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NEXT-generation physics and data-based Battery Management Systems for optimised battery utilisation

NEXTBMS

NEXTBMS - Deliverable report

D2.1 – Characterisation test results of physics-based cell models

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Project summary

NEXTBMS will develop an advanced battery management systems (BMS) built on fundamental knowledge and experience with the physicochemical processes of lithium-ion batteries, which will enable the significant enhancement of current modelling approaches, including the readiness for upcoming lithium (Li) battery material developments. These modelling approaches will be further improved by optimising sensors and measurement techniques to meet modelling needs (and optimising models based on physical sensor data) and the physical cell configurations to form a framework that supports improving the battery state prediction and -control. By solving these challenges, NEXTBMS will ensure that the next generation of BMSs will enable higher performance, safety, and longer lifetime of the battery cells for an overall optimal utilisation of the battery system.

Publishable summary

The goal of the NEXTBMS project is to enhance the performance of battery electric applications. A major contributor to their performance and a key factor in maintaining performance and safety over the lifetime of the battery, is the Battery Management System (BMS). The NEXTBMS project aims to surpass contemporary BMS limitations by introducing physics-based and data-driven models and algorithms to the BMS itself. To train, validate and analyse the performance of these models and algorithms a complete set of data is required consisting of beginning of life characterisation data and extensive ageing testing. This deliverable describes the acquired data, explains why this exact data is required and outlines detailed planning of the to-be-acquired ageing data.

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Abbreviations & Definitions

Abbreviation	Explanation
BMS	Battery Management System
BOL	Beginning of life
CAD	Computer Aided Design
CCCV	Constant Current - Constant Voltage
C-rate	Parameter indicating a battery's charge and discharge rate
DoA	Description of the Action
DoD	Depth of Discharge
EC	European Commission
EIS	Electrochemical Impedance Spectroscopy
EOL	End of life
EU	European Union
Fe	Iron
GITT	Galvanostatic Intermittent Titration Technique
HPPC	Hybrid Power Pulse Characterisation
Li	Lithium
MOL	Middle of life
OCV	Open Circuit Voltage
SEI	Solid Electrolyte Interphase
SoC	State of Charge
WP	Work package
WLTP	Worldwide harmonized Light vehicles Test Procedure

1 Introduction

Cell characterisation testing is required for parameterization of the data-driven and advanced physics-based battery models developed in NEXTBMS. The test campaign for the characterisation of lithium-ion cells can be broadly divided into electrical, thermal, and aging characterisation tests, which are described in detail in the following chapters explaining the detailed plans and the need for collection of specific data.
For the cell characterisation also real load use scenarios from automotive applications as well as stationary use cases are considered in test scenarios (dynamic drive cycles and dynamic load cycles).

2 Electrical characterisation tests

Electrical behaviour of batteries can be split into static and dynamic behaviour. The former is concerned with modelling the terminal voltage of the battery when it is in rest in relation to its operating conditions such as State-of-Charge (SoC) or temperature. On the other hand, the dynamic behaviour describes the "add-on" behaviour as a result of excitation, i.e., charging or discharging. Like the static behaviour, the dynamic behaviour is subject to change as a result of differences in SoC, temperature and current direction. The tests described below are designed such that both components can clearly be distinguished and modelled independently.

To obtain some insight into the consistency of the acquired battery cells, all tests have been performed on three cells. In the presented measurement data, results from the different cells are plotted in the same figure for ease of comparison. In the remainder of this chapter, all performed tests will be considered one-by-one. An overview of all tests is provided in Table 1.

Table 1: Overview of the performed electrical characterisation tests.

#	Step
1	Initialisation
2	(Static) Galvanostatic Intermittent Titration Technique (GITT)
3	(Static) Constant current
4	(Dynamic) Drive cycles
5	(Dynamic) Hybrid Power Pulse Characterisation (HPPC)
6	(Dynamic) Electrochemical Impedance Spectroscopy (EIS)

2.1 Battery cells and test setup

The cells acquired for the NEXTBMS project have been ordered from China through a 3rd party vendor. The selected cells are generation 3b prismatic with Nickel-Manganese-Cobalt (NMC) 811 cathode and graphite anode, with 58 Ah rated capacity. Table 2 shows the key parameters of the acquired cells.

Table 2: Key parameters of the acquired cells for NEXTBMS.

Type	**Prismatic - NMC**
Operating temperature	-30 °C to 55 °C (discharging), -20 °C to 55 °C (charging)
Rated voltage	3.67 V
Work voltage	2.75-4.35 V (T ≥ 0 °C) 2.2-4.35 V (-30 °C ≤ T < 0°C)
Rated capacity	58 Ah
Max. C-rates charging / discharging	1.2C (0 °C ≤ T < 45 °C) / 1C (20 °C ≤T < 40°C)
Internal resistance	0.60 - 0.80 mΩ
Charging time	Approx. 4h
SOC Window	5 % - 97 %
Cycle life	≥ 2000 cycles
Dimensions	Thickness: 27 mm Width: 106 mm Length: 148 mm
Weight	926 g

In total 100 cells have been acquired, one of which is shown in Figure 1. Initial screening has been performed by TNO by labelling each cell and measuring and recording their cell weight, dimensions and terminal voltage. In this way, they can be tracked throughout the project. Also, the cells have been inspected for any signs of damage in the form of dents, deformation or other defects. In total, 18 cells showed defects in the form of dents on the front or sides faces. These cells have been selected to be used for microscopy tests or half-cell construction, such that they are avoided for the module construction or ageing tests in which small dents could potentially result in atypical behaviour in later life.

Figure 1: Example of the acquired 58Ah prismatic cell used in the NEXTBMS project.

All cell tests are executed using external applied pressure of 100kgF as specified in the datasheet. The force is applied using pressure plates forced down by springs compressed to a specific height. The resulting setup is shown in Figure 2 and Figure 3. Temperature of each cell is measured using a thermocouple positioned in the middle of the bottom main face.

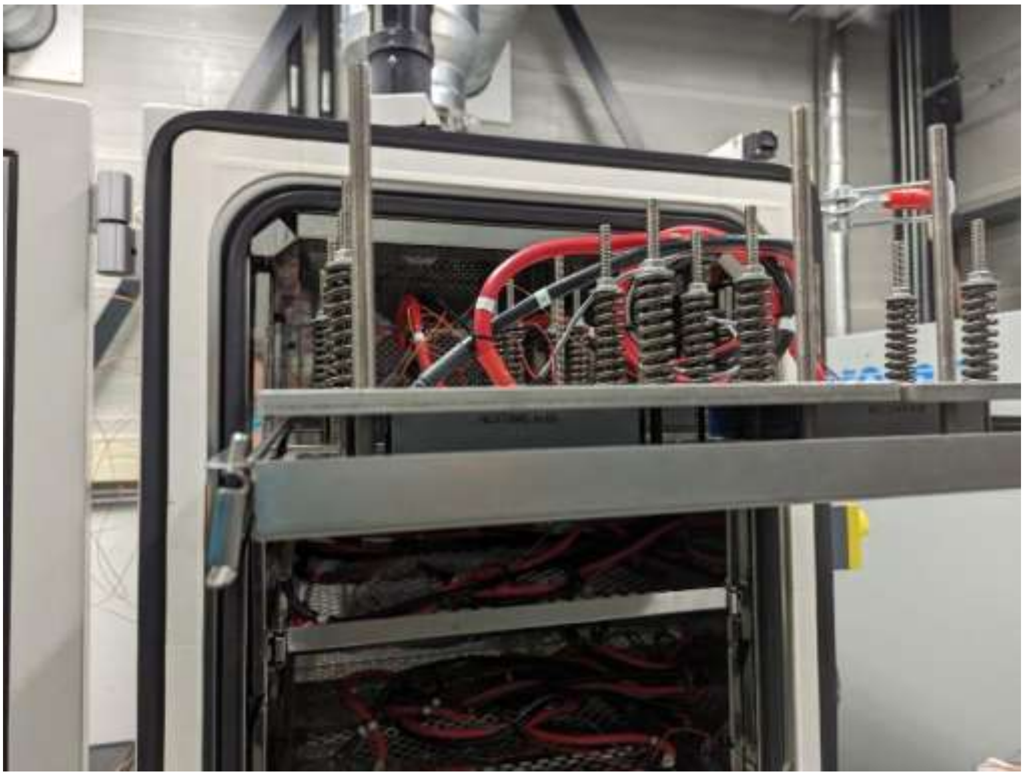

Figure 2: Side view of the tested cells and cell clamps. The cell labels are visible to the careful reader.

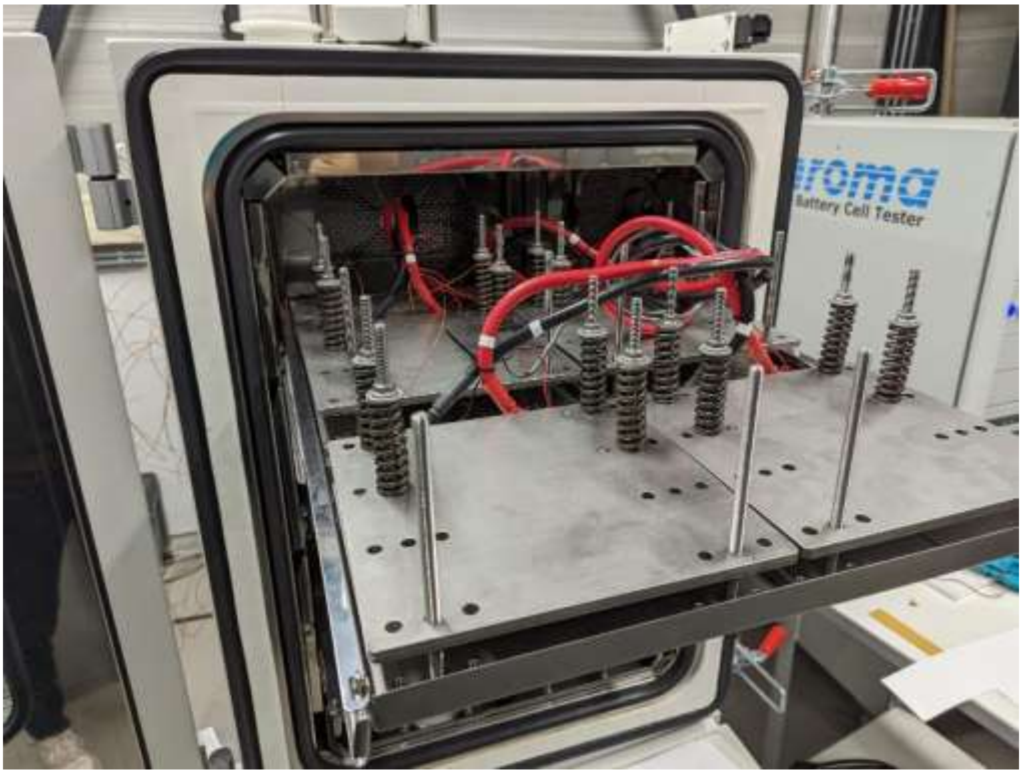

Figure 3: Top view of the tested cells and cell clamps. Four springs are used to compress each cell.

2.2 Initialisation

Before starting the characterisation tests, all cells have first been subjected to five initialisation cycles, as shown in Figure 4. This entails a C-rate of 1/4C Constant-Current Constant-Voltage (CCCV) charge and Constant-Current (CC) discharge. These initial cycles have been applied to ensure that any initial ageing or other changes in parameters, which are often observed in the first few cycles, are not present in the characterisation measurements.

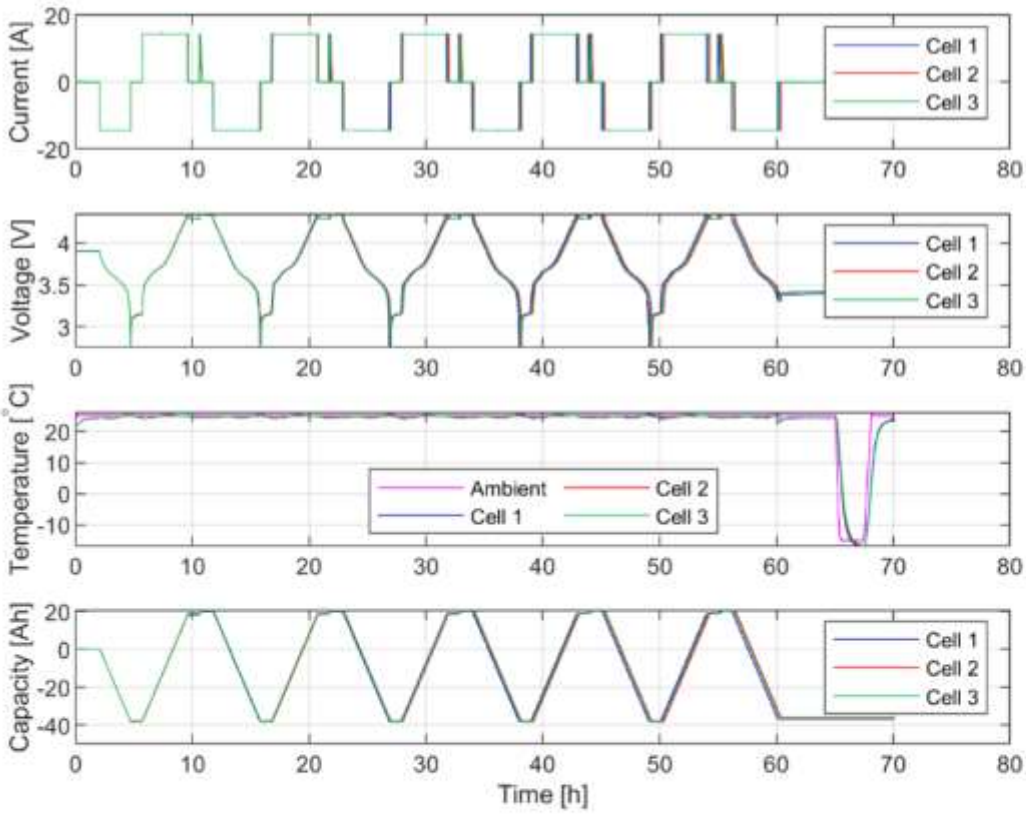

Figure 4: Measurement data of the initialisation cycles.

2.3 (Static) Galvanostatic Intermittent Titration Technique

The first characterisation test is a GITT experiment which is used to model the Open-Circuit Voltage (OCV) as a function of SoC and temperature. The basic concept of the experiment is to discharge or charge the cell in fixed increments after which a period of zero current is applied to let the cell voltage settle. In this case, the experiment is designed as follows:

- OCV for discharge followed by charge direction
- 25 rest points in each direction
- All current/cycling is applied at 25°C
- Every 6th rest point a temperature sweep from 25°C -> 0°C -> -15°C -> 45°C -> 25°C is performed to measure entropic relation of the OCV (temperature dependency).

- Steps are applied with a current of 0.2C, i.e., 11.6A.
- Cell voltage is considered to be fully settled when dV/dt < 1mV/h, after which the cycler automatically (dis)charges to the next rest point.

The resulting data, shown in Figure 5, shows a high consistency between the cells with some deviation at low SoC. The discharged capacities are 59.82Ah, 60.25Ah and 60.25Ah for cells 1, 2 and 3, respectively.

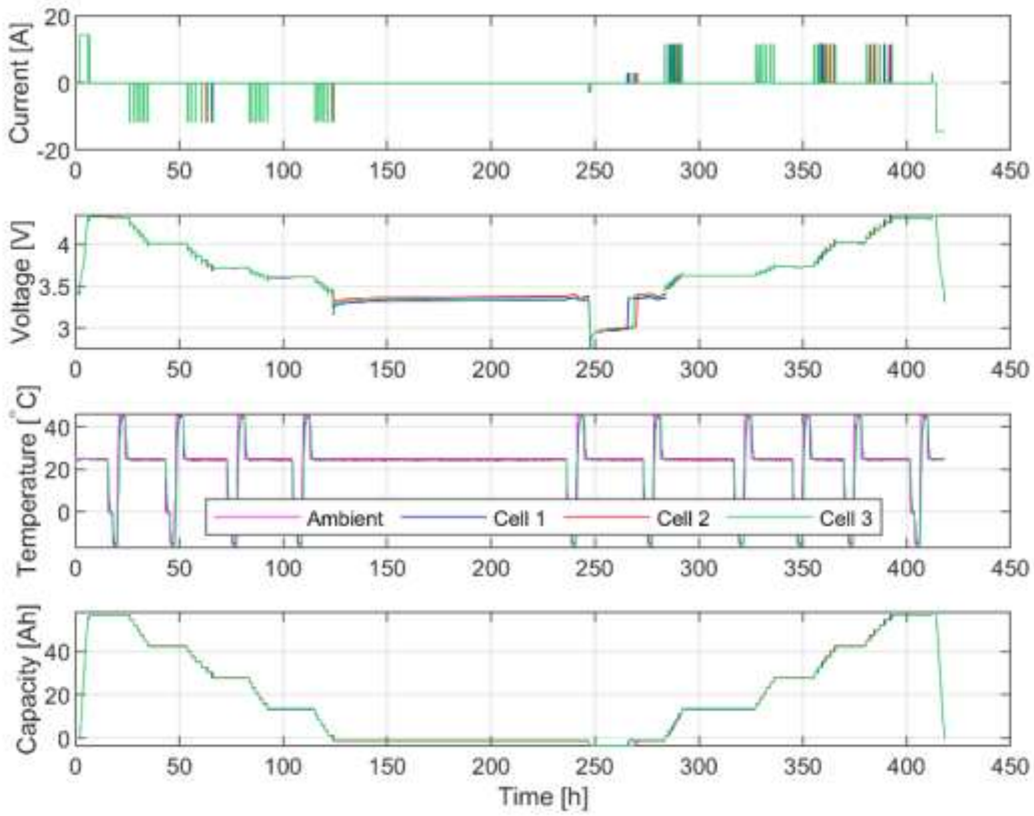

Figure 5: Measurement data of the GITT experiment.

2.4 (Static) Constant current

The second test consists of CC charging and discharging at various temperatures and C-rates, as shown in Figure 6. First, the cells are charged and discharged with 1/20C at 25°C, 45°C, 5°C and -5°C. This data is used to model temperature dependency of the capacity of the cell. Secondly, the cells are kept at 25°C, but different C-rates are applied, namely 0.1C, 0.2C, 0.5C and 1.0C. This data can be used to validate the rate-dependency of the physics-based models. For the higher C-rates, i.e., 0.5C and higher from time marker 400h and after, some self-heating is also observed in the temperature data.

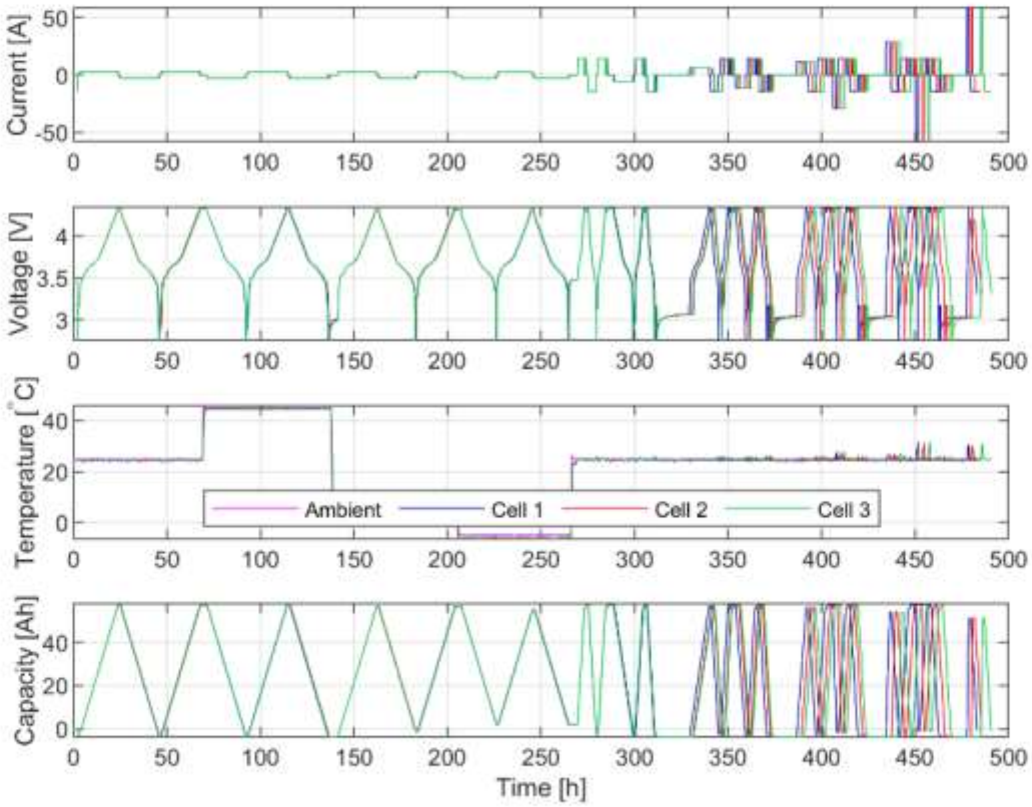

Figure 6: Measurement data of the constant current cycling at various temperatures and C-rates.

2.5 (Dynamic) Drive cycles

The third part consists of dynamic excitation in the form of drive cycles, as shown in Figure 7. The first and most important part of the test is constructed such that two different drive cycles are applied at different temperature levels. One cycle is intended for identification (training) of models and the other for validation. Training data is acquired at -5°C, 5°C, 25°C and 45°C, while validation data is acquired at 0°C, 15°C, 25°C and 35°C. In this way, the model can be validated for temperatures in between the training temperatures and also at 25°C, which can be used to access the validity of the modelled SoC or current direction dependency. The drive cycles have been provided by the project partner TOFAS, where the training cycle is a custom cycle (Figure 8) and the validation cycle (Figure 9) is based on a WLTP standard drive cycle.

The last part of the test, time marker 300 h onward, consists of 1) partial drive cycle discharge, followed by “fast” charge to 80% SoC and then another drive cycle discharge, and 2) partial charge and discharge with converging SoC window. Both tests are designed such that possible hysteresis effects and shifts between charging and discharging can be analysed.

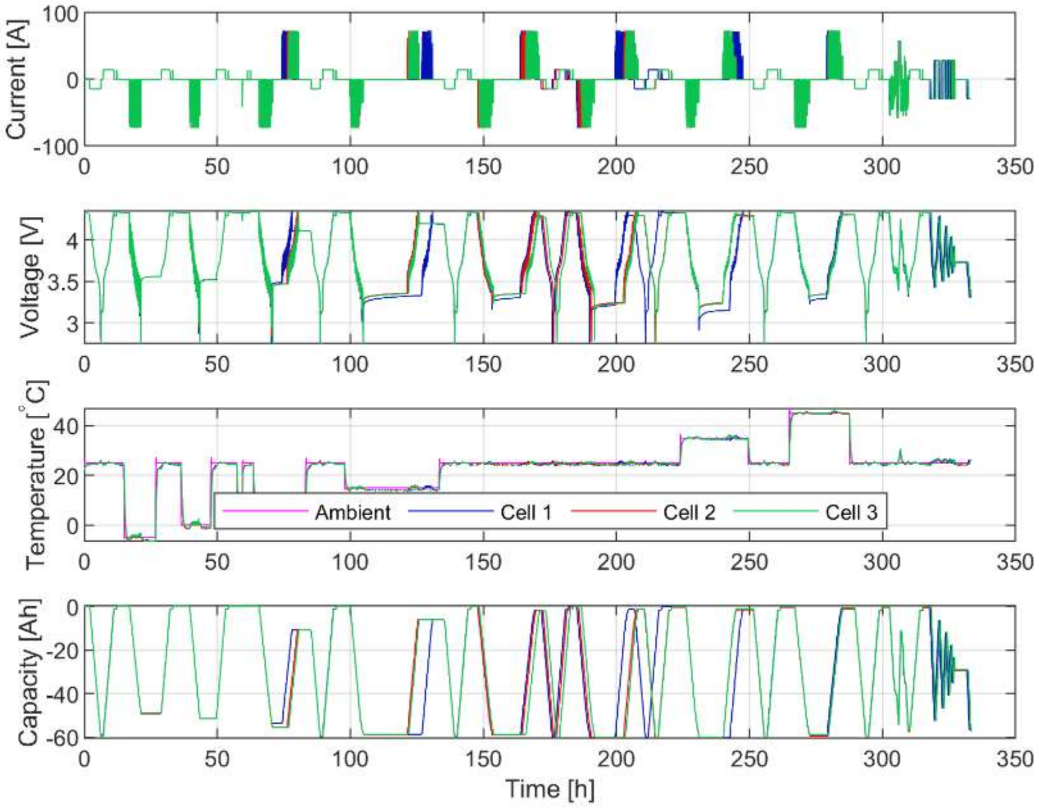

Figure 7: Measurement data of the dynamic excitation cycles.

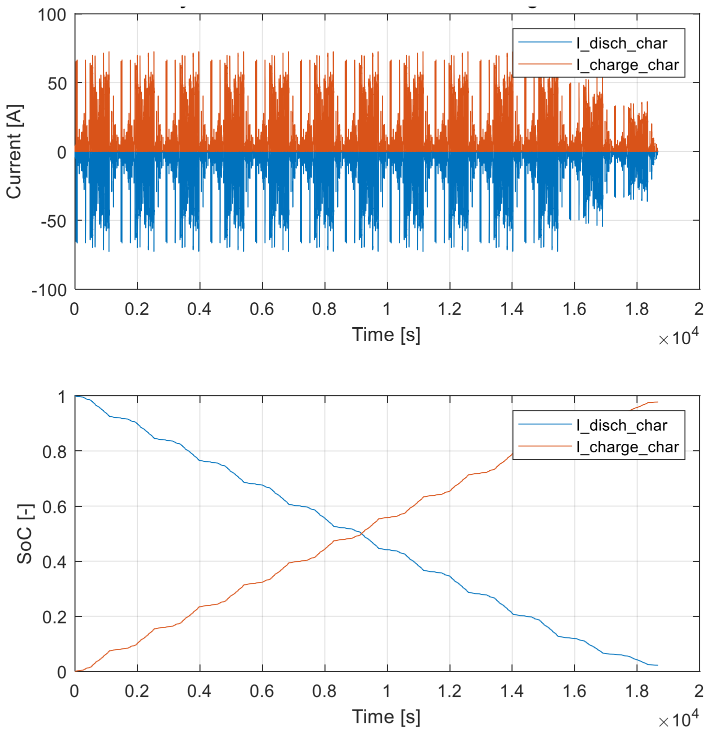

Figure 8: Characterisation (training) cycle based on TOFAS realistic driving on test track.

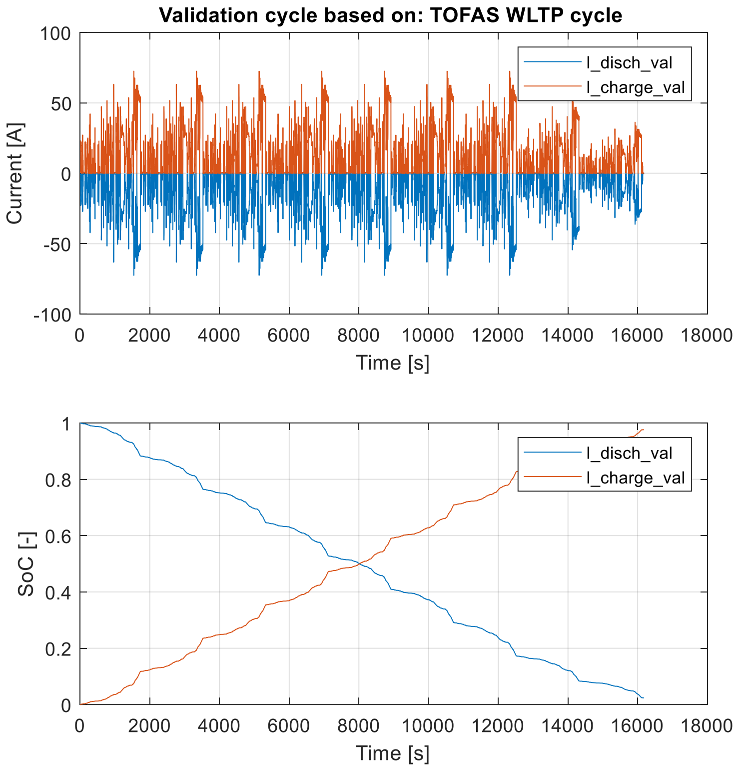

Figure 9: Validation cycle based on WLTP cycle recorded on TOFAS test track.

2.6 (Dynamic) Hybrid Power Pulse Characterisation

The fifth test consists short CC charging and discharging pulses performed at various C-rates, temperatures and SoC levels. This test is also commonly referred to as an HPPC test. In this case, the applied C-rates consist of 0.1C, 0.2C, 0.5C, 1.0C and 1.5C executed consecutively, with charging and discharging for each C-rate, 30 second pulse duration and 10 min resting time in between pulses. This sequence has been measured for temperatures 25°C, 5°C and 45°C and SoC levels 100%, 80%, 60%, 40%, 20% and 0%, the result of which is presented in Figure 10. The goal of this test, similar to the dynamic cycles, is to model/validate the battery impedance at various operating conditions.

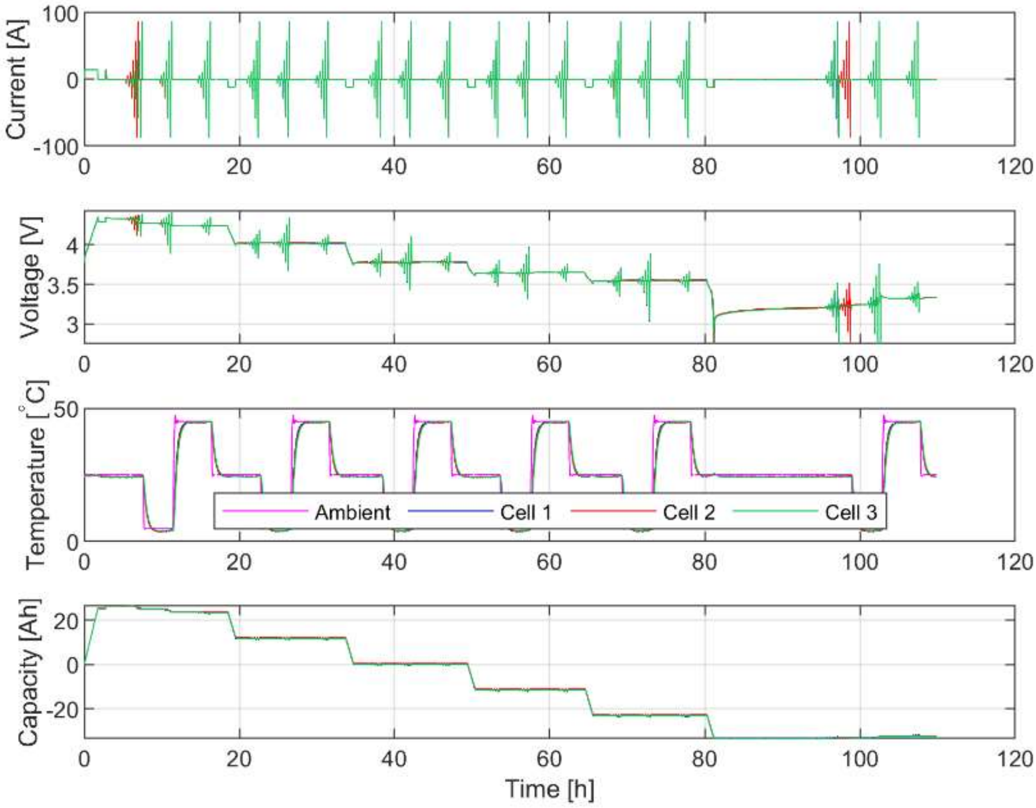

Figure 10: Measurement data of the HPPC pulses at various SoC and temperature levels.

2.7 (Dynamic) Electrochemical Impedance Spectroscopy

Lastly, EIS is performed on all three cells measuring a frequency sweep of 100 kHz until 10 mHz, with current excitation amplitude of 1/10C at SoC levels 90%, 50% and 10% at temperatures 0°C, 5°C, 25°C and 45°C. While maintaining all cells in the climate chamber, the cells were first brought to 90% SoC, and then, in sequence, EIS tested and then discharged via 15A CCCV @C/20 until the next SoC setpoint. Upon completion of the three SoC points, the temperature was changed in the climate change and after a 2h temperature soak, the above procedure was repeated.

The results of the EIS tests are presented as Nyquist diagrams in Figure 11 and Figure 12. In the former, a comparison is shown of the resulting impedance spectra obtained through excitation at different temperatures. As expected, higher temperatures yield a lower impedance which is especially pronounced in the mid-frequency range. Namely, a complete disappearance of the semi-circle at 45°C. A lower signal-to-noise ratio due to lower impedance at 45°C also results in a number of small deviations visible in the resulting impedance curve. In Figure 12, a comparison is made between impedance spectra obtained at different SoC conditions (90%, 50% and 10%) for 3 different cells. The careful reader will observe a largely high level of similarity between the curves of different cells at the three SoC levels, but with some deviations at low and high frequencies.

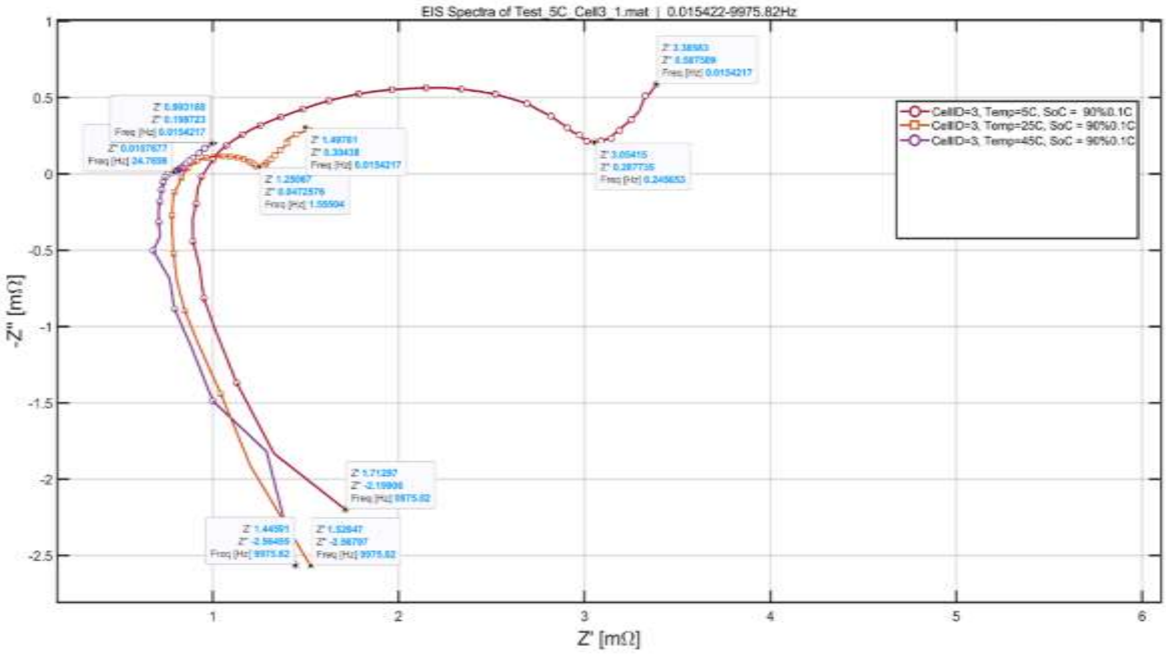

Figure 11: EIS Nyquist plot, comparison of curves for different temperatures but same SoC.

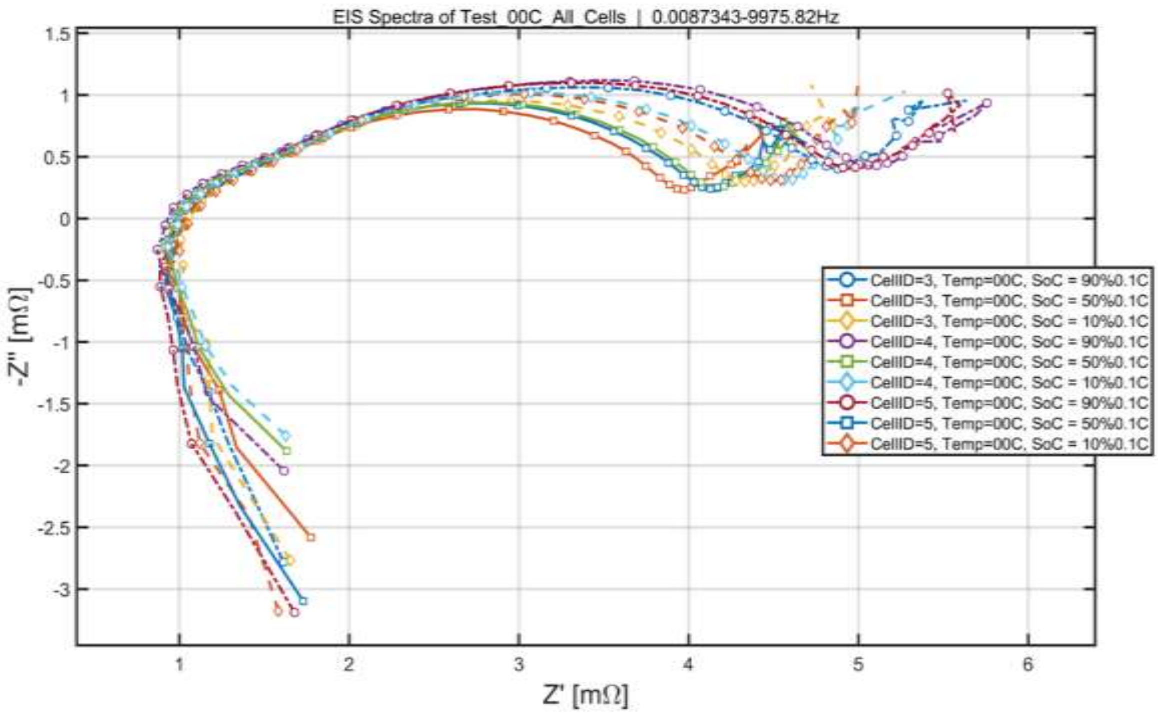

Figure 12: EIS Nyquist plot, clustering of curves at different SoCs exacerbated by low temperatures (0°C as additional test).

3 Thermal characterisation tests

Thermal characterisation tests have been performed by AIT. The goal of these tests is to extract the thermal parameters to model the thermal behaviour of the cell.

For this purpose, the cell was alternately charged and discharged (each at 1C) under hot ambient temperature conditions at 45 °C. After heating up the current was switched off and several decay curves of the cell temperature were measured.

Figure 13 depicts the preparation of the cell for the thermal characterisation tests. Afterwards the cell was placed in an incubator to simulate the hot ambient temperature conditions (cf. Figure 14 and Figure 15).

Figure 13: Application of the thermocouple (cell-temperature) positioned in the middle of the bottom main face (left) and compressed cell by using pressure plates (right).

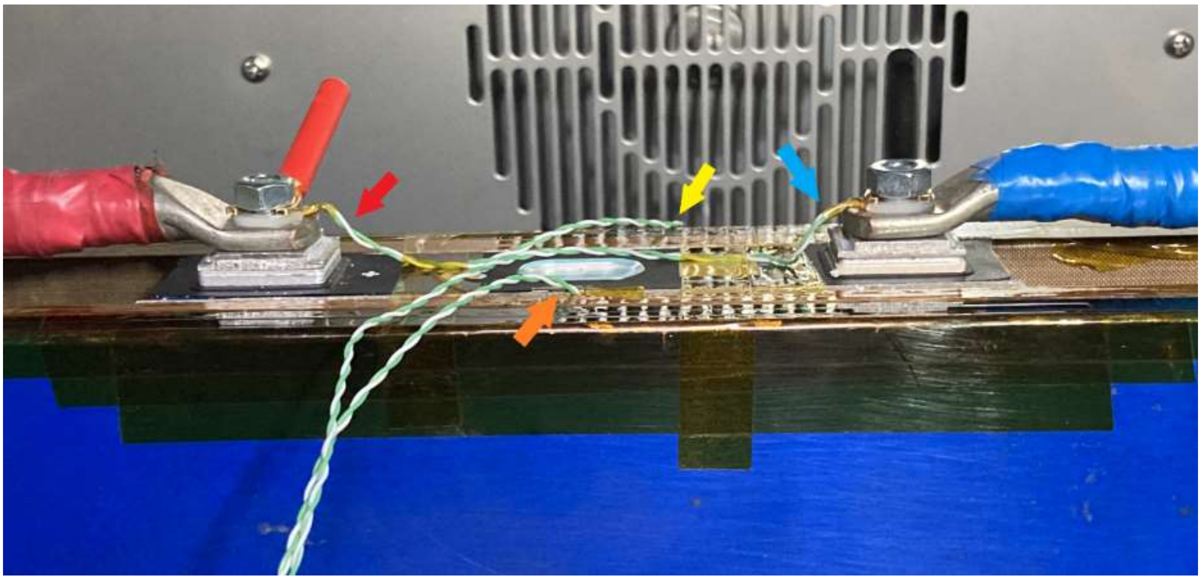

Figure 14: Wiring of the cell including additional thermocouples for temperature monitoring (cf. red arrow: plus-terminal, blue arrow: minus-terminal, orange arrow: cell-temperature, yellow arrow: temperature in the incubator).

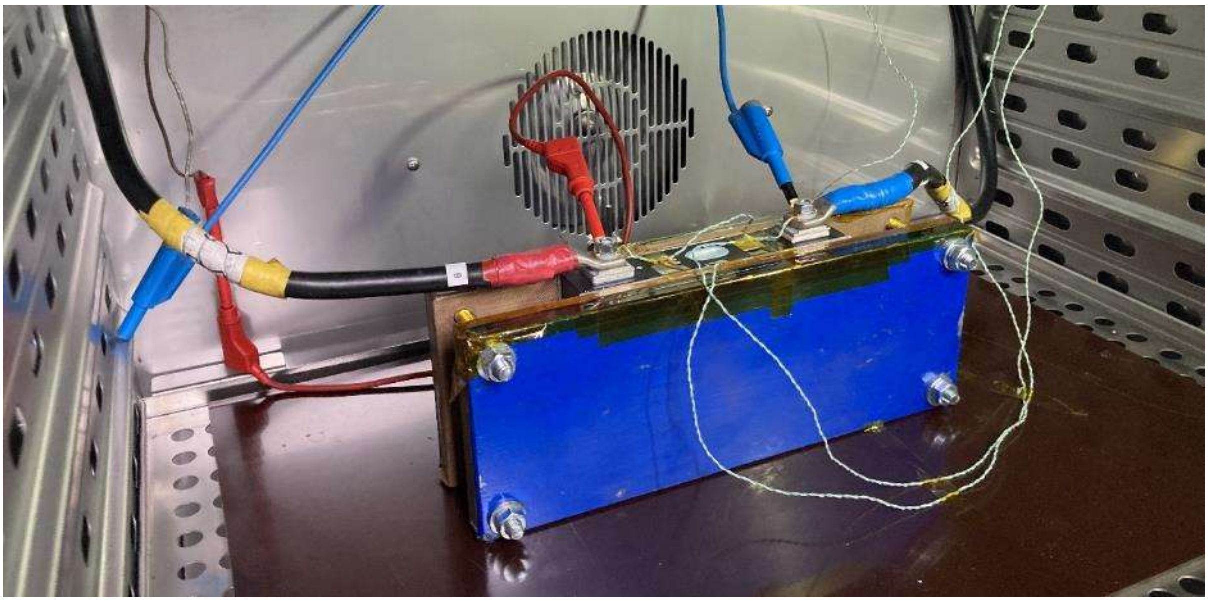

Figure 15: Entire cell setup placed in the incubator.

Figure 16 depicts the screenshot of a representative decay curve of the cell temperature. The thermal time constant of the entire cell setup (i.e., cell plus pressure plates[1] with $\tau_{plates} = 40$ s) can be determined to $\tau_{tot} = 140$ s.

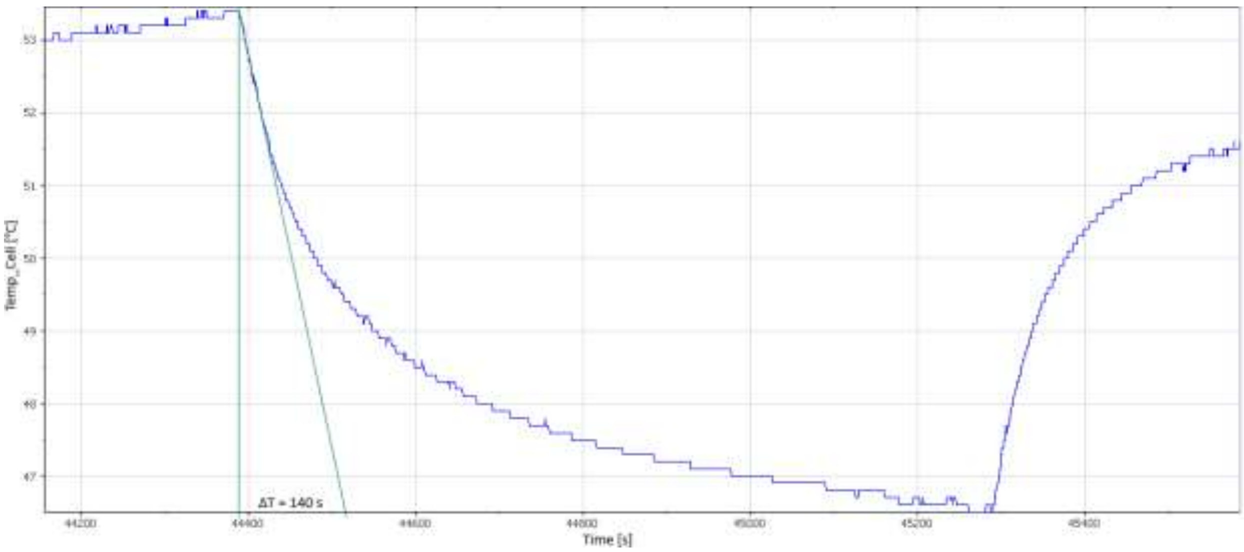

Figure 16: Decay curve of the cell temperature

[1] τ_{plates} can be calculated from geometric data and material data (Fe) as the product of heat capacity and thermal resistance.

4 Ageing tests

In this section, the ageing tests, intended to run from February 2024 to February 2025, are described in detail. The main goal of the ageing tests is to trigger the various ageing mechanisms known to occur in Li-ion batteries like SEI layer build up, Li plating [2], pore clogging, etc. To trigger these different modes of degradation, the common approach is to cycle cells at different conditions such as average SoC, DoD, temperature, and charging and discharging C-rates. In total, the ageing plan consists of 38 cells divided over four different climate chambers, as shown in Table 3. Tests can be divided into three parts, namely calendar ageing (green), cycling ageing (blue), dynamic/validation testing (orange).

Table 3: Overview of the ageing tests.

0°C	(TNO)				C-rate		
Channel	**Cell name**	**Type**	**DoD (V-based)**	**Average SoC**	**Charge**	**Discharge**	**Effect**
1	NEXTBMS_A1.01	Calendar ageing	0%	100%	0	0	
2	NEXTBMS_A1.02	CC cycle	100%: (2,75V-4.35V)	50%	0.5	0.5	Monitor effect of Temp
3	NEXTBMS_A1.03	CC cycle	100%: (2,75V-4.35V)	50%	0.25	0.5	Monitor effect of C-rate
4	NEXTBMS_A1.04	CC cycle	100%: (2,75V-4.35V)	50%	0.75	0.5	Monitor effect of C-rate
5	NEXTBMS_A1.05	CC cycle	100%: (2,75V-4.35V)	50%	1	0.5	Monitor effect of C-rate
6	NEXTBMS_A1.06	CC cycle	100%: (2,75V-4.35V)	50%	[0.25, 0.5, 0.75, 1]	0.5	Monitor effect of C-rate variations
7	NEXTBMS_A1.07	Load cycle EDF	100%: (2,75V-4.35V)	50%	n/a	n/a	Validation
8	NEXTBMS_A1.08	Drive cycle TOFAS	100%: (2,75V-4.35V)	50%	0.5	n/a	Validation
25°C	**(TNO)**						
Channel	**Cell name**	**Type**	**DoD (V-based)**	**Average SoC**	**Charge**	**Discharge**	**Effect**
1	NEXTBMS_A2.01	Calendar ageing	0% (4.35V)	100%	0	0	
2	NEXTBMS_A2.02	CC cycle	100%: (2.75V-4.35V)	50%	0.5	0.5	Monitor effect of Temp
3	NEXTBMS_A2.03	CC cycle	10%: (3.676V-3.747V)	50%	0.5	0.5	Monitor effect of DoD
4	NEXTBMS_A2.04	CC cycle	40%: (3.617V-3.936V)	50%	0.5	0.5	Monitor effect of DoD
5	NEXTBMS_A2.05	CC cycle	70%: (3.511V-4.120V)	50%	0.5	0.5	Monitor effect of DoD
6	NEXTBMS_A2.06	CC cycle	100%: (2.75V-4.35V)	50%	1	0.5	Monitor effect of C-rate
7	NEXTBMS_A2.07	CC cycle	100%: (2.75V-4.35V)	50%	1.5	0.5	Monitor effect of C-rate
8	NEXTBMS_A2.08	CC cycle	100%: (2.75V-4.35V)	50%	2	0.5	Monitor effect of C-rate
9	NEXTBMS_A2.09	CC cycle	100%: (2.75V-4.35V)	50%	0.5	1.5	Monitor effect of C-rate
10	NEXTBMS_A2.10	Load cycle EDF	n/a	50%	n/a	n/a	Validation
11	NEXTBMS_A2.11	Drive cycle TOFAS	100%: (2.75V-4.35V)	50%	0.5	n/a	Validation
45°C	**(AIT)**						
Channel	**Cell name**	**Type**	**DoD (V-based)**	**Average SoC**	**Charge**	**Discharge**	**Effect**
1	NEXTBMS_A3.01	Calendar ageing	0% (3.474V)	10%	0	0	Monitor effect of SOC
2	NEXTBMS_A3.02	Calendar ageing	0% (3.706V)	50%	0	0	Monitor effect of SOC
3	NEXTBMS_A3.03	Calendar ageing	0% (4.35V)	100%	0	0	Monitor effect of SOC
4	NEXTBMS_A3.04	CC cycle	100%: (2.75V-4.35V)	50%	0.5	0.5	Monitor effect of Temp
5	NEXTBMS_A3.05	CC cycle	50%: (3.706V-4.35V)	75%	0.5	0.5	Monitor effect of avg SoC
6	NEXTBMS_A3.06	CC cycle	50%: (2.75V-3.706V)	25%	0.5	0.5	Monitor effect of avg SoC
7	NEXTBMS_A3.07	CC cycle	50%: (3.587V-3.999V)	50%	0.5	0.5	Monitor effect of avg SoC
8	NEXTBMS_A3.08	CC cycle	100%: (2.75V-4.35V)	50%	1	0.5	Monitor effect of C-rate
9	NEXTBMS_A3.09	CC cycle	100%: (2.75V-4.45V)	50%	1	0.5	Monitor effect of high voltage levels
10	NEXTBMS_A3.10	CCCV charge & CC cycle	100%: (2.75V-4.45V)	50%	1	0.5	Monitor effect of high voltage levels
11	NEXTBMS_A3.11	CC cycle	100%: (2.75V-4.35V)	50%	0.5	1	Monitor effect of C-rate
12	NEXTBMS_A3.12	CC cycle	100%: (2.75V-4.35V)	50%	1	1	Monitor effect of C-rate
13	NEXTBMS_A3.13	Load cycle EDF	n/a	50%	n/a	n/a	Validation
14	NEXTBMS_A3.14	Drive cycle TOFAS	100%: (2.75V-4.35V)	50%	0.5	n/a	Validation
0°C - 45°	**(AIT)**						
Channel	**Cell name**	**Type**	**DoD (V-based)**	**Average SoC**	**Charge**	**Discharge**	**Effect**
1	NEXTBMS_A4.01	CC cycle	100%: (2.75V-4.35V)	50%	0.5	0.5	Reference conditions
2	NEXTBMS_A4.02	Load cycle EDF	n/a	50%	n/a	n/a	Validation
3	NEXTBMS_A4.03	Drive cycle TOFAS	100%: (2.75V-4.35V)	50%	0.5	n/a	Validation
4	NEXTBMS_A4.04	TOFAS 1 (1-2m) - TOFAS 2 (3-4m) - EDF 1 (5-6m) - TOFAS 1 (7-8m) - EDF 2 (9-12m)	100%: (2.75V-4.35V)	50%	0.5	n/a	Validation
5	NEXTBMS_A4.05	TOFAS 1 (1-6m) - EDF 1 (7-12m)	100%: (2.75V-4.35V)	50%	0.5	n/a	Validation

When charging to a specific SoC level in the aging tests, a representative SoC-OCV correlation table, which is shown in Figure 17, is used to map the required SOC level to a distinct voltage level. Using the SoC-OCV correlation instead of coulomb counting (integration of current) is more time consuming but it eliminates the need to regularly compensate the SoC drift induced by the offset in current measurements, which is usually the case when using the coulomb counting method. The data for the table has been extracted from the GITT characterization measurements performed in chapter 2.3. The procedure foresees to either charge or discharge to the respective SoC using the CCCV method with a cut-off c-rate of 0.01C (0.58 A) for the CV phase. When assuming an internal resistance of 0.8 mΩ and a nominal voltage of 3.7 V (from the datasheet) and 1 mV tolerance of the measurement equipment, this means an error of below +/-0.05 % with regard to the target SoC level.

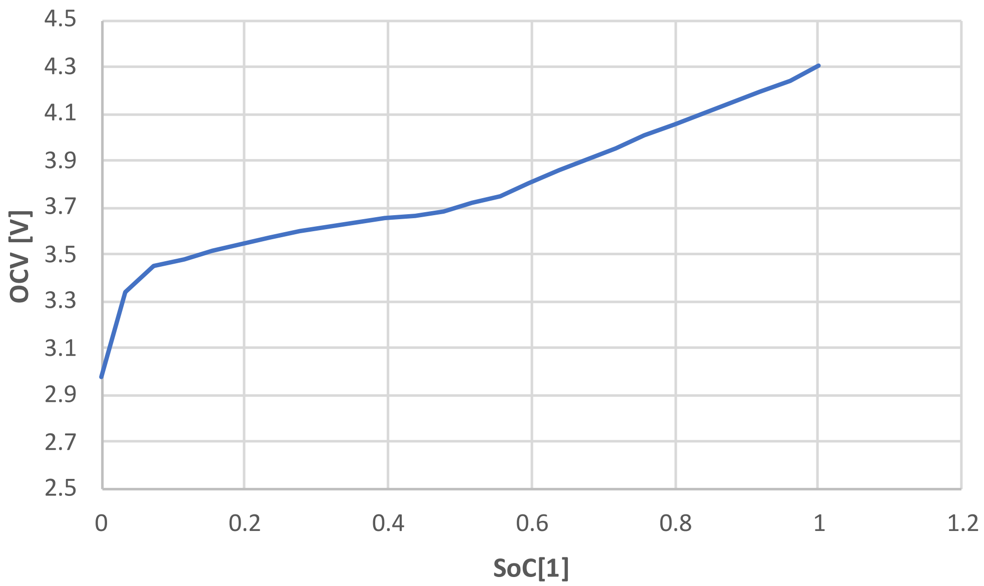

Figure 17: SoC-OCV correlation curve

4.1 Preparation of test campaign

The testing activities are split between TNO and AIT. TNO will perform 0°C and 25°C measurements and AIT will perform 45°C and varying temperature measurements from 0°C - 45°C (see also overview of the ageing tests in Table 3). For the implementation of the measurement setup TNO and AIT use the same hardware components required such as clamping plates (same steel thickness), separator sheets (same types) and compression springs (same types), cf. Figure 2, Figure 3and Figure 18.

Figure 18: Cell before (left) and after assembly of the clamping plates (right).

Figure 19 shows the arrangement of the prepared cells in a temperature controlled climatic chamber.

Figure 19: Arrangement of the prepared cells in the climatic chamber

Since the ageing test plan exceeds boundaries from the cell specification sheet (cf. lines in Table 3 with last column coloured in light pink), pretests were required to check the operating behaviour to exclude hazardous testing under hot ambient conditions (i.e., 45 °C) for exceeding C-rates and cell-voltages (overvoltage).

4.1.1 Pretests under hot ambient conditions

High C-rates tests

The first pretest to investigate the thermal operating behaviour at high ambient temperature and high C-rates was performed by using an abuse chamber (including a climatic chamber), cf. Figure 20.

Figure 20: Abuse chamber equipped with cameras (left) and a climatic chamber with arranged cell inside (right).

For the test the cell is exposed at 45°C by applying CC charging and discharging for one test run at 1.5C and for another one at 1C as shown in Figure 21 and Figure 22, respectively.

For safety reasons, the test with 1.5C cycling had to be stopped after 13 hours at a cell temperature of 61 °C, as the cell temperature continuously increased and observably exceeded the permissible upper operating temperature of 55°C. However, the cell passed the test with CC cycling at 1C (i.e., the nominal C-rate).

The evaluated data therefore shows that higher C-rates at high ambient temperatures are a problem because the cell temperature does not remain within valid temperature limits. As a consequence, the maximum C-rate for cycling under hot ambient conditions (45 °C) in the ageing test plan must be limited to 1C.

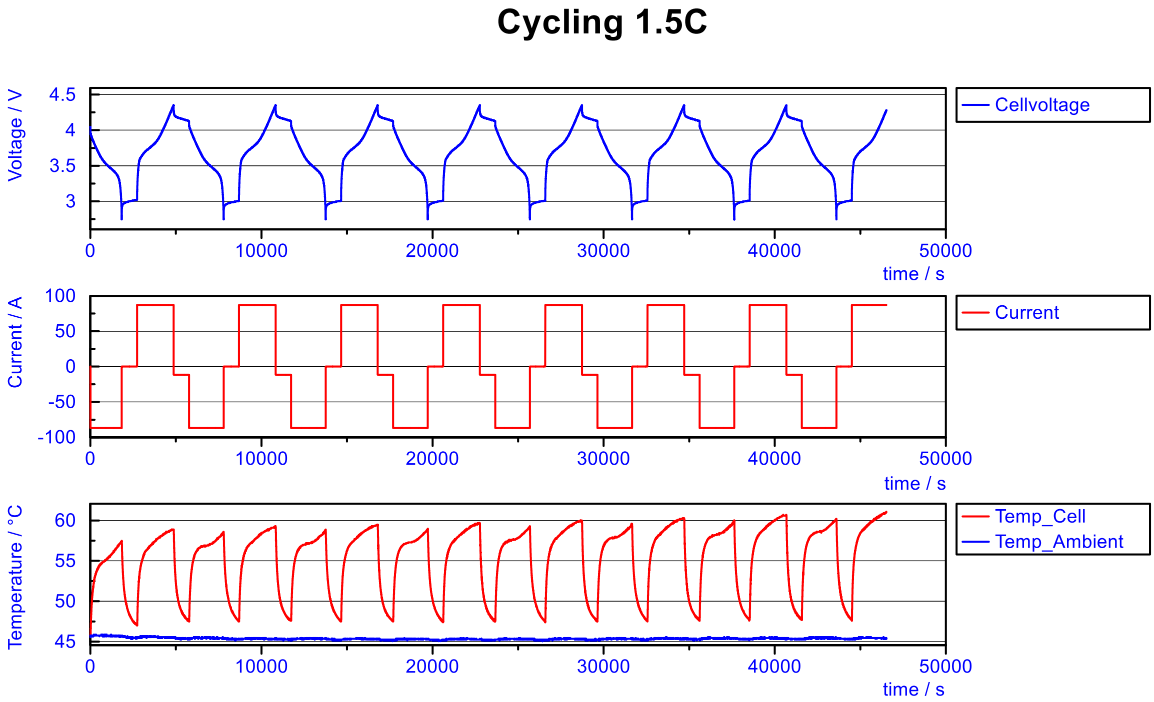

Figure 21: CC cycling with 1.5C under high ambient temperature conditions (45 °C).

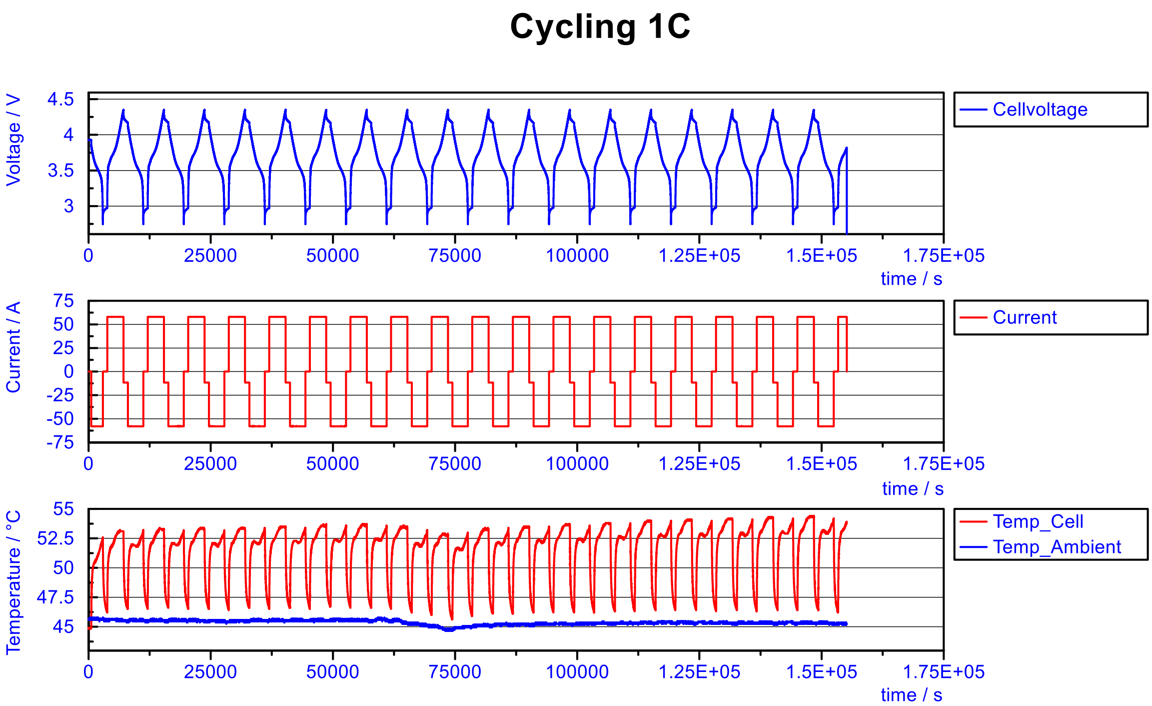

Figure 22: CC cycling with 1C under high ambient temperature conditions (45 °C).

Overvoltage tests

For safety reasons also the second pretest to investigate the thermal operating behaviour at high ambient temperature and exceeding cell voltages (overvoltage) was performed within an abuse chamber (including a climatic chamber), cf. Figure 23.

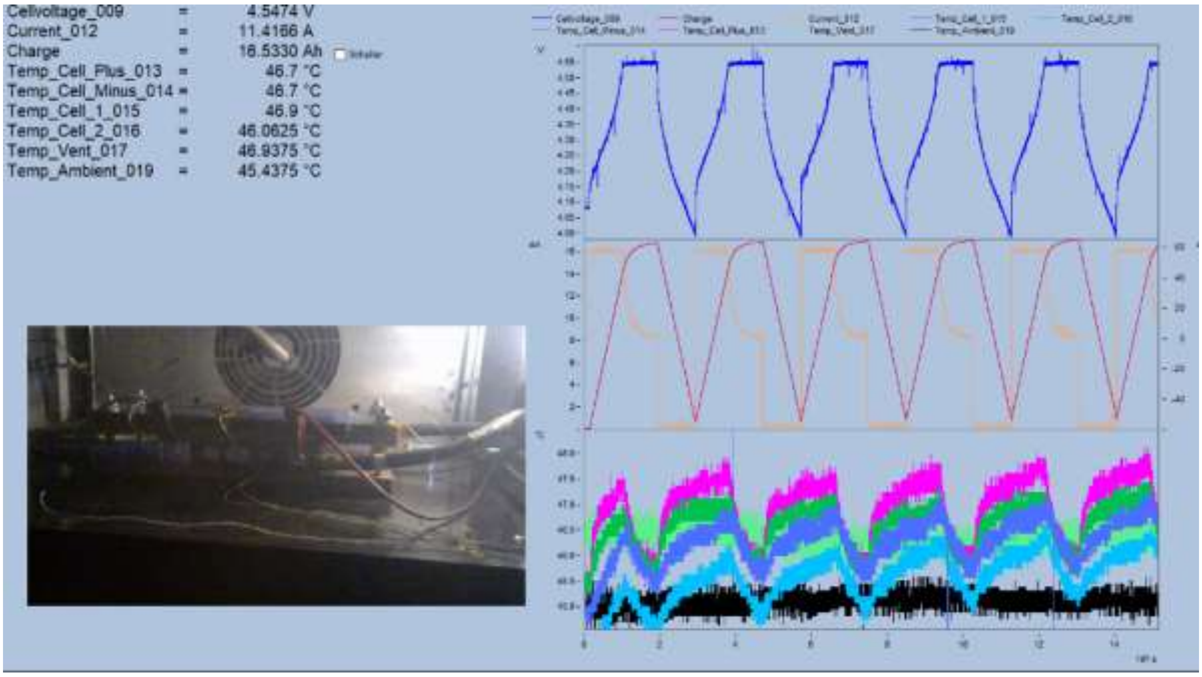

Figure 23: Screenshot of monitoring camera (left) during overvoltage tests and real-time oscillogram data (right).

The overvoltage cycling test (up to 9 cycles at 45 °C hot ambient conditions) entails a C-rate of 1C Constant-Current Constant-Voltage (CCCV) charge (CC until the desired Vmax is achieved, then CV for 15 min to keep Vmax) and Constant-Current (CC) discharge (back to 75 % SoC). The first overvoltage cycling test starts with Vmax = 4.45 V and will be increased after each cycling in steps of 0.1 V. The test results are depicted in Figure 24-Figure 29.

During cycling test with Vmax = 4.95 V (cf. Figure 29) a continuously and significant temperature rise could be observed. It was decided to stop the measurements for an optical inspection of the cell (cf. Figure 30 and Figure 31). The images show that the cell did not release gases but inflate significantly.

As a consequence, to remain on the safe side, the maximum overvoltage for cycling under hot ambient conditions (45 °C) in the ageing test plan will be limited to Vmax = 4.45 V.

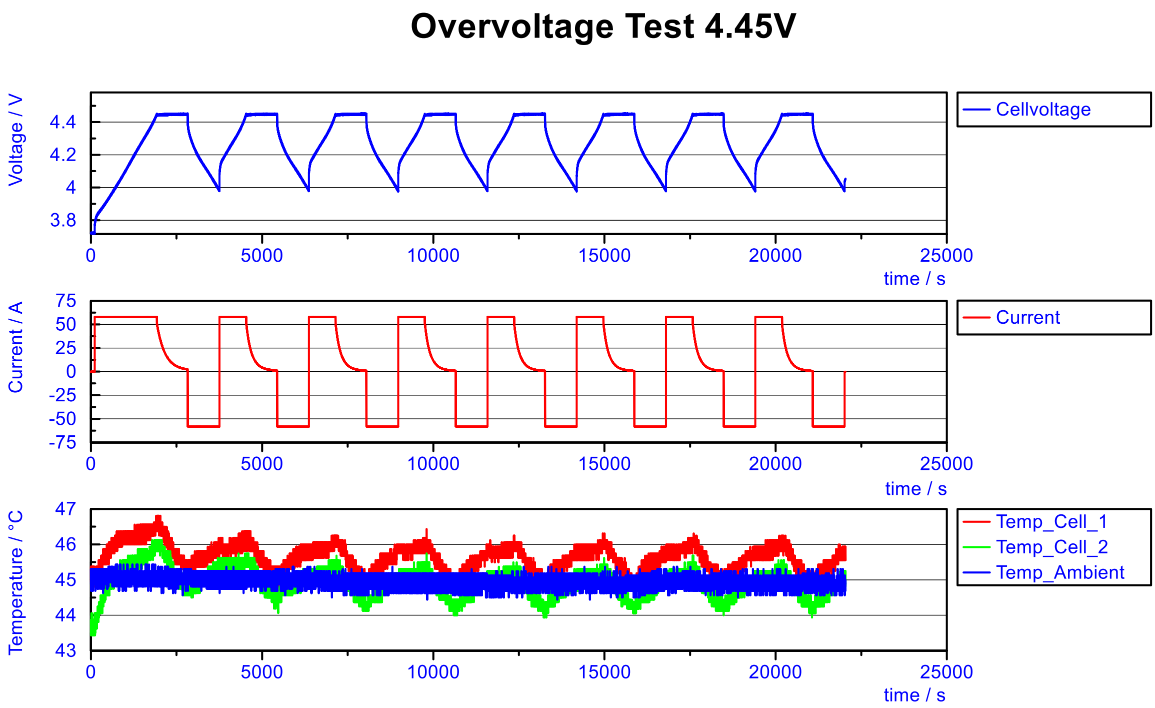

Figure 24: Overvoltage CCCV cycling test at 1C (CC until V_{max} = 4.45 V is achieved, then CV for 15 min to keep V_{max}).

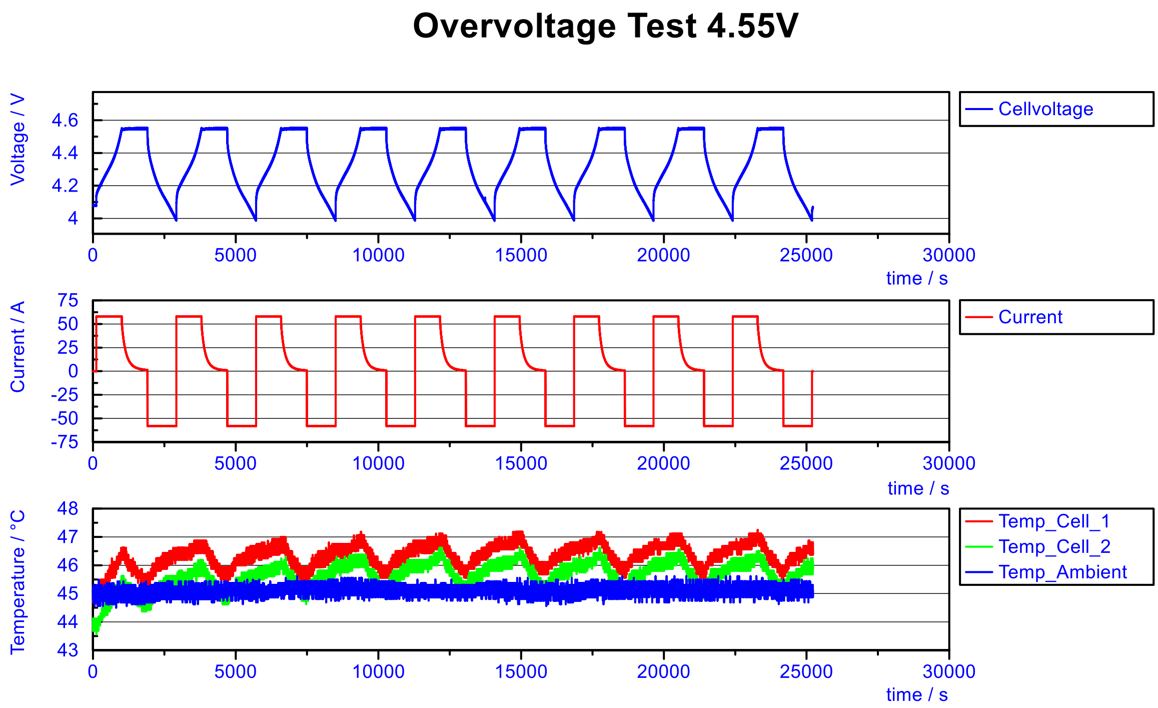

Figure 25: Overvoltage CCCV cycling test at 1C (CC until V_{max} = 4.55 V is achieved, then CV for 15 min to keep V_{max}).

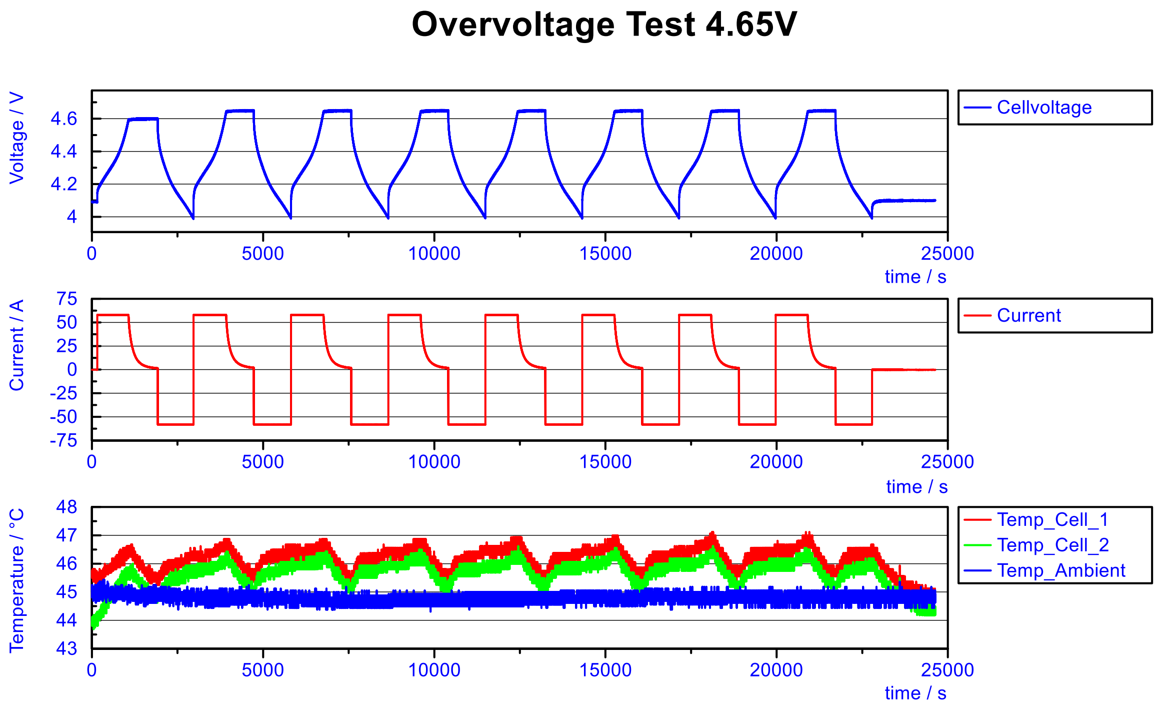

Figure 26: Overvoltage CCCV cycling test at 1C (CC until V_{max} = 4.65 V is achieved, then CV for 15 min to keep V_{max}).

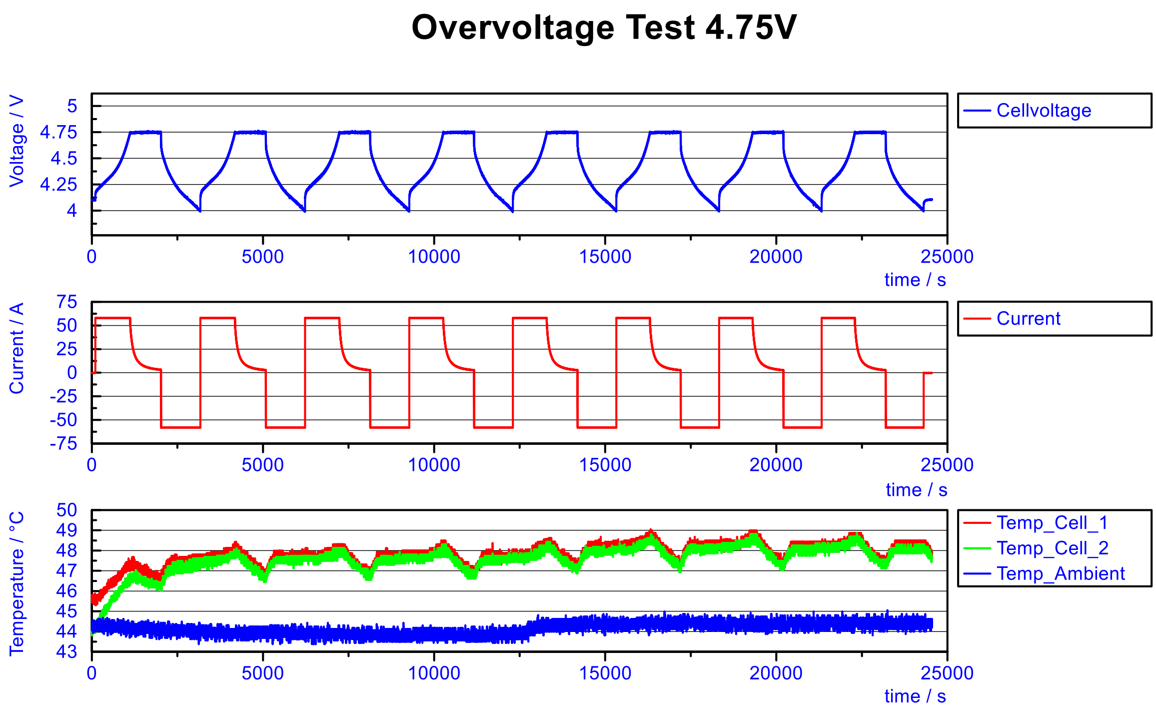

Figure 27: Overvoltage CCCV cycling test at 1C (CC until V_{max} = 4.75 V is achieved, then CV for 15 min to keep V_{max}).

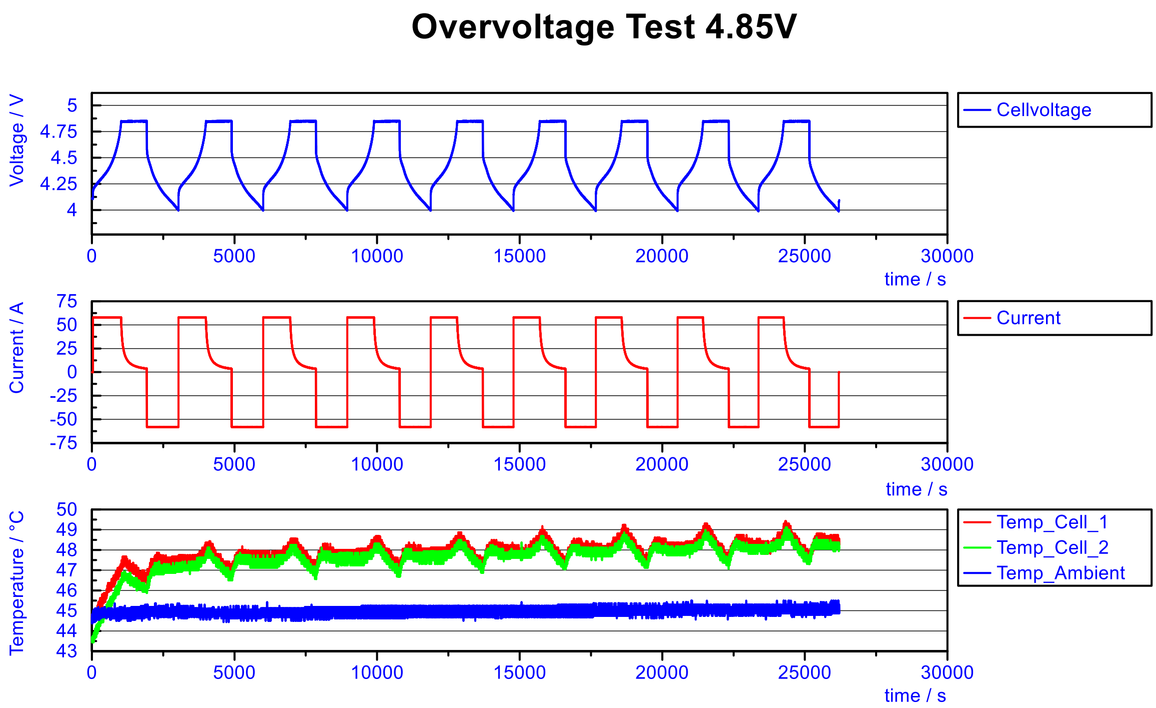

Figure 28: Overvoltage CCCV cycling test at 1C (CC until V_{max} = 4.85 V is achieved, then CV for 15 min to keep V_{max}).

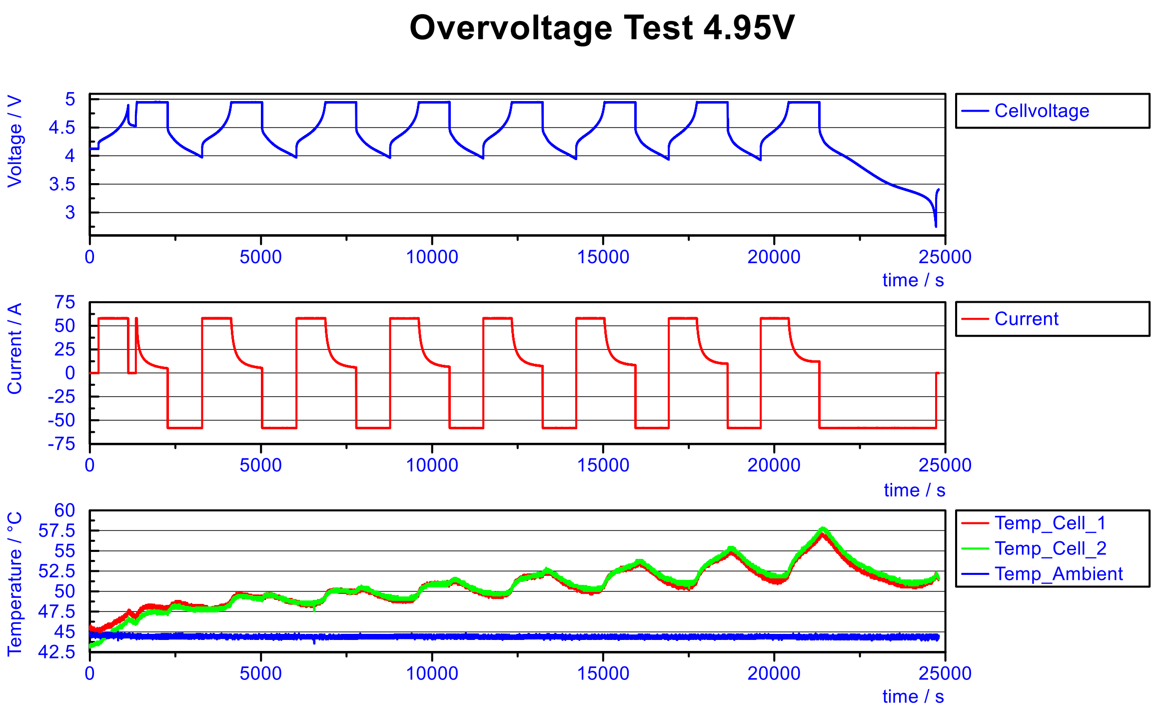

Figure 29: Overvoltage CCCV cycling test at 1C (CC until V_{max} = 4.95 V is achieved, then CV for 15 min to keep V_{max}).

Figure 30: Optical inspection of the damaged and inflated cell (view on terminal side)

Figure 31: Optical inspection of the damaged and inflated cell (side view)

4.2 Calendar ageing

Calendar ageing means that the cell's ageing rate is proportional to time and therefore independent of whether the cell is cycled or not. Depending on the cathode and anode materials used and the cell chemistry, calendar ageing can occur at different rates. The main environmental factors that influence calendar aging rates are the cell temperature and its SoC. The higher these values are, the faster the calendar aging progresses [3].

The calendar ageing plan consists of three cells divided over three different climate chambers to monitor the effect of the ambient temperature (0 °C, 25 °C and 45 °C, each cell at SoC max.), as shown in Table 4. Two additional cells (SoC 10 % and 50 %) are stored in the climate chamber at 45 °C (cf. Table 4) to monitor together with the cell at SoC 100 % the effect of various SoC on calendar ageing.

Table 4: Overview of the calendar ageing tests at different ambient temperatures and different SoC's under hot environmental conditions.

					C-rate		
0°C	**(TNO)**						
Channel	**Cell name**	**Type**	**DoD (V-based)**	**Average SoC**	**Charge**	**Discharge**	**Effect**
1	NEXTBMS_A1.01	Calendar ageing	0%	100%	0	0	
25°C	**(TNO)**						
Channel	**Cell name**	**Type**	**DoD (V-based)**	**Average SoC**	**Charge**	**Discharge**	**Effect**
1	NEXTBMS_A2.01	Calendar ageing	0% (4.35V)	100%	0	0	
45°C	**(AIT)**						
Channel	**Cell name**	**Type**	**DoD (V-based)**	**Average SoC**	**Charge**	**Discharge**	**Effect**
1	NEXTBMS_A3.01	Calendar ageing	0% (3.474V)	10%	0	0	Monitor effect of SOC
2	NEXTBMS_A3.02	Calendar ageing	0% (3.706V)	50%	0	0	Monitor effect of SOC
3	NEXTBMS_A3.03	Calendar ageing	0% (4.35V)	100%	0	0	Monitor effect of SOC

4.3 Cycle ageing

Cycle ageing considers ageing effects which are caused due to charge transfer. The cycle ageing plan consists of 23 cells divided over 4 different climate chambers to monitor the influence of different ambient temperature conditions (0 °C, 25 °C, 45 °C and varying temperature from 0 °C to 45 °C), different C-rates (0.25C, 0.5C, 0.75C, 1C, 1.5C, 2C, different DoDs (10%, 40%, 50%, 70% and 100%) around different mean SoCs (25 %, 50 %, 75 %), and overvoltage levels (4.45 V) on cycle ageing, as shown in Table 5.

The lines in Table 5 with last column coloured in light pink exceeds boundaries from the cell specification sheet (cf. Table 2). The exceeding C-rates at cold environment conditions should induce Li plating which is one of the major aging mechanisms of lithium-ion batteries. The exceeding C-rates at moderate and hot environment conditions (i.e., 25 °C and 45 °C) will trigger increased SEI layer build up, which is another major ageing mechanism known to occur in Li-ion batteries. Early detection of Li plating will be one focus in the NEXTBMS project. Another one will be understanding the build-up and effect of the SEI layer. Therefore, a lot of knowledge about the cell is necessary. The planned measurements will enable the NEXTBMS consortium to gain deep insights into these aging phenomena.

Table 5: Overview of the cycling ageing tests to monitor the influence of different ambient temperature conditions, different C-rates, different DoDs, different SoCs, and overvoltage level.

0°C	(TNO)				C-rate		
Channel	Cell name	Type	DoD (V-based)	Average SoC	Charge	Discharge	Effect
2	NEXTBMS_A1.02	CC cycle	100%: (2,75V-4.35V)	50%	0.5	0.5	Monitor effect of Temp
3	NEXTBMS_A1.03	CC cycle	100%: (2,75V-4.35V)	50%	0.25	0.5	Monitor effect of C-rate
4	NEXTBMS_A1.04	CC cycle	100%: (2,75V-4.35V)	50%	0.75	0.5	Monitor effect of C-rate
5	NEXTBMS_A1.05	CC cycle	100%: (2,75V-4.35V)	50%	1	0.5	Monitor effect of C-rate
6	NEXTBMS_A1.06	CC cycle	100%: (2,75V-4.35V)	50%	[0.25, 0.5, 0.75, 1]	0.5	Monitor effect of C-rate variations
25°C	(TNO)						
Channel	Cell name	Type	DoD (V-based)	Average SoC	Charge	Discharge	Effect
2	NEXTBMS_A2.02	CC cycle	100%: (2.75V-4.35V)	50%	0.5	0.5	Monitor effect of Temp
3	NEXTBMS_A2.03	CC cycle	10%: (3.676V-3.747V)	50%	0.5	0.5	Monitor effect of DoD
4	NEXTBMS_A2.04	CC cycle	40%: (3.617V-3.936V)	50%	0.5	0.5	Monitor effect of DoD
5	NEXTBMS_A2.05	CC cycle	70%: (3.511V-4.120V)	50%	0.5	0.5	Monitor effect of DoD
6	NEXTBMS_A2.06	CC cycle	100%: (2.75V-4.35V)	50%	1	0.5	Monitor effect of C-rate
7	NEXTBMS_A2.07	CC cycle	100%: (2.75V-4.35V)	50%	1.5	0.5	Monitor effect of C-rate
8	NEXTBMS_A2.08	CC cycle	100%: (2.75V-4.35V)	50%	2	0.5	Monitor effect of C-rate
9	NEXTBMS_A2.09	CC cycle	100%: (2.75V-4.35V)	50%	0.5	1.5	Monitor effect of C-rate
45°C	(AIT)						
Channel	Cell name	Type	DoD (V-based)	Average SoC	Charge	Discharge	Effect
4	NEXTBMS_A3.04	CC cycle	100%: (2.75V-4.35V)	50%	0.5	0.5	Monitor effect of Temp
5	NEXTBMS_A3.05	CC cycle	50%: (3.706V-4.35V)	75%	0.5	0.5	Monitor effect of avg SoC
6	NEXTBMS_A3.06	CC cycle	50%: (2.75V-3.706V)	25%	0.5	0.5	Monitor effect of avg SoC
7	NEXTBMS_A3.07	CC cycle	50%: (3.587V-3.999V)	50%	0.5	0.5	Monitor effect of avg SoC
8	NEXTBMS_A3.08	CC cycle	100%: (2.75V-4.35V)	50%	1	0.5	Monitor effect of C-rate
9	NEXTBMS_A3.09	CC cycle	100%: (2.75V-4.45V)	50%	1	0.5	Monitor effect of high voltage levels
10	NEXTBMS_A3.10	CCCV charge & CC cycle	100%: (2.75V-4.45V)	50%	1	0.5	Monitor effect of high voltage levels
11	NEXTBMS_A3.11	CC cycle	100%: (2.75V-4.35V)	50%	0.5	1	Monitor effect of C-rate
12	NEXTBMS_A3.12	CC cycle	100%: (2.75V-4.35V)	50%	1	1	Monitor effect of C-rate
0°C - 45°	(AIT)						
Channel	Cell name	Type	DoD (V-based)	Average SoC	Charge	Discharge	Effect
1	NEXTBMS_A4.01	CC cycle	100%: (2.75V-4.35V)	50%	0.5	0.5	Reference conditions

4.4 Dynamic cycles

The dynamic cycles ageing plan, as shown in Table 6, consists of real, dynamic current profiles applied to 10 cells divided over 4 different climate chambers (0 °C, 25 °C, 45 °C and varying from 0 °C to 45 °C) to validate application scenarios from stationary use case and from automotive perspective.

Table 6: Overview of the dynamic cycles ageing test plan.

0°C	(TNO)				C-rate		
Channel	Cell name	Type	DoD (V-based)	Average SoC	Charge	Discharge	Effect
7	NEXTBMS_A1.07	Load cycle EDF	100%: (2,75V-4.35V)	50%	n/a	n/a	Validation
8	NEXTBMS_A1.08	Drive cycle TOFAS	100%: (2,75V-4.35V)	50%	0.5	n/a	Validation
25°C	(TNO)						
Channel	Cell name	Type	DoD (V-based)	Average SoC	Charge	Discharge	Effect
10	NEXTBMS_A2.10	Load cycle EDF	n/a	50%	n/a	n/a	Validation
11	NEXTBMS_A2.11	Drive cycle TOFAS	100%: (2.75V-4.35V)	50%	0.5	n/a	Validation
45°C	(AIT)						
Channel	Cell name	Type	DoD (V-based)	Average SoC	Charge	Discharge	Effect
13	NEXTBMS_A3.13	Load cycle EDF	n/a	50%	n/a	n/a	Validation
14	NEXTBMS_A3.14	Drive cycle TOFAS	100%: (2.75V-4.35V)	50%	0.5	n/a	Validation
0°C - 45°	(AIT)						
Channel	Cell name	Type	DoD (V-based)	Average SoC	Charge	Discharge	Effect
2	NEXTBMS_A4.02	Load cycle EDF	n/a	50%	n/a	n/a	Validation
3	NEXTBMS_A4.03	Drive cycle TOFAS	100%: (2.75V-4.35V)	50%	0.5	n/a	Validation
4	NEXTBMS_A4.04	TOFAS 1 (1-2m) - TOFAS 2 (3-4m) - EDF 1 (5-6m) - TOFAS 1 (7-8m) - EDF 2 (9-12m)	100%: (2.75V-4.35V)	50%	0.5	n/a	Validation
5	NEXTBMS_A4.05	TOFAS 1 (1-6m) - EDF 1 (7-12m)	100%: (2.75V-4.35V)	50%	0.5	n/a	Validation

Stationary load cycles

The load cycles from the project partner EDF are stationary cycles, meaning that the SoC at the end and beginning are the same. There will be two cycles, i.e. 'Stationary cycle #1' (cf. the current profile in Figure 32) and 'Stationary cycle #2' (cf. Figure 33), whereas both of them start and end at 65 % SoC. This means that these cycles can be used in sequence without any additional cycling/charging/discharging. One more additional cycle, i.e. 'Stationary cycle #3', is a bit different and assumes start and end at 30 % SoC (cf. the current profile in Figure 34).

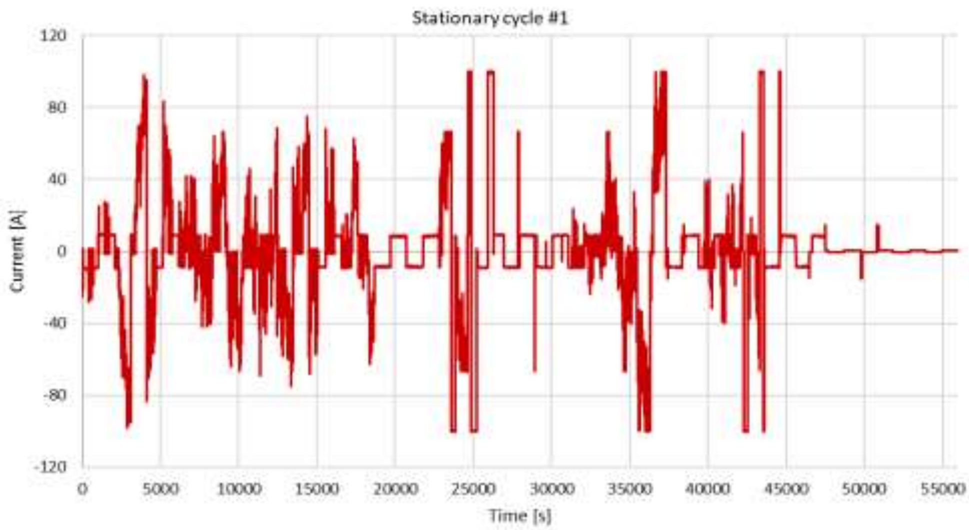

Figure 32: Current profile of 'Stationary cycle #1'

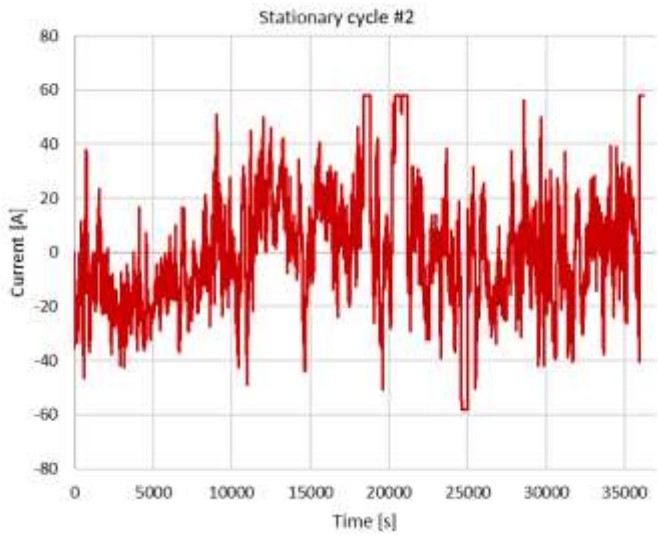

Figure 33: Current profile of 'Stationary cycle #2'

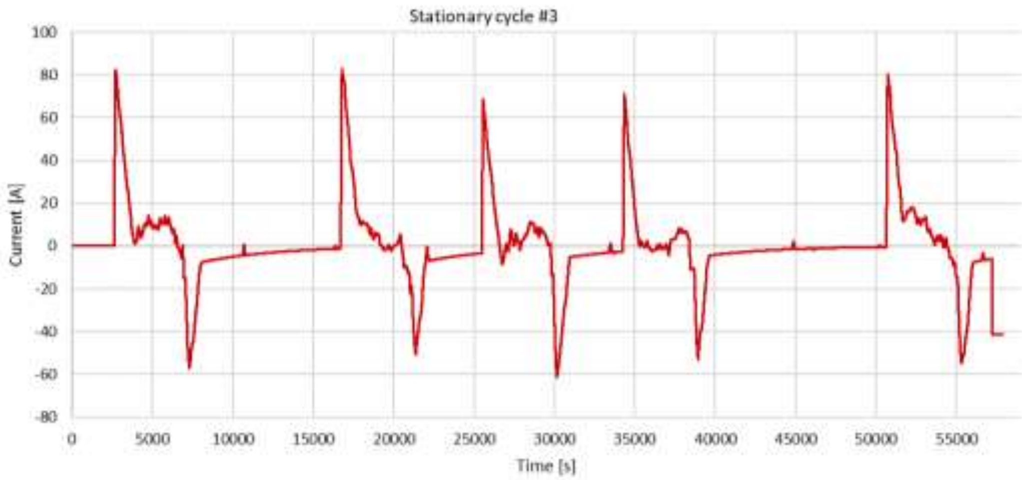

Figure 34: Current profile of 'Stationary cycle #3'

Automotive load cycles

The two drive cycles 'Automotive cycle #1' and 'Automotive cycle #2' provided from the project partner TOFAS are discharge oriented cycles. Also these cycles are used in alternating sequence but with additional 0.5C CC-charge sections in between. Figure 35 and Figure 36 show the current profiles of both automotive load cycles.

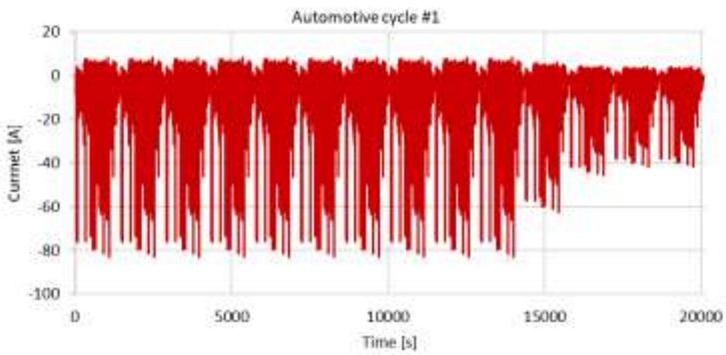

Figure 35: Current profile of 'Automotive cycle #1'

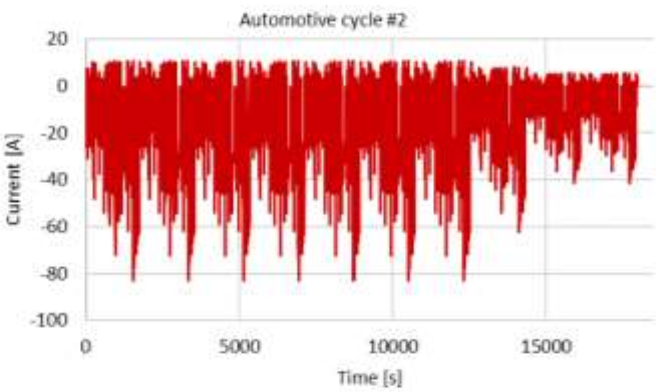

Figure 36: Current profile of 'Automotive cycle #2'

4.5 Check ups

The check up tests will be executed every 4 weeks. These tests will enable intermediate characterization of the cell and hence to regularly track the aging effects of the different load scenarios.

All check up tests will be executed at a unified temperature of 25 °C. In general, the check up procedure can be split into the following parts:

1. Check capacity
2. Check internal resistance
3. Check dynamic behaviour
4. Additionally, only at BOL, MOL and EOL, perform EIS measurements

In detail, the check up procedure will be executed as follows:

First, all cells will be thermally re-conditioned at 25 °C. Then, the cell will be fully discharged and charged again using CCCV to always achieve similar starting states of the batteries (one full charging cycle before starting the next step). Next, the charge capacity of the cells will be tested by using CCCV discharge, rest and CCCV charge at a current rate of 0.02C. Afterwards, the CCCV charge and -discharge procedure will be repeated also for the current rates of 0.5C and 1C, respectively. Then, the resistance check up will be executed. The procedure comprises discharging the batteries to 50 % SOC and then applying both a discharge- and charge pulse at 1C for 30 s, each followed by a resting period of 2 h. In order to determine the dynamic behaviour of the cells, they will be first fully charged and then discharged using a dynamic load cycle (TOFAS 1) to entirely discharge the cells.

Only at BOL, MOL and EOL the cells will go through an additional EIS test campaign. The reason why these tests will be only executed three times throughout the entire aging test campaign is that firstly, the entire EIS procedure takes a lot of additional testing time (which would mean the pure cycle- and calendar test scenarios would be much shorter then), and secondly, the EIS can only be performed with a separate cell test unit, which cannot be automated and must be therefore manually connected. The EIS testing protocol looks as follows:

First, the cells will be cully charged using CCCV at 0.25C and then discharged with CCCV at 0.25C. After a rest of 2h (to allow for relaxation of the cells) the EIS procedure begins. It will be executed at 90 %, 50 % and 10% SOC, respectively and use the Galvanostatic EIS method with a frequency range of 100 kHz to 10 mHz with a current amplitude of 5A and 10 points per decade.

4.6 Initial characterisation

The initial characterisation tests will be executed only at BOL before starting the actual aging tests. The tests will initially characterise each individual cell in terms of charge capacity and internal resistance. The procedure will be executed as follows:

First, the cells will be thermally stabilised at 25 °C for 5 h, followed by an initialization procedure. This procedure includes CC discharge to the minimum voltage at 0.25C followed by CC charge and then CV charge to maximum voltage, with 1 h rest in between each of these steps. The entire cell initialisation procedure will be repeated 5 times. After that a rest of 2 h is foreseen.

Next, the pulse discharge and pulse charge tests will be executed. There, the cells will be discharged with CC at 0.2C in 2.4167 Ah steps (58 Ah / 24 steps = 2.4167 Ah /step), where each step will be followed by a 2 h resting period.

If the cell voltage reaches the minimum cell voltage, the procedure will be continued in CV mode until the cutoff current of 0.05C is reached. This procedure will be repeated for a total number of 24 steps. Afterwards, the cell will be completely emptied in CCCV mode and then the amount of charge from the CV phase will be recharged into the battery to start the following charging pulses at the same SOC level where the discharge pulses ended. The charging pulses follow the same procedure like the discharge pulses, but in charge direction, i.e., the cells will be charged with CC at 0.2C in 2.4167 Ah steps, where each step will be followed by a 2 h resting period. Finally, the cell will be fully charged using CCCV mode, followed by a 2 h rest.

5 Conclusions

The NEXTBMS project aims at enhancing the performance and functionality of a BMS in order to increase battery utilisation and safety over the lifetime. Therefore, thorough testing procedures have been elaborated executed to systematically characterize the selected battery cells in terms of their electrical and thermal operating behaviour. The cells have been put into a climatic chamber to ensure consistent ambient conditions. Then, commonly used testing techniques, such as constant current charge and discharge, GITT, HPPC, Galvanostatic EIS and dynamic load cycles have been used to test and characterize the cells. The acquired measurement data can be used to extract the required parameters for the battery models that will be developed in the NEXTBMS project.

In the next step, also the aging behaviour of the cells will be tested and investigated. Therefore, detailed aging test plans have been elaborated. The test plans consider single-parameter variation with at least three variations per parameter to capture also the second derivative of the influence of the respective parameters on the aging rate of the battery. As the cells will be tested also in operating conditions outside the boundaries of the specification sheet, pre-aging tests have been conducted to investigate the operating behaviour and to analyse possible safety issues in advance, before the actual aging tests will be started. These tests have been used to gather information e.g. about the maximum current rate and maximum overpotential level of the cells, regardless of the values from the specification sheet.

The aging tests will be conducted for a total duration of 56 weeks. As soon as these tests will be finished, this deliverable D2.1 will be updated in terms of the acquired aging test data.

6 References

[1] Grant Agreement 101103898 - NEXTBMS, 15/03/2023.
[2] Detecting the Onset of Lithium Plating and Monitoring Fast Charging Performance with Voltage Relaxation. Zachary M. Konz, Eric J. McShane, and Bryan D. McCloskey. ACS Energy Letters 2020 5 (6), 1750-1757. DOI: 10.1021/acsenergylett.0c00831
[3] Model-based investigation of electric vehicle battery aging by means of vehicle-to-grid scenario simulations. C. Guenther, B. Schott, W. Hennings, P. Waldowski, and M. A. Danzer. Journal of Power Sources, vol. 239, pp. 604-610, 2013.

7 Acknowledgement

7.1 The consortium

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Project partners:

#	Partner short name	Partner Full Name
1	AIT	AIT Austrian Institute of Technology GmbH
2	TNO	Nederlandse organisatie foor toegepast natuurwetenschappelijk onderzoek TNO
3	UL	Univerza v Ljubljani
4	VUB	Vrije Universiteit Brussel
5	UNR	Uniresearch BV
6	AVL	AVL List GmbH
7	AVL-SFR	AVL Software and Functions GmbH
8	AVL-TR	AVL Arastirma ve Muhendislik Sanayi ve Ticaret Limited Sirketi
9	BOSCH	Robert Bosch GmbH
10	NXP	NXP Semiconductors Austria GmbH & Co KG
11	EDF	Electricite de France
12	TOFAS	TOFAS Turk Otomobil Fabrikasi Anonim Sirketi

7.2 Disclaimer/ Acknowledgment

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