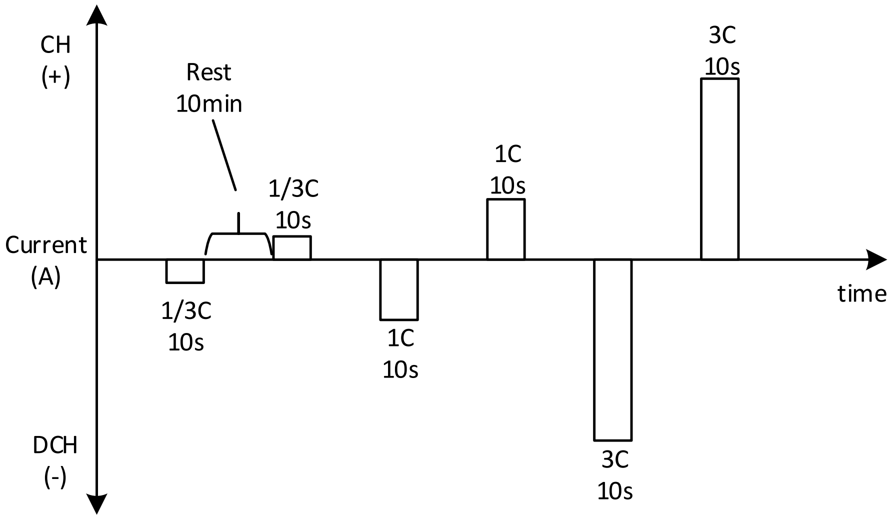

Figure 3. Test order of the current-voltage characteristic test for BEV application.

Data Deliverables

The (dis)charge power and (dis)charge resistance at all SOC and temperature levels shall be calculated according to the equation below and rounded to 3 significant decimal figures (e.g. 0.123).

$$P_{ch/dch} = U \cdot I_{ch/dch}$$

and

$$R_{ch/dch} = \frac{U_{0s} - U_{10s}}{I_{ch/dch}}$$

Where $P_{ch/dch}$ is the (dis)charge power (W); $R_{ch/dch}$ is the (dis)charge resistance, U_{0s} (V) is the voltage of the cell shortly before the beginning of the current pulse and U_{10s} (V) is the measured voltage at the end of the 10s pulse of a I_{ch} charge or a I_{dch} discharge; If $P_{ch/dch}$ is an estimated value, it shall be stated.

The power density shall be calculated according to equations below.

$$\rho_{pvd} = \frac{P_{ch/dch}}{V}$$

$$\rho_{pmd} = \frac{P_{ch/dch}}{M}$$

Where ρ_{pvd} is the volumetric (dis)charge power density (W/l); ρ_{pmd} is the gravimetric (dis)charge power density (W/kg); V is the volume of cell (l) and M is the mass of the cell (kg). The volume is initially defined by the cell manufacturer.

3.13 Energy Density

Purpose

Gravimetric energy density (Wh/kg) and volumetric energy density (Wh/l) of cells at a certain discharge rate of 1/3C, 1C and 3C shall be determined according to the following procedure.

Procedure

The value of the average voltage during discharging in capacity test (see Sec. 3.12) shall be obtained using the following method: Discharge voltages U_1, U_2, ..., U_n are recorded every 5s from the time the discharging starts and voltages that cut off the end of discharge voltage in less than 5s are discarded. The average voltage U_{avr} is then calculated in a simplified manner using the equation below up to three significant figures by rounding off the result.

$$U_{avr} = \frac{U_1 + U_2 + \cdots + U_n}{n}$$

Data Deliverables

The gravimetric energy density shall be calculated using equations below up to three significant figures by rounding off the result.

$$W_{ed} = C_{dch} \cdot U_{avr}$$

$$\rho_{edg} = \frac{W_{ed}}{M}$$

$$\rho_{edv} = \frac{W_{ed}}{V}$$

W_{ed} is the electric energy of cell (Wh); C_{dch} is the discharge capacity (Ah) at a 1/3C, 1C and 3C; U_{avr} is the average voltage during discharging (V); ρ_{edg} is the mass energy density (Wh/kg); M is the mass of cell (kg); ρ_{edv} is the volumetric energy density (Wh/l) and V is volume of cell (l).

3.14 Cycle Life

The cycle-life performance of the cell in an EV application shall be determined by the following test methods. As the performance test counts for a significant number of cycles, those need to be included in the final cycling data → Overall cycles = Cycles from ageing tests + Cycles from performance tests.

<u>Procedure</u>

In Figure 4 the sequence for cycle life testing is depicted.

1. Set temperature to 25°C, thermal equilibrium for 1h (see sec. 3.3).
2. Characterization with a performance test (see sec. 3.12).
3. Set ambient temperature
    a. to 25°C for ageing under standard conditions
    b. or to 45°C for accelerated ageing.
4. Cycle cell with SC (see sec. 3.8).
5. After 50 full cycles
    a. Set temperature to 25°C, thermal equilibrium for 1h (see sec. 3.3).
    b. Characterization with a performance test (see sec. 3.12).
6. End of test criteria reached (500 cycles or $C<0.8C_n$)
    a. Yes → End of test
    b. No → Go to step 3.

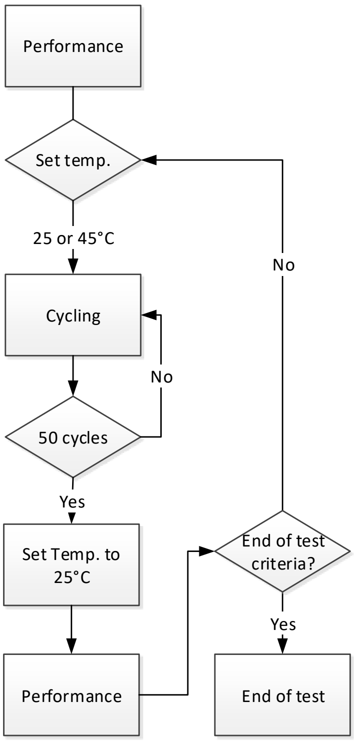

Figure 4. Flow diagram for cycle life test.

<u>Data deliverables</u>

The capacity over all cycles, and the capacity and resistance for the performance tests should be reported.

3.15 Calendar Life

These tests should reveal the influence of the additional materials in the cell-on-cell characteristics without cycling. Further also the impact of the cell chemistry on the sensors while storing the cell at temperatures and SOC levels that may produce harsh environmental conditions for the sensors is investigated.

Procedure

In Figure 5 the sequence for calendar-life testing is depicted.

1. Set temperature to 25°C, thermal equilibrium for 1h (see sec. 3.3).
2. Characterization with a performance test (see sec. 3.12).
3. SCH (set SOC 1)
4. Set ambient temperature to 55°C for accelerated ageing (see sec. 3.3).
5. Store cell at open-circuit condition
6. After 2 weeks
    a. Set temperature to 25°C, thermal equilibrium for 1h (see sec. 3.3).
    b. Characterization with a performance test (see sec. 3.12).
7. End of test criteria reached (12 weeks or $C < 0.8C_n$)
    a. Yes → End of test
    b. No → Go to step 3.

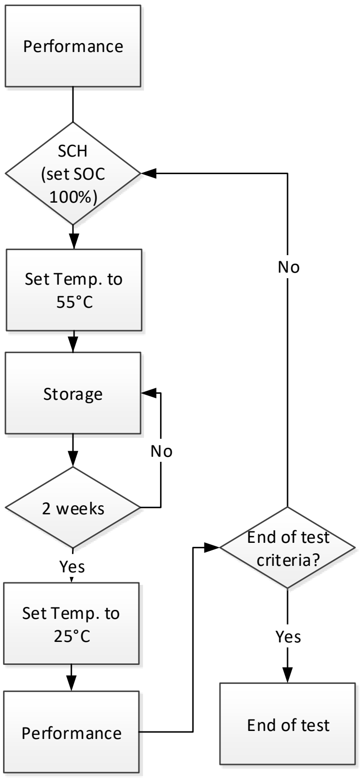

Figure 5. Flow diagram for calendar life test.

Data deliverables

The capacity and resistance for the performance tests should be reported.

4 Safety

4.1 Hazard Classification

For classification of cell reactions in abuse cases the EUCAR Hazard-Level Classification is used. Although the severity of the reaction depends on the specific abuse test, the hazard level must not exceed 3 to ensure basic safety requirements.

Table 13. EUCAR hazard level classification.

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, fire or flame; no rupture; 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 flames requires the presence of an ignition source in combination with fuel and oxidizer in concentrations that will support combustion. A fire or flame will not be observed if any of these elements are absent. For this reason, we recommend that a spark source be used during tests that are likely to result in venting of cell(s). It is believed that "credible abuse environments" would likely include a spark source. Thus, if a spark source were added to the test configuration and the gas or liquid expelled from the cell was flammable; the test sample would quickly progress from hazard level 3 or 4 to hazard level 5.

4.2 Electrical Safety

To determine the reaction of the cells when subjected to out-of-safe-operation-window conditions electrical safety tests should be considered. These conditions can be caused by faulty equipment, handling or operation in case of e.g., a defect in the charging system, BMS or power electronics or short circuit during assembly or maintenance. The tests in the following sections aim to reveal the impact on the cell and its behavior.

4.2.1 External Short Circuit

This test is performed to characterize cell responses to external short circuit, which might occur during a crash, assembly or maintenance or in the unlikely case of a fault of the power electronics.

Procedure

The test shall be performed as follows:

1. Adjust the SOC of cell to 1 in accordance with sec. 3.6.
2. Wait for thermal stabilization at RT (see sec. 3.3).

3. The adjusted cell shall be short-circuited by connecting the positive and terminals with an external resistance for 10 min. After removing the short-circuit, the cell should be monitored for another 60min or until the cell temperature goes back to RT. The total external resistance shall be equal to or less than 5 mΩ. The actual resistance value should be measured before the test and stated in the protocol.

Data Deliverables

The following shall be measured and recorded as test results:

- Cell current, cell voltage and cell temperature must be recorded. Minimum sample frequency is F_S=10kHz for the initial phase for current and voltage and F_S=1Hz for temperature. For the idle period 1Hz for all values is sufficient.
- Graph with recorded values including charge withdrawn.
- Value of external resistance.
- Conditions of the cell at the end of test in accordance with the description specified in Table 13.
- Video during the test.
- Picture of cell before and after test. Damaged spots and parts need to be documented.
- Picture of test setup.

4.2.2 Overcharge

This test is performed to characterize cell responses to overcharge, which might occur because of a faulty charger and/or BMS.

Procedure

The test shall be performed as follows.

1. Adjust the SOC of cell to 1 in accordance with sec. 3.6.
2. Wait for thermal stabilization at RT (see sec. 3.3).
3. Continue charging the cell beyond the SOC 1 value with charging current of 2C at room temperature using a power supply sufficient to provide the constant charging current. The overcharge test shall be discontinued when 24V are reached or a reaction occurred.

Data Deliverables

The following shall be measured and recorded as test results:

- Cell current, cell voltage and cell temperature must be recorded. Minimum sample frequency is F_S=1Hz for all values.
- Additional auxiliary voltages by sensors will be detected with comparable frequency.
- Graph with recorded values including total charge transfer during the test.
- Conditions of the cell at the end of the test in accordance with the description specified in Table 13.
- Video during the test.
- Picture of the cell before and after test. Damaged spots and parts need to be documented.
- Picture of test setup.

4.3 Thermal Safety

To determine the reaction of the cells when subjected to out-of-safe-operation-window conditions caused by faulty equipment or harsh environmental conditions as might be observed during a car accident, transport or defective cooling system, thermal safety experiments must be carried out.

4.3.1 Thermal Stability

This test is performed to characterize cell responses to high-temperature environments that might occur during an accident because of fire.

Procedure

The test shall be performed as follows[6].

1. Adjust the SOC of cell to 1 in accordance with sec. 3.6.
2. The cell, stabilized at room temperature (see sec. 3.3), shall be placed in a gravity or circulating-air convection oven. The oven temperature shall be raised at a rate of 5 °C/min to a temperature of T_{ONSET}=80°C ± 2°C. The cell shall remain at this temperature for 60 min before the test is continued.
3. Raise the temperature by 5°C/min to a temperature of T_{ONSET}=120°C ± 2°C. The cell shall remain at this temperature for 60 min before the test is continued.
4. Raise the temperature by 5°C/min to a temperature of T_{ONSET}=150°C ± 2°C. The cell shall remain at this temperature for 60 min before the test is continued.
5. Raise the temperature by 5°C/min to a temperature of T_{ONSET}=200°C ± 2°C. The cell shall remain at this temperature for 60 min before the test is continued.

In case of a repetition of the test T_{ONSET} can be adjusted 20°C below the temperature where the first self-heating was detected.

Data Deliverables

The following shall be measured and recorded as test results:

- Cell voltage and cell temperature must be recorded. Minimum sample frequency is F_S=1Hz for all values.
- Additional auxiliary voltages by sensors will be detected with comparable frequency.
- Graph with recorded values.
- Conditions of the cell at the end of the test
- Video during the test in accordance with the description specified in Table 13.
- Picture of cell before and after test. Damaged spots and parts need to be documented.
- Picture of test setup.

4.3.2 Temperature Cycling

This test is performed to characterize thermal durability of the cell by exposing it to a low- and a high-temperature environment alternately to cause expansion and contraction of cell components, which might result from transport or operation in a harsh environment.

Procedure

The test shall be performed as follows.

1. Adjust the SOC of cell to 1 in accordance with sec. 3.6.
2. Perform the temperature cycling in accordance with ISO 16750-4 as shown in Table 14. The minimum operating temperature shall be –40°C or T_{min} specified by the manufacturer and the maximum operating temperature shall be 85°C or T_{max} specified by the manufacturer[7]. Perform 30 test cycles as specified.

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[6] If necessary, to prevent deformation, the cell may be fixed during the test in a manner that does not violate the test purpose.

[7] If temperature chamber cannot handle the required time for change between the two extreme temperatures, 2 climate chambers can be used and the device under test can be switched between those two.

Table 14. Temperatures and time duration for temperature cycling.

Cumulative time (min)	Temperature (°C)
0	25
60	T_{min}
150	T_{min}
210	25
300	T_{max}
410	T_{max}
480	25

Data Deliverables

The following shall be measured and recorded as test results:

- Cell voltage and capacity determined with 2 consecutive SC (Section 3.8) at the beginning and at the end of the test.
- Conditions of the cell at the end of test in accordance with the description specified in Table 13.
- Picture of cell before and after test. Damaged spots and parts need to be documented.
- Picture of test setup.
- If possible, cell voltage and temperature shall be recorded during the test. Minimum sample frequency is F_S=1Hz for both values.
- Graph with recorded values.

4.4 Mechanical Safety

Mechanical safety tests are applied to determine the response of the cells to mechanical deformation which can be caused by accidents or wrong handling during assembly or transport.

4.4.1 Nail Penetration

This test is performed to characterize the cells' response to external load forces that may cause deformation.

Procedure

The test shall be performed as follows.

1. Adjust the SOC of cell to 1 in accordance with sec. 3.6.
2. The cell shall be placed on an electrically insulated flat surface with a hole for the nail reaching out of the cell (or a setup allowing comparable mechanical conditions). The nail shall be made of steel, have a diameter of 3mm, a conical tip at an angle of 60° and shall be electrically insulated. Insertion speed for the nail will be 80mm/s. The pouch cell shall be penetrated perpendicular to its surface.
3. After penetration the cell shall be observed for 1h.

Data Deliverables

The following shall be measured and recorded as test results:

- Cell voltage and cell temperature must be recorded. Minimum sample frequency is F_S=1Hz for all values.
- Additional auxiliary voltages by sensors will be detected with comparable frequency.
- Speed, displacement and force of the nail.
- Graph with recorded values.
- Conditions of the cell at the end of the test in accordance with the description specified in Table 13.
- Picture of cell before and after test. Damaged spots and parts need to be documented.
- Picture of test setup.

5 Post-Mortem Analysis

Since material parameters and their change over the lifetime can only be determined to a limited extent by means of non-destructive tests, it can be necessary to open the cells in order to enable analysis to determine the material properties.

Opening of a cell for analysis is often referred as ante or post-mortem analysis. It requires opening a cell and separating the components and thus is a destructive analysis. Detailed ex-situ information about anode, cathode, separator and electrolyte can be generated.

Procedure:

The destructive analysis is about getting more detailed information about the processes within the cell, or to learn about their (current) composition. For this purpose, the components anode, cathode, separator and ideally electrolyte are usually extracted. In order to create a comprehensive material balance or to obtain data for a simulation (if required), it can also be very helpful to correctly separate the passive components such as housings and current conductors and to measure them precisely.

Once all components have been separated, methods such as mass determination, mechanical dimensions, materials, adhesion, grain sizes, surface finish, etc. can be determined. The samples should be packaged airtight, if further analysis regarding composition and crystal structure should be conducted. Ideally, the sample is transferred directly to the sample holder of the respective analysis tool.

For the SENSIBAT project, the influence of the sensor integration on the cell degradation needs to be determined. It is therefore mainly focused on analysis of increased Li deposition in the area of the sensor, dry patches (in case of local electrolyte evaporation) and any undesired change of the sensor itself. The latter could for instance be noted by a discoloration of the encapsulating material or partial dissolution due to electrolyte/Li side reactions taking place. In any case, the analysis of the sensor area is therefore sensitive of air and humidity. The analysis is to be carried out in an inert environment, such as a glove box. In general, all disassembly should take place under such conditions, due to safety concerns when opening a cell. When cells are not fully discharged (only for SoC-dependent analysis), opening a cell for post-mortem analysis is safety critical.

When further analysis for the components is planned, it is important to keep the samples uncontaminated. Fresh bags or cleaned surface should be used to store the layers.

For further material analysis or half-cell test, it might be required to remove excess salt from drying electrolyte of the electrode surface. The salt can be removed better when it is not fully dry yet. Rinsing is favorable soon after separation of the layers. To do so a suitable solvent should be put in glass containers and the electrode should be rinsed inside. Add some time for drying afterwards, before the samples are put in a bag.

Data Deliverables:

The following shall be measured and recorded as test results:

- Cell voltage and SOC before disassembly.
- Weight and dimensions of the cell before disassembly (all parts), including thickness in case of cell swelling.
- Total mass of each component (cathode, anode, separator, sensor (if applicable), packaging (including tabs).
- Visual inspection (pictures) of each electrode.

- Visual inspection (pictures) of the sensor area and adjacent cathode, anode and separator layer.
- Compositional analysis (XRD/XRF) of the cathode and anode adjacent to the sensing structure compared to non-adjacent ones of the same cell.

6 Long-Term Stability of Sensors

The sensors will be checked in a regular interval throughout the testing or at least at the end of testing and their performance will be compared to the initial values. The procedure is to be developed in WP3 and 4.

7 Module Tests

7.1 Performance tests

Use the same procedure as for cell characterization (see sec. 3.12).

7.2 WLTP cycling

For the modules real-world driving cycles are used to determine performance / lifetime gains by the implementation of the integrated sensors and the use of their outcome in innovative algorithms for the BMS. The WLTP cycle[8] (world-harmonized light-duty-vehicles test procedure) was chosen as it is a widely used standard for determination of energy consumption and emissions of vehicles of all classes.

To get the power demands for the battery a model was implemented using the data from the reference vehicle (Porsche Taycan):

- Drag coefficient: 0.22
- Frontal area: 2.33m²
- Operating weight: 2300kg

As the power-to-weight ratio clearly is >34, a WLTP3 cycle (high-power-class vehicles) was selected. This WLTP3 profile is divided into 4 different sub-parts, each one with a different maximum speed:

- Low: up to 56.5 km/h
- Medium: up to 76.6 km/h
- High: up to 97.4 km/h
- Extra high: up to 131.3 km/h

simulating urban, suburban, rural and highway scenarios respectively. There is nearly an equal division between urban and non-urban paths (52% and 48%)[8]. The speed profile is shown in Figure 6.

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[8] https://en.wikipedia.org/wiki/Worldwide_Harmonised_Light_Vehicles_Test_Procedure

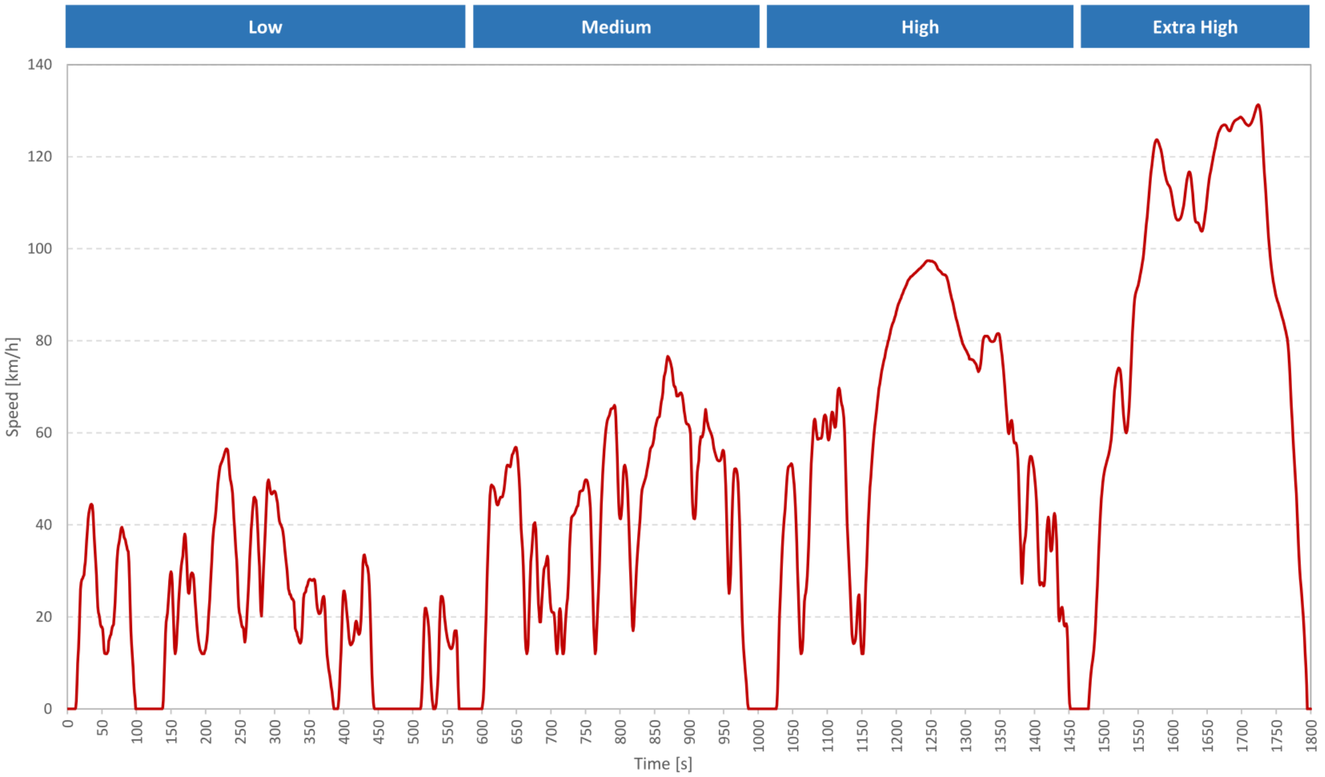

Figure 6. Speed profile of WLP 3 cycle[8].

This profile was used as input for a simulation on a vehicle model with the parameters described above. The resulting power profile can be found on the SENSIBAT share-point in a machine-readable ASCII comma separated value (CSV) file.

https://uniresearch.mett.nl/h2020+projects/sensibat/sensibat+documents/sensibat+work+packages/HandlerDownloadFiles.ashx?idnv=1890028

In Figure 7 the power profile for the full WLTP3 cycle gained by simulation of the vehicle model is shown.

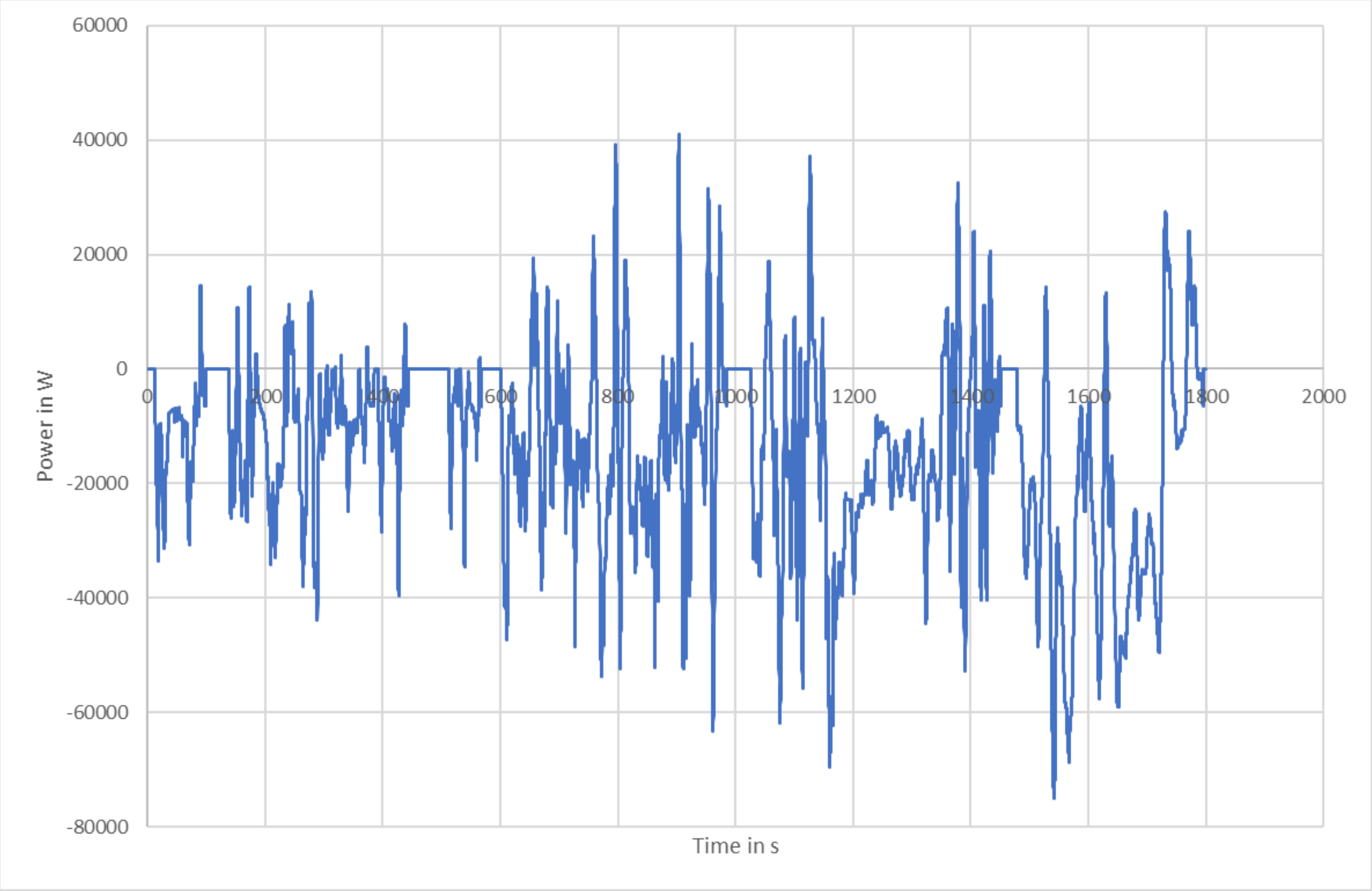

Figure 7. Power profile of WLTP 3 for full Porsche Taycan battery pack.

The downscaling factor of the full battery pack and to module level is calculated as follows:

- Porsche Taycan useable energy: 83700Wh
- Sensibat estimated energy per cell: 18.5Wh

→ Scaling factor down to cell: 4524
→ Scaling factor to a 6s1p module: 754

This is under the assumption that the energy is the limiting scaling factor and that the SENSIBAT cells/module allow for full use of the nominal energy due to the advanced monitoring.

As the Taycan uses approx. 90% of the capacity (performance battery plus: 83.7kWh (net), 93.4kWh (gross)) the modules with deactivated sensors and common operational strategy should be operated within an SOC window of 5% to 95%. The modules with sensor-based strategy can be operated within the full range.

7.3 State-Estimation Algorithm Testing

As discussed in deliverable D1.1 ‘Requirement Specification (Use cases, KPIs and cell, module requirements)’, section 4.6, the intention of the algorithm testing on the two modules mentioned in Table 4 is to see how novel algorithms using the level-1 sensors added to the module can lead to improved state estimation. In general, state-of-the-art or baseline algorithms will be run on the module while disregarding the level-1 sensor information for the operation of the module, but the data is logged for comparison, whereas innovative algorithms developed during the SENSIBAT project will run on the module with activated level-1 sensors. For each of the state estimations (SOC, SOH, SOE, SOP and SOS), a reference value needs to be defined to which both the state-of-the-art baseline algorithms as the innovative algorithms can be compared. Below sections describe at high level how these reference values should be obtained.

7.3.1 SOC (State of Charge)

Based on the capacity determination procedure in section 3.12.1, the battery capacity shall be determined, and this capacity shall be the 100% reference of all SOC 1 indication methods.

The reference SOC is then determined by starting any experiment from a known SOC value (e.g. a fully charged cell as defined in section 3.6), and then using a laboratory-grade current sensor, which has the highest possible accuracy. Current integration using the output of this sensor, and the maximum capacity obtained from the capacity test determines the SOC value (according to the equations stated in section 0)

For the baseline SOC method, a well-known Kalman-filter-based estimator using a production-grade current sensor will be used (with a similar accuracy as the current sensor to be used in the demonstrator module).

7.3.2 SOH (State of Health)

The starting point for SOH determination will be the capacity as determined in section 3.12.1. This capacity will be the denumerator of the SOH estimation, i.e. C_r in section 0. The reference SOH is then determined by regularly determining C_{actual} (see section 0) and using this C_{actual} in the ratio to the initial capacity.

For the baseline SOH method, as a starting definition it is assumed that a simple existing method is used to track the actual capacity, i.e. C_{actual} in section 0, e.g. based on relating SOH differences from a baseline SOH estimator to actual charge differences determined with the production-grade current sensor that is also used for the baseline SOC estimator.

7.3.3 SOE (State of Energy)

The baseline SOE algorithm will calculate the energy content of the module based on baseline SOC and SOH methods. The innovative SOE algorithm will be based on the innovative SOC and SOH algorithms. In both cases, the obtained SOE value, together with the power profile in Figure 7, can be used to determine the remaining time the module can be used. The reference in this case will be to continue discharging the module with this the reference WLTP profile and to determine the actual remaining time or corresponding mileage.

7.3.4 SOP (State of Power)

The baseline and innovative SOP estimation will give an impression what power level can be obtained from the cell. The reference here is to use a similar test procedure as the one in section 3.12.2 and determine the actual available power from the cell.

7.3.5 SOS (State of Safety)

As SOS concepts presented in the literature are still in an early maturity stage, this definition shall also be refined throughout the project.

8 Discussion and Conclusions

This document contains the testing plan for cells and modules to be developed in the SENSIBAT project.

This plan serves as basis for an in-depth evaluation of the influence of the integrated sensors on the operational parameters of the cell, comparing results obtained from tests to be performed on baseline cells (no integrated sensors) and prototype cells (with integrated sensors). On module level, the effect of a smart operating strategy that is enabled by the data obtained from the sensors in the cells and actuated by the BMS will be analysed.

In WP5 – 'Testing, validation and assessment (performance, cost, disassembly and recycling)', the baseline and prototype cells, together with the module(s) from WP4 will be tested according to the presented testing plan.

9 Risks

The risks identified in this deliverable are already listed in the Risk Management Register and reported in the deliverable D7.2.

Table 15. Identified Risks in D1.2.

Risk No.	***WP***	***Description***	***Type of Risk***	***Probability***	***Effect***	***Priority***	***Prevention plan***	***Contingency plan***	***Responsible***	***Period***
8	WP1	Relevant data are not being supplied in time by the partners.	Part	3	1	Medium	The Consortium will specify relevant backup data to work with		IKE/ ABEE	M1-36
13	WP1	Delays in providing the components in time for following WPs activities	Part	2	2	Medium	Track development progress and focus efforts especially in the most sensible components.		IKE/ ABEE	M4-30

Tech = Technological, Part = Partnership, Mana = Management, Ext = External

Probability risk will occur: 1 = High, 2 = Medium, 3 = Low 3

Effect of risk: 1 = High, 2 = Medium, 3 = Low

Priority of risk: Critical, High, Medium, Low

10 Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners

#	PARTICIPANT SHORT NAME	PARTNER ORGANISATION NAME	COUNTRY
1	IKE	IKERLAN S. COOP.	Spain
2	BDM	BEDIMENSIONAL SPA	Italy
3	POL	POLITECNICO DI TORINO	Italy
4	FHG	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	Germany
5	FM	FLANDERS MAKE VZW	Belgium
6	TUE	TECHNISCHE UNIVERSITEIT EINDHOVEN	The Netherlands
7	NXP NL	NXP SEMICONDUCTORS NETHERLANDS BV	The Netherlands
8	NXP FR	NXP SEMICONDUCTORS FRANCE SAS	France
9	ABEE	AVESTA BATTERY & ENERGY ENGINEERING	Belgium
10	VAR	VARTA MICRO INNOVATION GMBH	Germany
11	AIT	AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH	Austria
12	UNR	UNIRESEARCH BV	The Netherlands

DISCLAIMER/ ACKNOWLEDGMENT

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 957273. The information and views set out in this publication does not necessarily reflect the official opinion of the European Commission. Neither the European Union institutions and bodies nor any person acting on their behalf, may be held responsible for the use which may be made of the information contained therein.