Electric Vehicle Enhanced Range, Lifetime And Safety
Through INGenious battery management

D2.3 – Report containing aging test profiles and test results

February 2020

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DISCLAIMER

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EXECUTIVE SUMMARY

To extend a Li-ion battery pack lifetime and to guarantee its function in a safe manner, it's necessary to understand the ageing behaviour of one of its components which is the cell. Thus several accelerated ageing tests were designed based on the end user application conditions.

The ageing stress factor investigated in this study are:

- the environmental temperature during life cycling and during storage where it was shown that high (45°C) and very low (0°C) temperatures increases the ageing rate. This was observed for both calendar and life cycling tests.
- the cycling C-rate where the charge and discharge currents were varied. It was shown that high discharge rate (3C) led the cell to its EOL in less than 600 equivalent cycles.
- the cycling window where the two most common ranges were used *i.e.* 70 to 90%SOC (corresponding to home to work daily trip) and 10 to 90%SOC. This study shows that cycling in a wide SOC window decreases the cells' lifetime.
- the storage SOC level. This test simulates the effect of car parking on the cell lifetime. It was shown that high (45°C) and low (0°C) temperatures increases the cell's ageing rate. And low SOC (10%) has the lowest degradation effect compared to 70% and 90%SOC. However it was shown that compared the cells stored at 90%SOC, the ones stored at 70%SOC has a higher degradation rate. Additional ageing tests were started to better understand this behaviour rand will be reported in later reports and SCI papers.

Based on the results of the ageing tests an optimum use condition matrix could be defined to assure an extended and safe cell lifetime.

Also based on the temperature measurements carried out during the tests (on the cell's skin), an optimum thermal management system was designed that takes into account the cell's temperature variation when in use.

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INTRODUCTION

Battery lifetime prognosis is a key requirement for successful market introduction of electric and hybrid vehicles. The method approached in the Everlasting project is based on an accelerated ageing tests. This might differ from real operation conditions but might be used with ageing models. These tests were then designed based on the need of the different other WPs and tasks but especially those dealing with modelling. The design of the experiment has taken into account the data required for models related to aging and cycle life prediction while taking into account the end user application requirements.

1 CELL SELECTION

Based on multiple criteria and in full consensus of all EVERLASTING partners, a commercially available cell has been selected to carry out the different tests and characterisations within this projects. The cell is an 18650 high energy lithium-ion cell from LGChem (INR18650 MJ1). According to the manufacturer data sheet [1] it has a nominal capacity of 3.5Ah and specific energy of 259.6 Whkg^{-1}. The recommended operating voltage window varies between 2.5 and 4.2V.

Analysis performed during this project revealed that this cell is constituted with a nickel (Ni)-rich lithium nickel manganese cobalt oxide (811) positive electrode and graphite based negative electrode with a presence of Si [2].

1.1 DEFINITIONS

SoH: refers in this document to relative remaining capacity based on the 1C CC discharge measured during every (extended and short) check-up test and is calculated as follows:

$$SOH = \frac{C_i}{C_0} \times 100$$

with C_i is the discharge capacity measured at the end of the second standard cycle of the check-up test and C_0 the discharge capacity measured at the end of the second standard cycle of the first check-up test (initial capacity).

Ah throughput : counts the coulombs that go through and out of a cell. Charging and discharging a 3.5 Ah cell at nominal conditions leads to a throughput of 7 Ah.

Equivalent cycle: is calculated by dividing the total capacity throughput by a 1 cycle nominal capacity.

1.2 ABBREVIATIONS

SoC : State of charge.
SoH : State of Health
SCU : Short check-up test
ECU : Extended check-up test
DST : Dynamic stress test (part of the check-up tests)

2 AGEING TEST PLAN

The ageing tests consist of cycle-life tests and calendar ageing tests (also called storage test). During these ageing tests, the charge and discharge current, the cell's ambient temperature and the storage state-of-charge are varied to investigate their effect on the cell's lifetime. The different ageing conditions are described in details in the following sections. To check the test reproducibility, every test is carried out on two cells.

2.1 REFERENCE TESTS

These ageing tests are interrupted at regular intervals to conduct check-up tests to follow up the evolution of the cells' performances over time. As these check-ups are performed only regularly, they should ideally have no impact on the cell's degradation rate. However, a small influence is inevitable. Consequently, the check-up tests should be a compromise between quality of measured parameters and its potential additional ageing effect.

These tests are divided into two types: the extended check-up test (ECU) and the short check-up test (SCU). The ECU is performed before and at the end the ageing test (SoH=80%). Ideally, another ECU is performed at mid-life. The SCU is performed at a more regular interval. In this study it was performed every month. These tests are performed at a room temperature of 25°C. A stabilisation period of minimum of 8 hours and maximum 24 hours is applied before and after the check-up test.
Both check-up tests consist of a nominal capacity test (1C) and a charge and discharge pulse test (30 sec 1C pulses at different SOC levels). However, during ECU, a DST test is added along with a C/20 cycle and discharge capacity test (C/20, C/5, C/2 and 2C) (see ECU voltage profile in Figure 1).

The SOC cycling window is updated after each check-up test with the latest discharge capacity value.

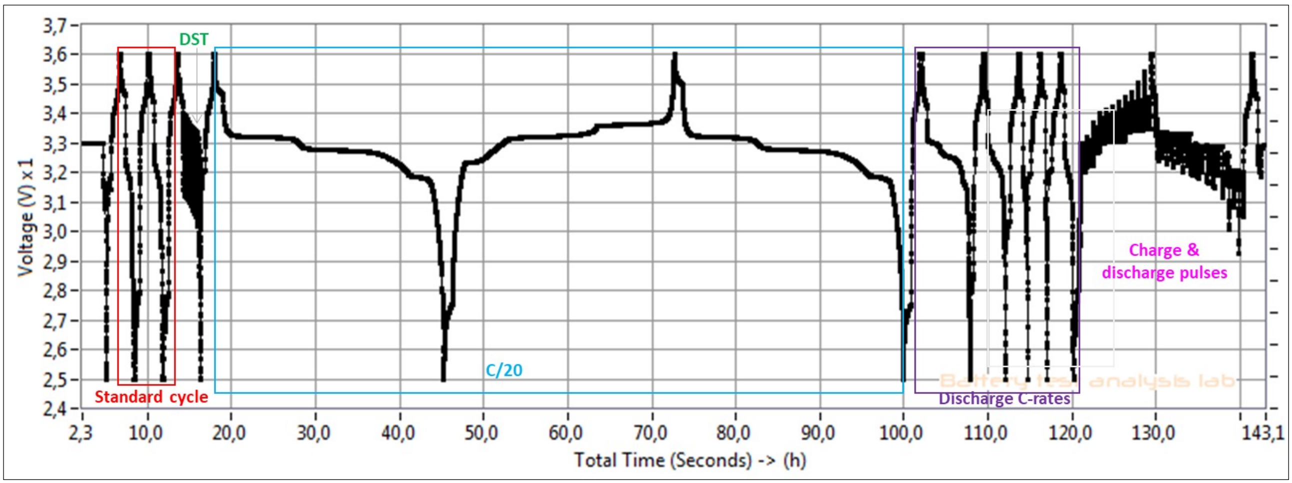

Figure 1 : Description of the check-up tests used during the different ageing tests

The results of the check-up tests were analysed and then stored in an individual Excel file on an Everlasting-server. These results were taken as the basis for the ageing analyses and will be input for the validation of the ageing models.

2.2 LIFECYCLE AGEING WITH REAL DRIVING PROFILES

To better understand the battery degradation behaviour under 'real' conditions, ageing tests are performed using real driving profiles recorded by VOLTIA (project partner) on one of their electric vehicles. These two capacity windows were selected as it represents the two most common automotive use *i.e.* 70-90% SOC which represents most common average daily use and 10-90% SOC which is less common but possible.

For the cells cycling between 70-90% SOC a city pattern was used (the current profile shown on the left side of Figure 2). For the cells cycling between 10-90% a combination of city, highway and intermediate roads is applied (the current profile shown on the right side of Figure 2).
The tests were performed at 4 different temperatures.

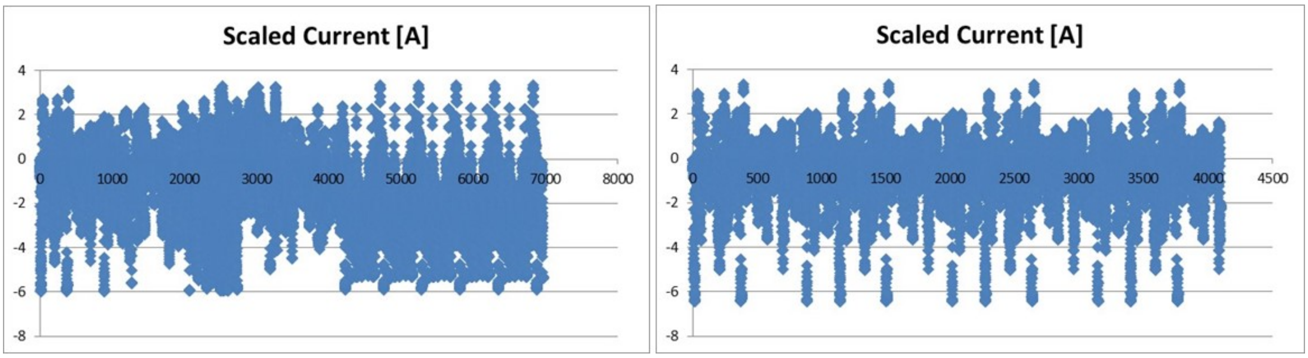

Figure 2 : The driving profiles obtained from the real measurements done by the project partner VOLTIA on their electric van.

Temperature	**I profile 70-90% SOC**	**I profile 10-90% SOC**	**P profile 10-90% SOC**	**Total**
0°C	X2	X2		4 TUV
10°C	X2	X2		4 TUV
25°C	X2	X2	X2	6 VITO
45°C	X2	X2		4 VITO

Table 1: life cycle conditions using driving profiles

2.3 LIFECYCLE AGEING

The lifecycle tests consist of constant current charge-discharge cycles within a 10-90%SOC capacity window. The tests were designed so they have similar capacity throughput per cycle as the tests performed with a driving profile (described above).

Cyclic ageing is performed at the same environmental temperatures as in the driving profile tests: 0°C, 5°C, 25°C and 45°C. Based on input from the end-user specifications and to fulfil the modelling needs, the charge and discharge current rates were varied as described in Table 2 and Table 3.
The test distribution between VITO and TÜV is as described in the tables below.

Due to several interruptions in the testing laboratory, due to maintenance of the battery testers and the climate chambers, the life cycling cells were paused during several days (up to 200 cumulative days) in non-controlled conditions (SOC and temperature). Although the tests are interesting to be analysed as they mix the calendar and the life-cycling parts, it was decided to report in this document only the life cycling tests results without interruptions as those data were used in modelling. The raw data will be however made accessible and will be part of a journal paper.

The tests performed at 0°C and 10°C were also interrupted during several days due to the renovation of the battery laboratory at TÜV SUD. Due to time constraints these tests were not redone.

Discharge C-rate Temperature	**0,5C**	**3C**	**Total**
10°C	X2	X2	4 TUV
25°C	X2	X2	4 VITO
45°C	X2	X2	4 VITO

Table 2: Life cycling with continuous charge and discharge currents with fixed CC-CV charge (C-rate=0.5C)

Charge C-rate (only CC-**CV**) Temperature	**0,5C**	**1C**	**Total**
10°C	X2	X2	4 TUV
25°C	X2	X2	4 VITO
45°C	X2	X2	4 VITO
0°C	X2	X2	4 TUV

Table 3: Life cycling with continuous charge and discharge currents with fixed discharge C-rate (C-rate=1.5C)

The 2 cells with a discharge rate of 3C at 45°C could not be started correctly as the cells heated up too fast. This effect, combined with the environmental temperature of 45°C, raises over-temperature alarms (set at 55°C). These tests were stopped and not restarted.

2.4 CALENDAR AGEING

The calendar ageing tests are performed by storing the cells at a constant temperature and at open circuit voltage (OCV). To have consistent analysis of the ageing behaviour, the cells were stored at 10%, 70% and 90% SoC (*i.e.* same SOC limits as in the life cycle tests). These tests are an extreme representation of the car when it's not in use, *e.g.* when it is parked for hours.

The calendar ageing tests are performed by storing the cells at a constant environmental temperature. The cells are not connected to the battery tester and they are thus at open circuit voltage. The cells are discharged at the different SOC levels with a 1C current.

SOC Temperature	**10**	**70**	**90**	Total
10°C	x2	X2	X2	6 TUV
25°C	X2	X2	X2	6 VITO
45°C	x2	X2	X2	6 VITO
0°C	x2	x2	x2	6 TUV

Table 4: Calendar ageing test conditions.

The SOC level of the executed tests deviates from the defined levels in the table above. The programming of the test regime ended with at CC discharge instead of a CC-CV which resulted in a higher SOC level than originally intended.

Despite that the results are usable, it was decided to redo the test to be able to compare the results of the different partners. In this document only the results of the tests carried with capacity based limits are reported.

3 AGEING TEST RESULTS

3.1 LIFECYCLE AGEING WITH REAL DRIVING PROFILES TEST RESULTS

As explained earlier, two driving profiles were made out of real battery measurements from the VOLTIA e-van. Figure 3 and Figure 4 show the test results where the capacity loss is plotted vs. the total capacity throughput and also the total ageing time. Indeed, when plotted in function of the total capacity throughput little difference is observed between cycling in a 10 to 90%Soc window and a 70 to 90% SOC window. However, when plotted versus the total ageing time it is clear that cycling in a wide SOC window ages the cell faster with a maximum difference of 16% at 45°C (right side of Figure 4).

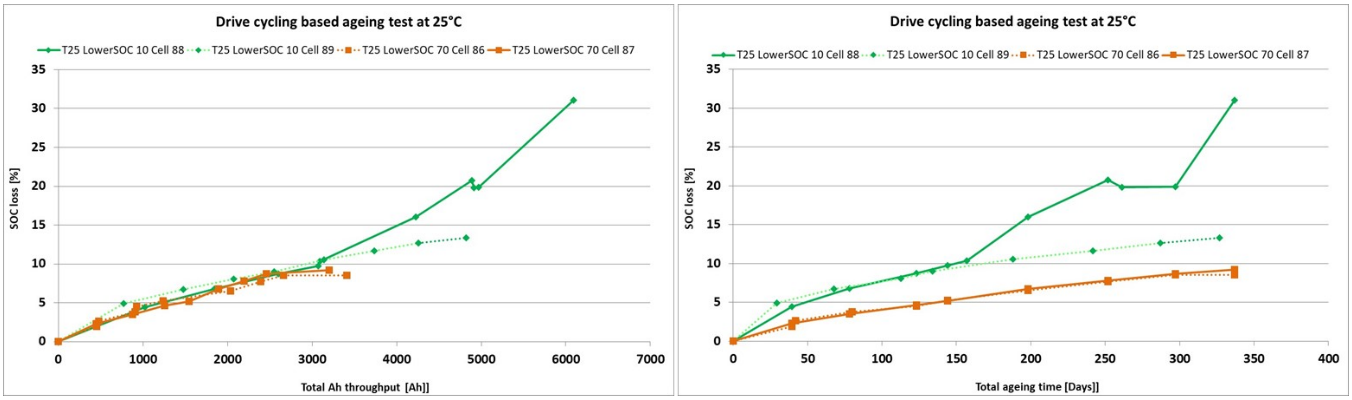

Figure 3 : Evolution of the cell SOH *vs.* Total capacity throughput (on the left) and *vs.* Total ageing time (on the right)

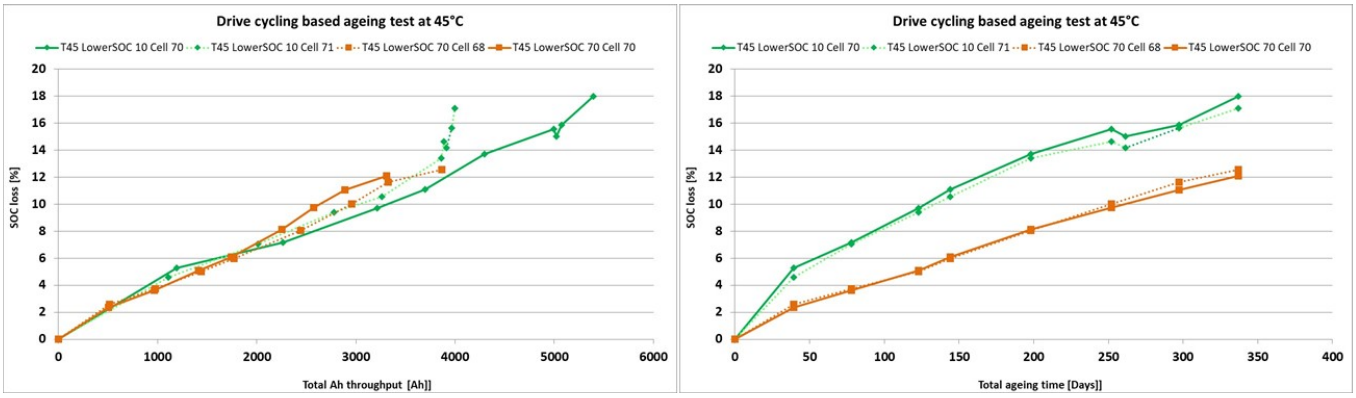

Figure 4 : Evolution of the cell SOH *vs.* Total capacity throughput (on the left) and *vs.* Total ageing time (on the right)

3.2 LIFECYCLE AGEING TEST RESULTS

While writing this report the life cycling tests lasted around 350 days where only 4 cells, cycling at 25°C and 45°C, reached end of life (*i.e.* 80% of the initial capacity) (see Figure 5). Although all precautions were taken to perform the tests in the same exact conditions (same machines, same climate chamber,…) some cells cycling at the same test conditions show different results.

Figure 6 shows the evolution of the SOH of the cells cycled at 25°C in function of the total capacity throughput. The cells cycled with a 3C discharge rate show the fastest rate of degradation compared to the rest of the cells. And as expected the cells cycling at 0.5C show the slowest ageing rate, no clear impact of the C-rates 1.5 and 1C (charge and discharge) on the ageing degradation rate is observed as shown in Figure 6.

The cells cycling at 45°C show different behaviour: the cells cycling at slow C-rates (0.5C during charge and discharge) show higher degradation rate than those for example cycling with a discharge rate of 1.5C and 1C charge rate (see Figure 7). This might be explained with an additional storage-like ageing effect as the C-rate is slow.

The capacity loss of the cells cycled at 10°C can be seen in the Figure 8. The cells cycling at low C-rate 0.5C charge and discharge show a higher degradation rate like the cells cycling at 45°C with 0.5C charge and discharge. The results of the cells cycled at a C-rate of 3C discharge were not comparable. Hence, it cannot be commented that 3C rate degrades the cell faster than lower C-rates at 10°C.

The cells cycled at 0°C showed a faster rate of degradation than comparable tests performed at 10°C. This can be seen in the Figure 9. However, after 6 to 7 months of cycling most of the cells cycled at 0°C and few cells cycled at 10°C showed an abnormal behaviour during the check-up. The cells charged for longer period in the CV phase during the CCCV charge, which resulted in a higher capacity than the nominal capacity (3.5Ah) of the cell. Due to this abnormality, the life cycling tests at 0°C and 10°C were not carried out further.

Although with more than 100 days of rest at room temperature, the cells cycled at 0 and 10°C and with 1.5C discharge and 0.5C charge currents show faster degradation rate compared to the tests at 25°C and 45°C as shown in Figure 10. The cells cycling at 0°C reached end of life after 286 equivalent cycles within the 10-90% SOC window.

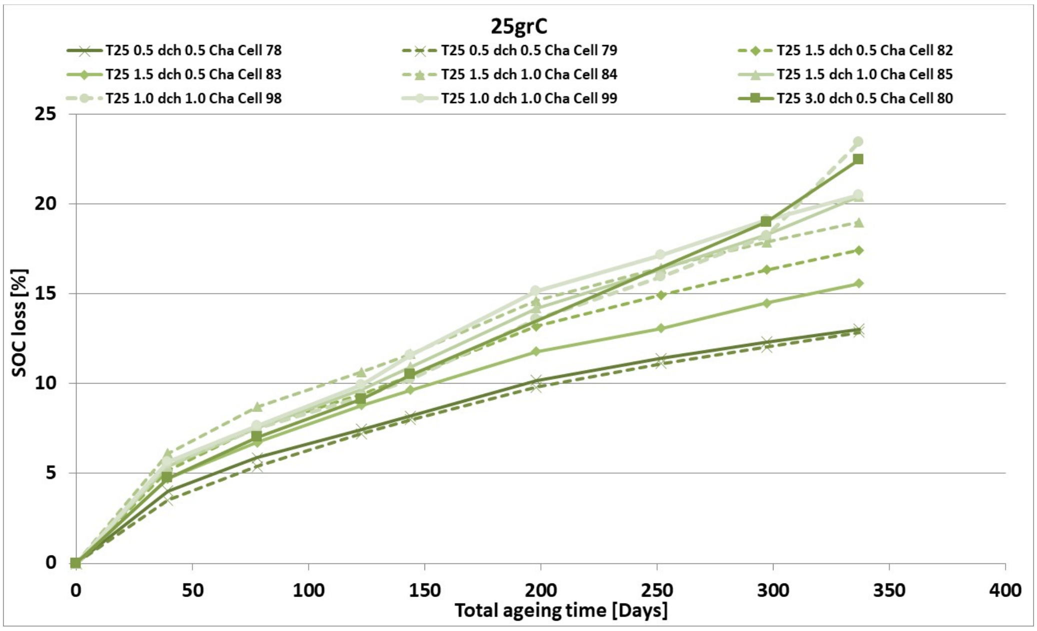

Figure 5 : Evolution of the cells SOH *vs.* Total ageing time during lifecycle test at 25°C

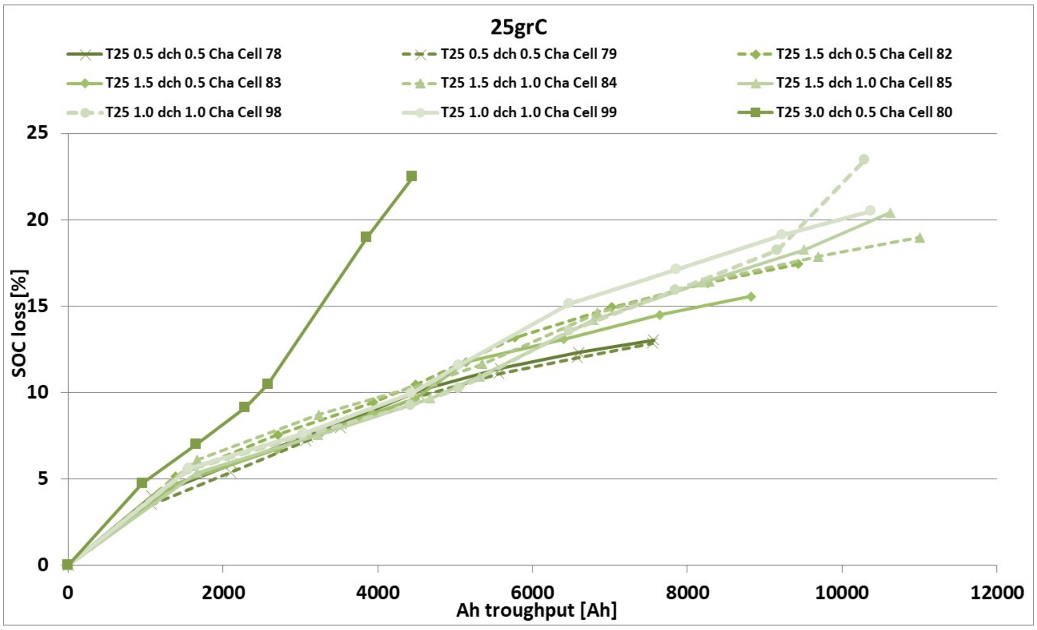

Figure 6 : Evolution of the cells SOH *vs.* Total capacity throughput during lifecycle test at 25°C

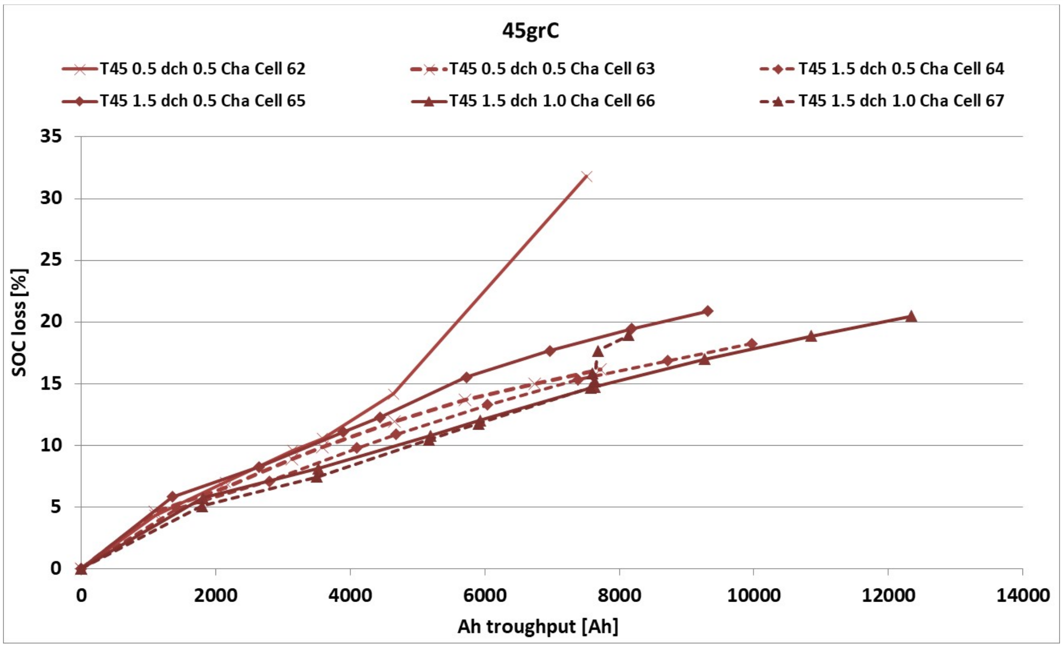

Figure 7 : Evolution of the cells SOH *vs.* Total capacity throughput during lifecycle test at 45°C

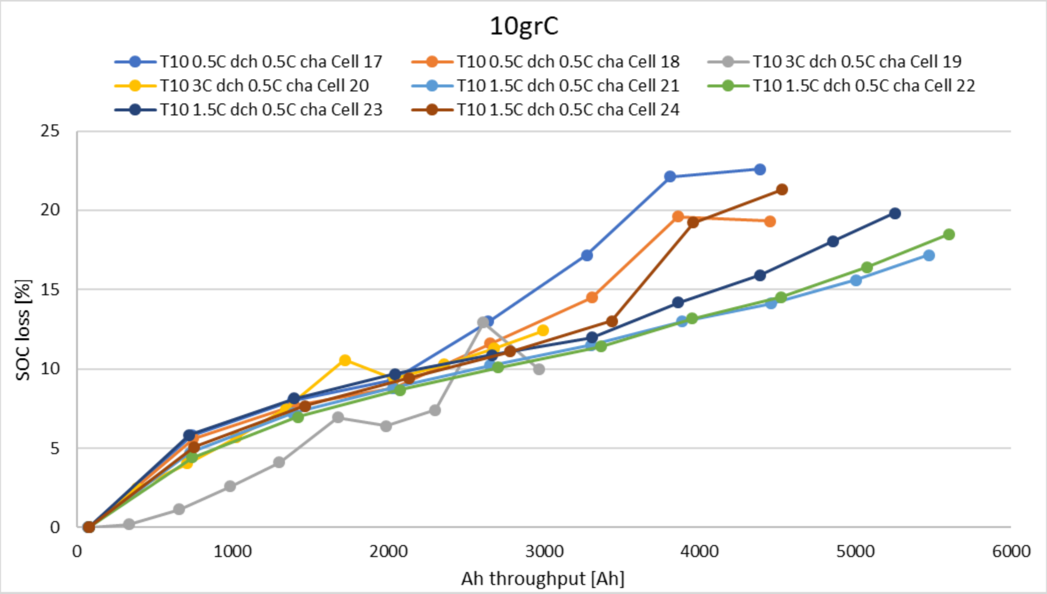

Figure 8 : Evolution of the cells SOH *vs.* Total capacity throughput during lifecycle test at 10°C

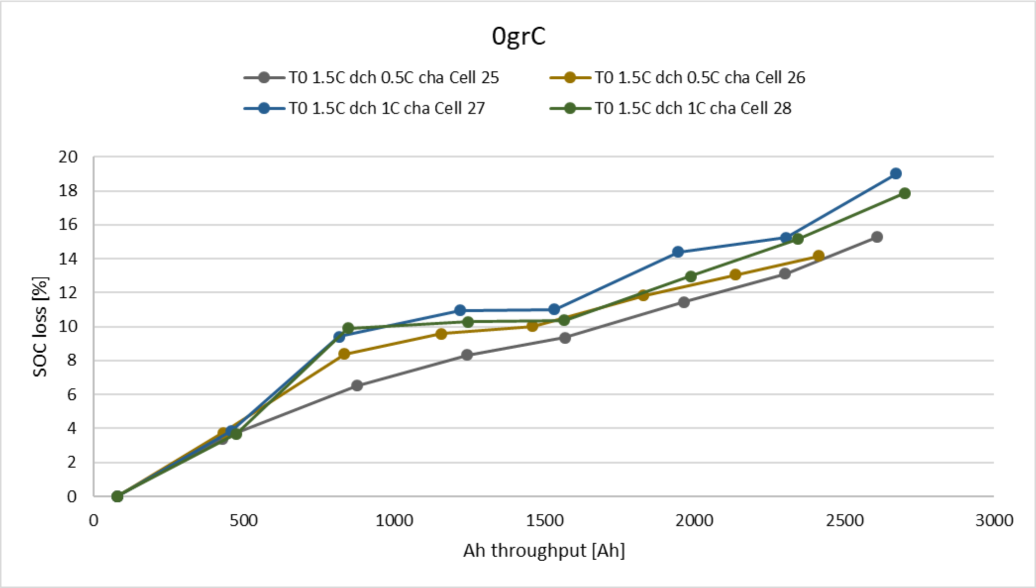

Figure 9 : Evolution of the cells SOH *vs.* Total capacity throughput during lifecycle test at 0°C

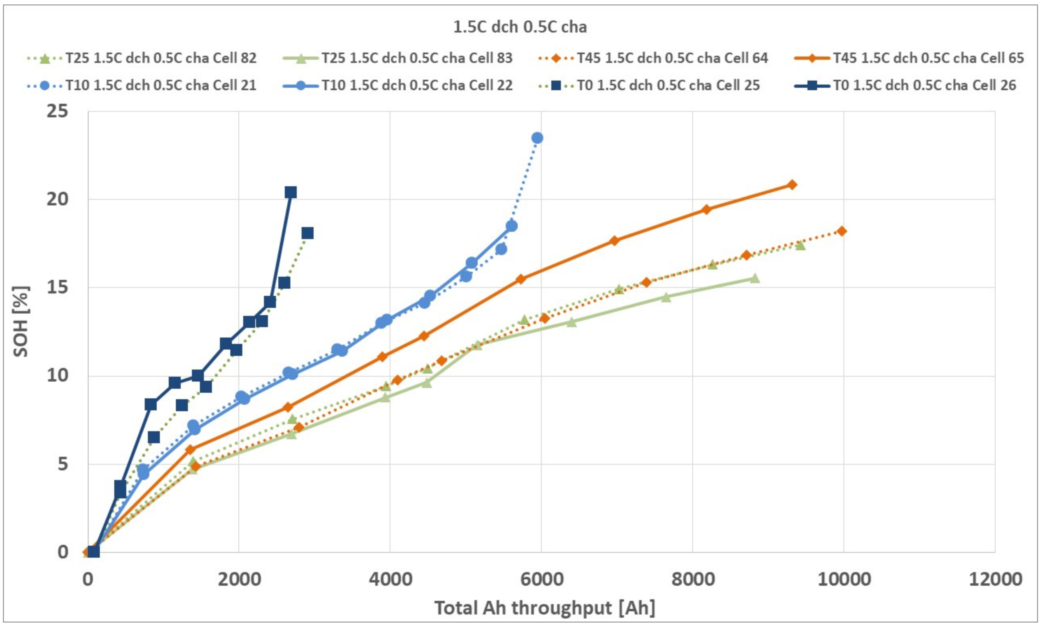

Figure 10 : Influence of the environmental cycling temperature of the cells cycling at 1.5C discharge rate (Tests at 0°C and 10°C have more than 100 days of 'non-planned' rest)

3.3 CALENDAR AGEING TEST RESULTS

The calendar ageing test consists of storing the cell at a defined SOC and at a fixed temperature. Figure 11 shows a comparison between the results obtained at 25°C and 45°C. It's clear that increasing the storage temperature from 25 to 45°C increases the degradation rate. This corroborates with literature studies on NMC/C based cells.

And as expected the cells stored at low SOC (here 10%) show the slowest degradation rate and the environmental temperature seems to have little effect on the ageing rate as shown in Figure 11. However this behaviour is not linear as the degradation rate is the highest at 70% SOC and not at 90% SOC as it would be expected.

It's interesting to note that the results of the tests at 45°C with and without unplanned-long-interruption-periods (total up to 200 days) (Figure 13) show a slight difference (up to 2%) between the ageing rates. This is probably due to the fact that during the interruptions the cells were stored at room temperature (~25°C).

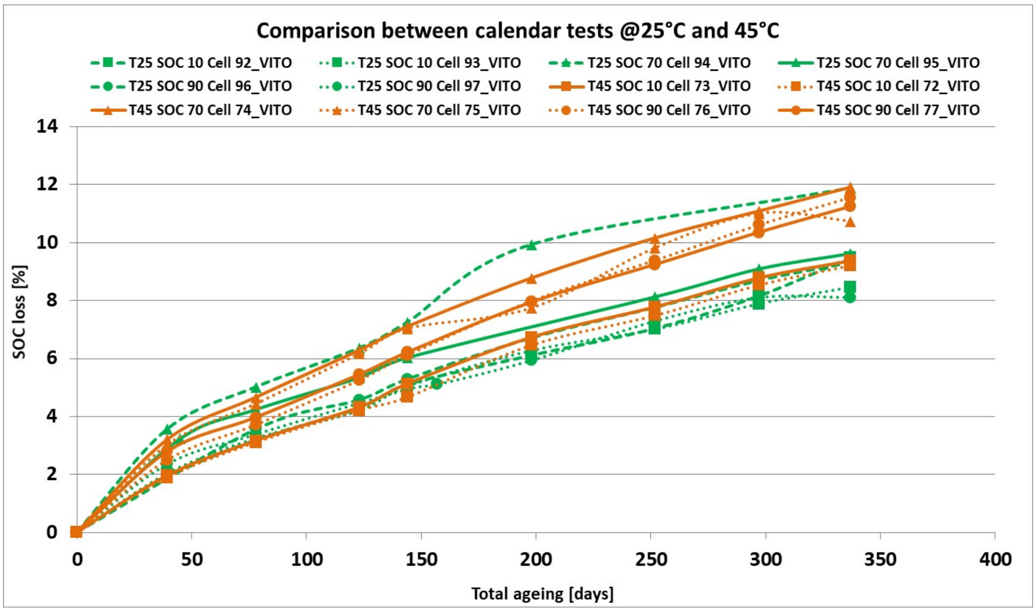

Figure 11 : Comparison between the calendar test results at 45°C and 25°C.

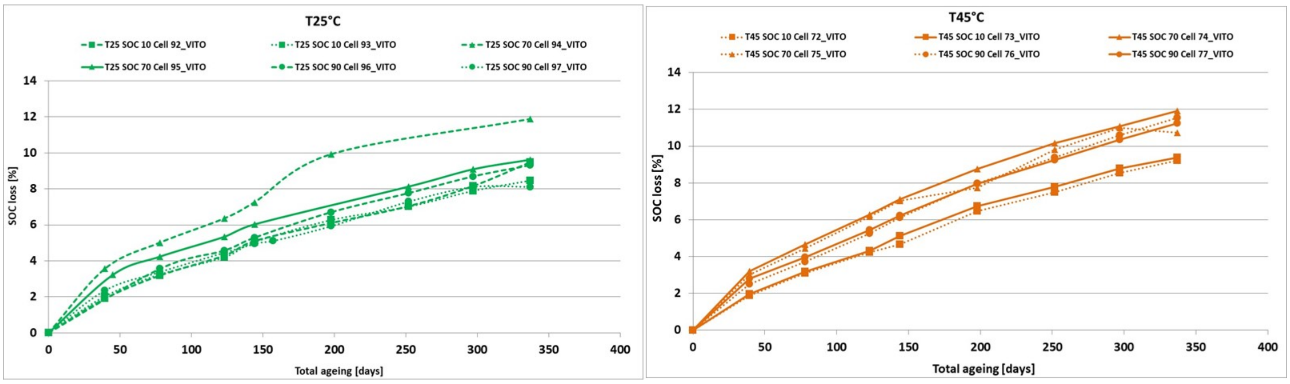

Figure 12 : Evolution of the cells' SOH *vs.* Total ageing time during calendar test at 25°C (on the left side) and at 45°C (on the right side).

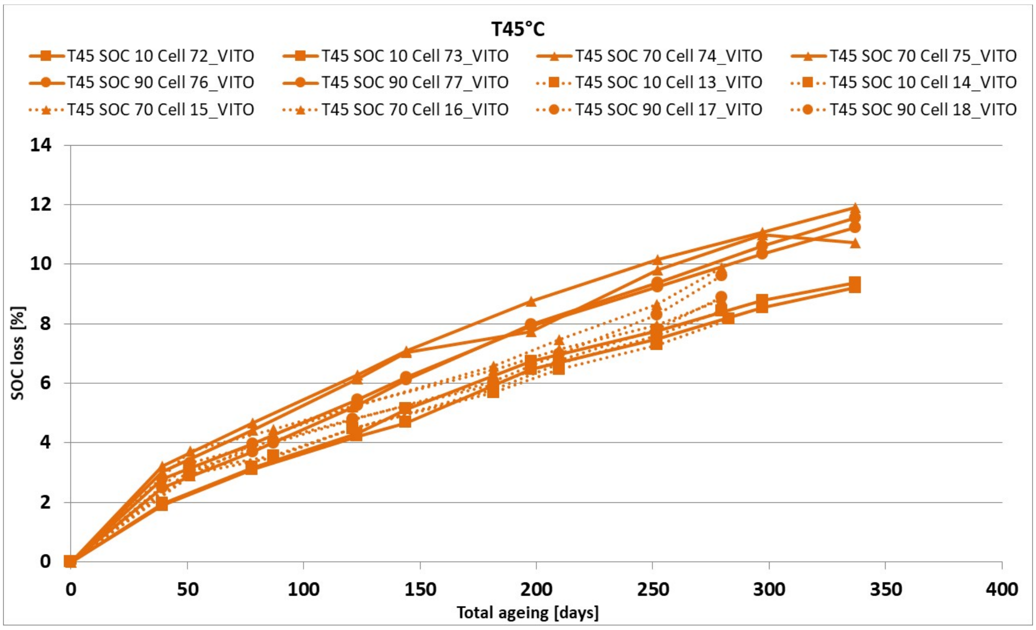

Figure 13 : Comparison between the calendar test results at 45°C with (bold line) and without (dotted line) non-planned-long-interruptions (additional to the planned check-up tests).

Figure 14 and Figure 15 show the ageing behaviour of the cells stored at 10°C and 0°C respectively. A linear loss in the capacity of the cells can be seen until interruptions in the test occurred due to laboratory renovation work at TUV SUD. During that period the cells were stored at RT for around 2-3 months. The capacity loss of the cells with respect to total ageing days is more non-linear after 325 days of uninterrupted tests as shown in the figures. For the purpose of clarity and readability the more non-linear and zigzag pattern results produced after 425 days of storage are not included in the graphs.

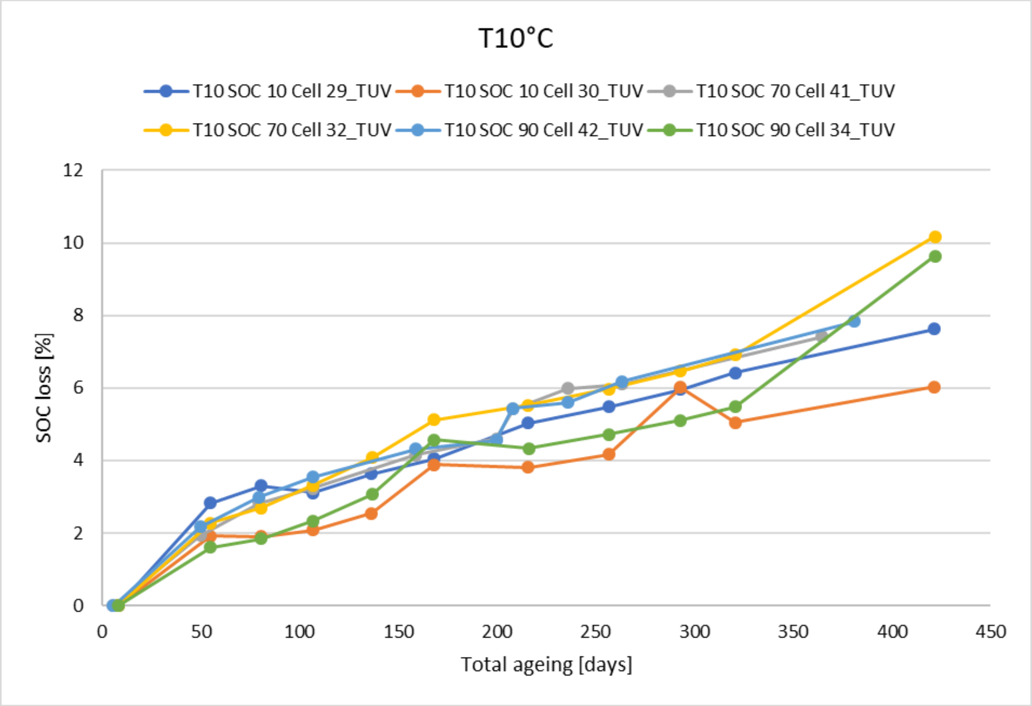

Figure 14 : Evolution of the cells SOH vs. Total ageing time during calendar test at 10°C

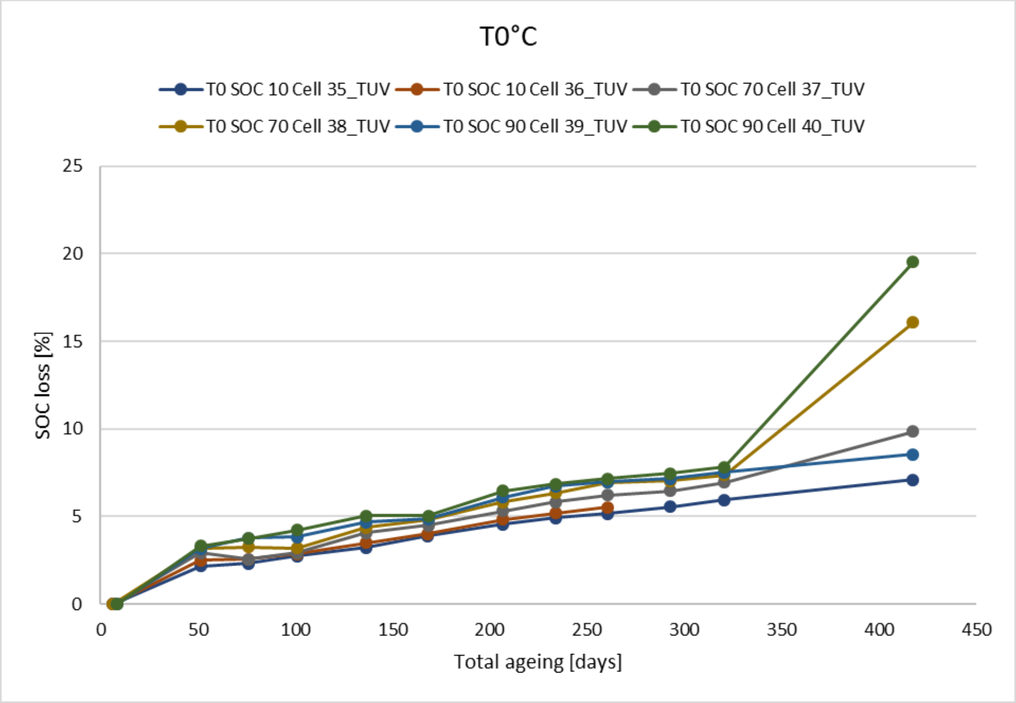

Figure 15 : Evolution of the cells SOH *vs.* Total ageing time during calendar test at 0°C

CONCLUSIONS

The life-cycling results show that high and low environmental temperatures decrease the cell lifetime. Also, high discharge C-rates have a negative impact of the lifetime.

The life-cycling tests using real driving profiles show results close to those obtained with continuous charge and discharge cycles.

The calendar ageing tests showed that decreasing or increasing the environmental storage temperature away from room temperature (25°C) increases the cells’ ageing rate. More tests would be necessary to define the optimum temperature window that would prolong the cells’ lifetime.

However, it was shown that the SOH variation *vs.* the storage SOC has an unexpected kick around at 70% SOC as at this level the cells showed the highest degradation rates at all temperatures. This phenomenon might be explained by the presence of Si in the anode, but this must be confirmed. Thus, additional ageing tests were launched where more SOC levels were added (100%; 80%; 60% and 50%). The results will be reported in future dissemination events.

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