



CT-Coating AG

Joint energy storage cell testing report

performed at

CT-Coating AG

long-time Testreport

- only for internal partners - according NDA

Rev.0.1 of 25/10/2021

Data collection during Lab tests executed between 28/9/2021 and 21/10/2021



CT-Coating AG

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Introduction and Lab setup description

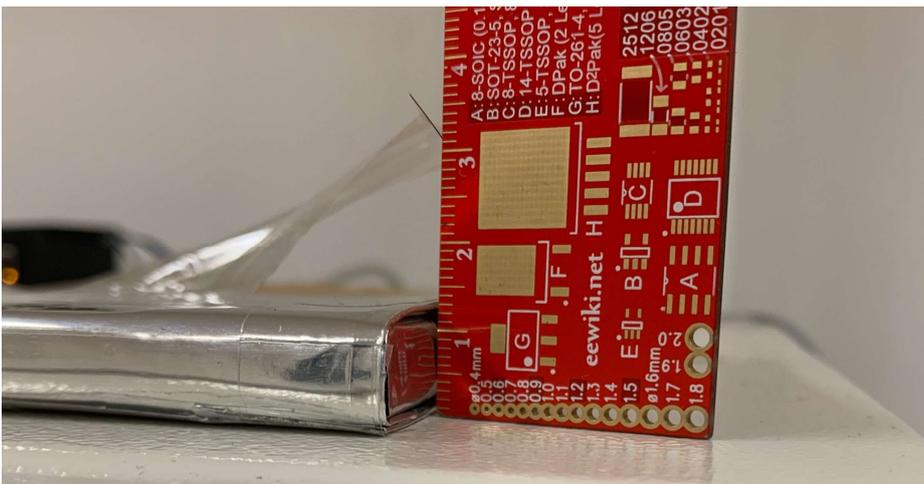
This report describes the tests executed between 28 September and 21 October, inside the interims- lab of CTCAG. Of one energy storage cell, shown in the 3 pictures of next page.

The Lab setup was as follows (picture 1):

- Climatic Chamber model VT-4002 from Vötsch
- Lab Precision Electronic load model PEL-3041 from GW-Instek
- Lab Precision power supply model PSW-30-36 from GW-Instek
- Complete Windows PC (Win10) for the cycling automation and data acquisition trough the battery testing software LinkView from GW-Instek (version: 1.50.08 r210331)
- Linux based Ambiental data acquisition system with following sensors:
 - TMP117 sensor from Texas Instruments for the acquisition of the Cell Temperature (directly applied on the cell)
 - TMP117 sensor from Texas Instruments for the acquisition of the surrounding temperature near to the cell under test
 - BME280 sensor from Bosch for the acquisition of the ambient pression and Relative Humidity near to the cell under test
- An UPS and ethernet Switch for the power supply and connection of all parts



Pictures of the cell under test.



The cell under test inside the climatic chamber. The applied digital thermometer is evident at the center of the cell, the other thermometer and Humidity and Pressor sensors are above the center of the cell.



Temperature sensor: Texas instruments TMP117 board



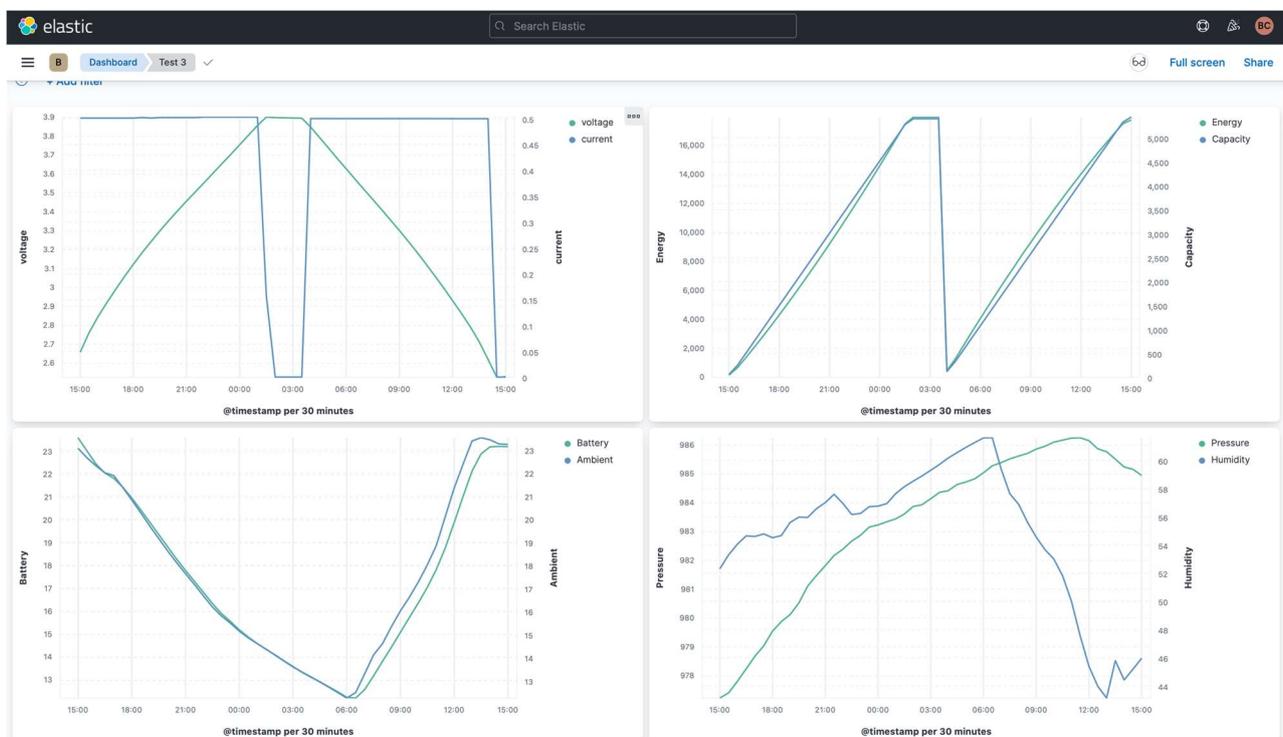
Note: data sheet of the thermometer can be retrieved at: <https://www.ti.com/product/TMP117>

MOU Test no. 1 – One slow Cycle at 0.1C

Test Process Steps:

1. Cell start status Empty (2,5V).
2. Charge with 500mA Constant Current (approx. C/10)
 - CC Start time: 15:15:06
 - CC End time 01:57:10
 - total elapsed time: 38524 seconds
 - total energy transferred: 17885 mWh
3. Charge Constant Voltage at 3,9V (end when C/100 reached = approx. 50mA)
 - CV Start time 01:57:11
 - CV End time 02:05:09
 - total elapsed time: 478 seconds
 - total energy transferred: 80 mWh
4. Pause: 7.200 seconds
5. Discharge with 500mA Constant current to 2,5V (approx. C/10)
 - Start time 04:05:11
 - End time 14:56:53
 - total elapsed time: 39103 seconds
 - total energy transferred: 17770 mWh
 - Total measured capacity: 5432 mAh

Climatic Chamber turned off. Temperature as graphed is ambient room temperature.

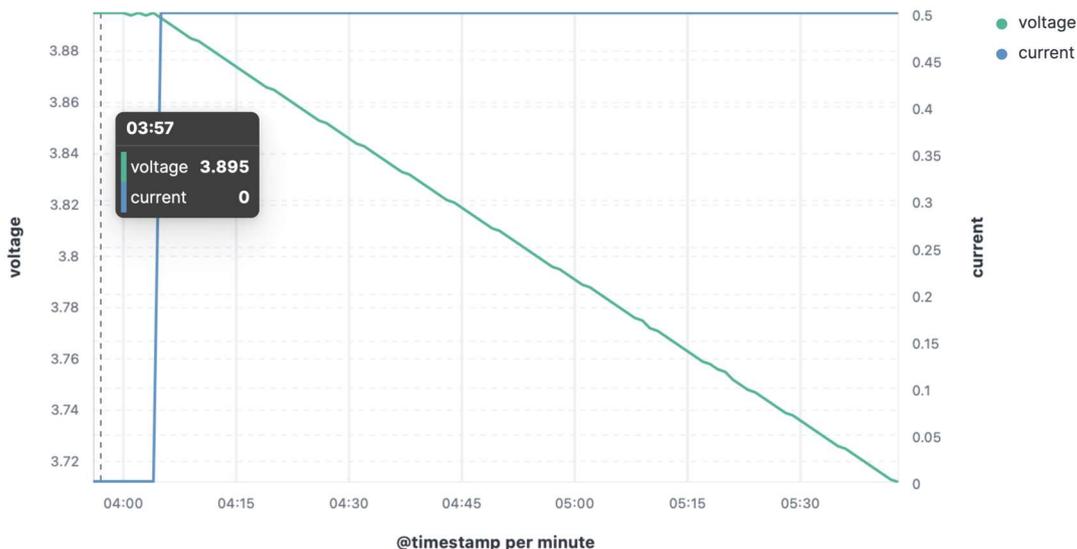


Picture 1. shows the overall test recording on the Sample battery cell. Most important graph is top left: Voltage and Current behavior. From left, first the Charging process then 2 hours of pause then the discharging process. Not like typical electrochemical processes the voltage during both charge and discharge rise and fall in an almost linear way.



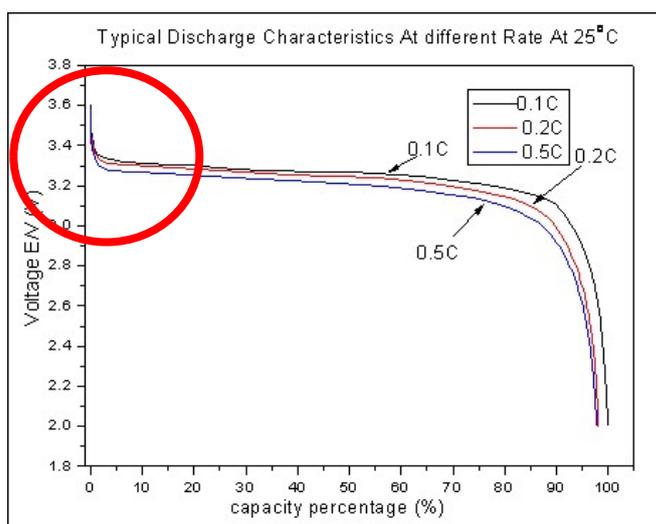
Picture 2. This image shows a closeup view (1) [left] on the data of the last CC charge phase, (2) [center] on the very short CV charge phase and (3) [right] on the first minutes of the 2h long pause (0 current). It is evident that:

- (1) Even in the last minutes of CC phase the very linear voltage growth is maintained: no typical end of charge fast voltage growth, characteristic of electrochemical processes, is visible.
- (2) Once the voltage set for the CC phase is reached, the following CV phase is extremely short (compared to typical electrochemical processes), this means that with no voltage increment almost no additional energy is transferred to the battery at end of CC charge phase.
- (3) in the minutes following the end of charge the voltage remains at the level reached during charge (within few mV)



Picture 3. This image shows a closeup view (1) on the very last minutes of the 0 current pause phase of 2 hours (most left part of picture 3), (2) on the first approx. 90 minutes of the CC discharge phase . It is evident that:

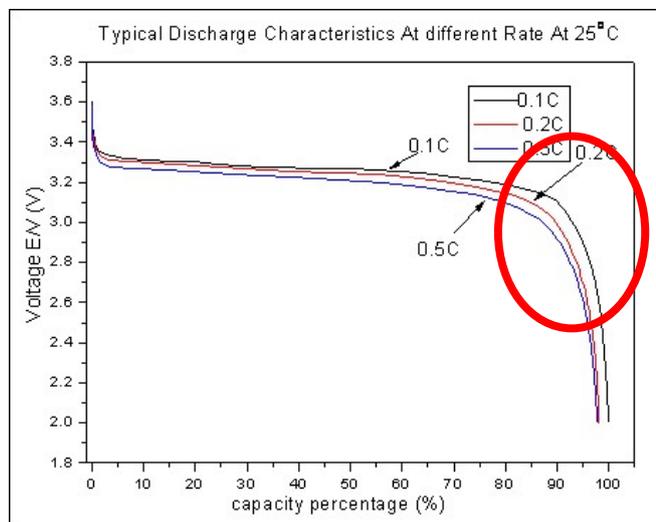
- (1) After 2 hours of pause, after a full charge, status was reached, the voltage remained within 5mV (highlighted), typical electrochemical cells show a relaxation phase of the voltage that drops immediately after end of charge.
- (2) Even in the very first seconds of CC discharge phase the voltage drop is very linear and constant: again not like usual electrochemical processes, where the voltage is rapidly decreasing at discharge start, and remains very constant for long time during the discharge phase; as reference and comparison a complete discharge phase of a Lithium Iron Phosphate (LFP) cell is shown in picture 3.1. In the Red circle the Voltage drop of 300mV at beginning of C/10 discharge is highlighted with the goal of showing the substantial difference to the same period that is Highlighted in picture 3 for the Cell under test.



Pic. 3.1



Picture 4. This image shows a closeup view on the data of the last approx. 90 minutes of the CC discharge phase. It is evident that also in the last discharge phase the voltage is almost linear with a slight flexion only in the very last phase. As reference following picture 4.1 highlights the flexion of Voltage of a typical LFP cell at end of charge (red circle). The difference is very strong, and the behavior of the Voltage of the cell under test resembles the one of electrostatic cells.



Pic. 4.1

MOU Test no. 2 – Charge at 3C, 24h pause, 3C discharge (TWO executions)

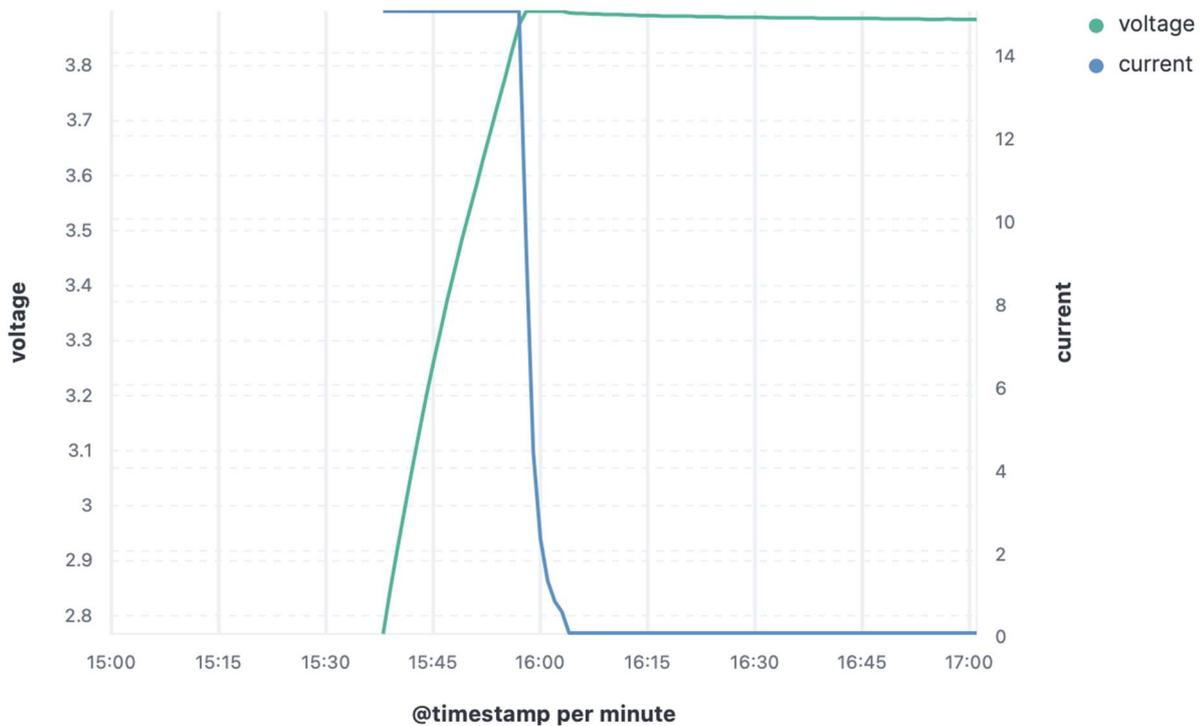
Test Process Steps:

- Cell start status: empty (2,5V).
- Charge with 15A constant current (approx. 3C)
 - CC start time: 13:38:22
 - CC end time 13:58:29
 - Total elapsed time: 1207 seconds
 - Total energy transferred: 17234 mWh
- Charge constant voltage at 3,9V (end when C/10 reached = approx. 500mA)
 - CV start time 13:58:29
 - CV end time 14:04:06
 - Total elapsed time: 337 seconds
 - Total energy transferred: 1253 mWh
 - Total measured capacity (CC+CV): 5340 mAh
- Pause: 24h (NOTE: the terminals of the cell were attached to the test equipment during the pause. Same test has been executed a second time leaving unchanged all parameters, but detaching the terminals during the 24h pause)
- Discharge with 15A constant current to 2,5V (approx. 3C)
 - Start time 14:04:06
 - End time 14:23:29
 - Total elapsed time: 1163 seconds
 - Total energy transferred: 15647 mWh
 - Total measured capacity: 4839 mAh

Climatic Chamber turned off. Temperature is ambient room temperature.



Picture 1. Shows the overall test recording of the sample battery cell. From left: first the fast 3C charging process, then 24 hours of pause (current in blue is 0 and cell voltage in green is almost constant) then right the discharging process at 3C speed. Unlike typical electrochemical processes the voltage after the charge is terminated remains within few millivolts.



Picture 2. This image shows a closeup view (1) [left] on the data of the whole CC charge phase, (2) [center] on the very short CV charge phase and (3) [right] on the first 60 minutes of the 24h long pause (0 current). It is evident that:

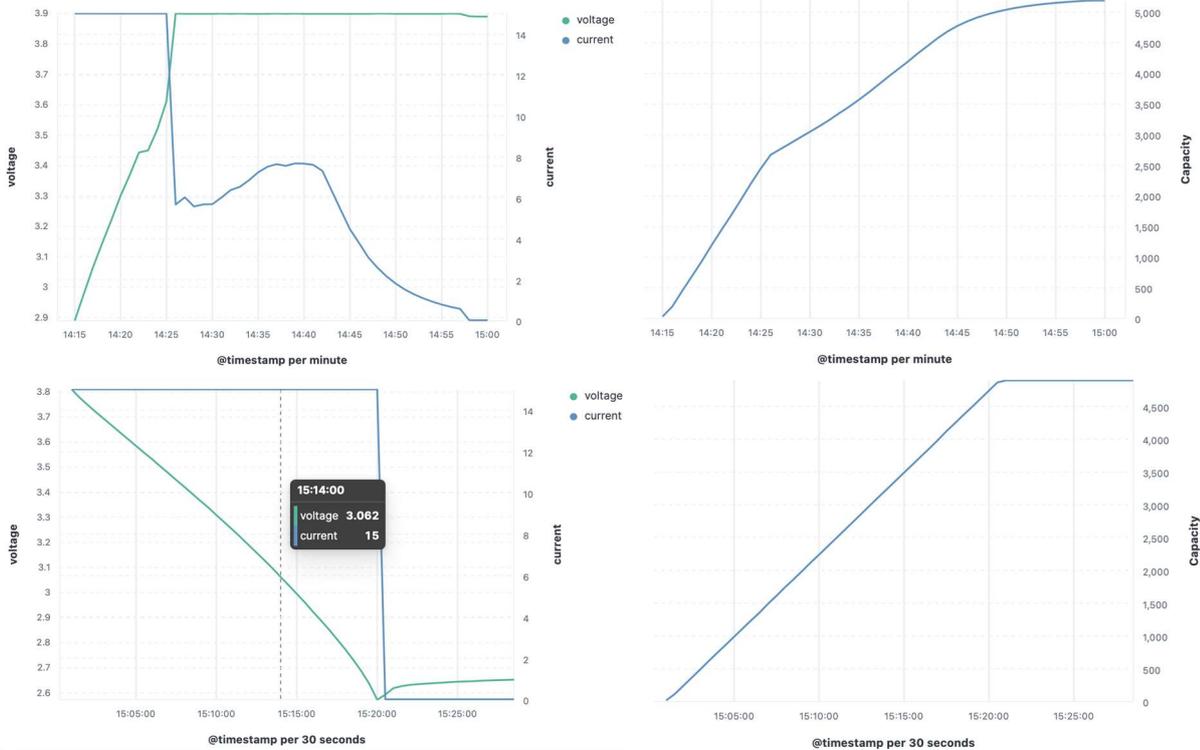
- (1) The CC charging phase has a quite linear voltage growth (green)
- (2) Once the voltage set for the CC phase is reached (3,9V), the following CV phase is short (compared to typical electrochemical processes): the current (blue) is dropping very quickly.
- (3) During the minutes following the end of charge, voltage remains at the level that was reached during charge. There is no sudden voltage drop, as happens usually with electrochemical processes.



Picture 3. This image shows a closeup view (1) on the last 15 minutes of the 0 current pause phase of 24 hours, (2) on the whole CC discharge phase. It is evident that:

- (1) After 24 hours of pause, the voltage dropped only 32mV (highlighted in the box), while typical electrochemical cells would show a relaxation phase of the voltage that drops immediately after end of charge.
- (2) Even in the very first seconds of CC discharge phase the voltage (green) drop is linear and continues almost constantly during the whole discharge process that ends at 2,5V.

A second execution of the same MOU Test 2 has been run (after the execution of MOU Test 6), with the complete detachment of the cell from the test devices; Following the graphs and results:



Picture 4. First two pictures show a second run of the 3C charging (executed after MOU Test 6 was terminated), followed by two pictures of a 3C discharge exactly 24h after the charge. During the pause the terminals of the cell were detached from the test equipment.

- The total charged capacity was in this run of 5185mAh
- The total discharged capacity after a pause of exactly 24h (with terminal detached) was of 4895mAh

These 2 values match well with the values acquired with the first run of the same test. Considering the not perfectly known initial condition of the cell and the very fast charge and discharge processes chosen for this test, it's not possible to state that the difference among these values is caused by self discharge.

Comment:

In both executions of this particular test, with the goal to evaluate the 24h loss of charged energy (self discharge), the charge and discharge speeds were set too fast to be able to appreciate in a correct way the "self discharge" effect.

The small value of the lost energy for a self discharge effect was too tiny to be shown through a so fast charge and discharge. The initial condition of the cell has an important impact compared to the searched value, and the integration (on which this test is based) introduced noises due to the very fast execution of the phases of charge and discharge (= smaller number of samples).

If a very slow charge and discharge (like 0.1C) speed had been chosen, the effect of the initial condition of the battery and the effect of the noise on the integration would have been probably much smaller than in this runs, permitting a more readable result about the searched value.

MOU Test no. 3 – 300 Cycles at 3C

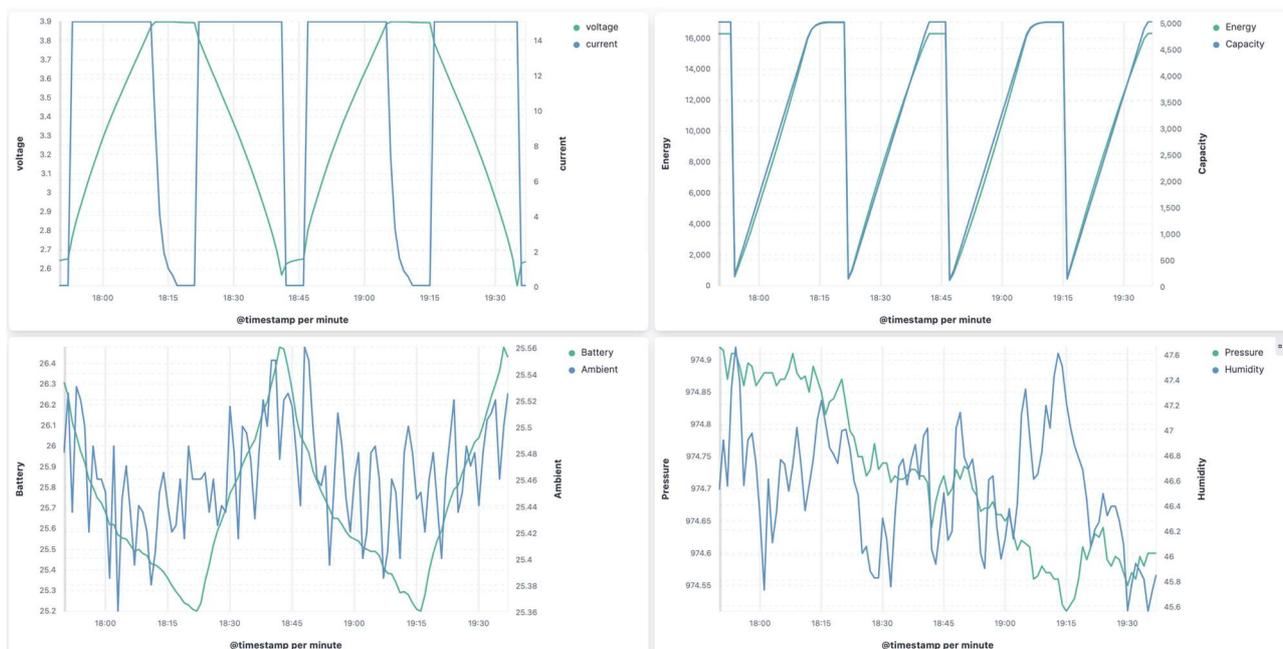
Following Test Process was repeated 300 times :

- Cell start status: empty (2,5V).
- Charge with 15A constant current (approx. 3C)
- Charge constant voltage at 3,9V (end when aprox. C/10 reached = 500mA)
- Pause: 5min
- Discharge with 15A constant current to 2,5V (approx. 3C)
- Pause: 5min

Climatic Chamber ON at 25 °C.

The following 4 Pictures show each two complete cycles taken:

- at the beginning of the test (1st October between aprox. 17.52 and 19.36)
- at approx. 25% of the test (4th October between aprox. 6.16 and 8.06)
- at approx. 70% of the test (9th October between aprox. 4.36 and 6.26)
- at end of the test (12th October between aprox. 19.20 and 21.10)



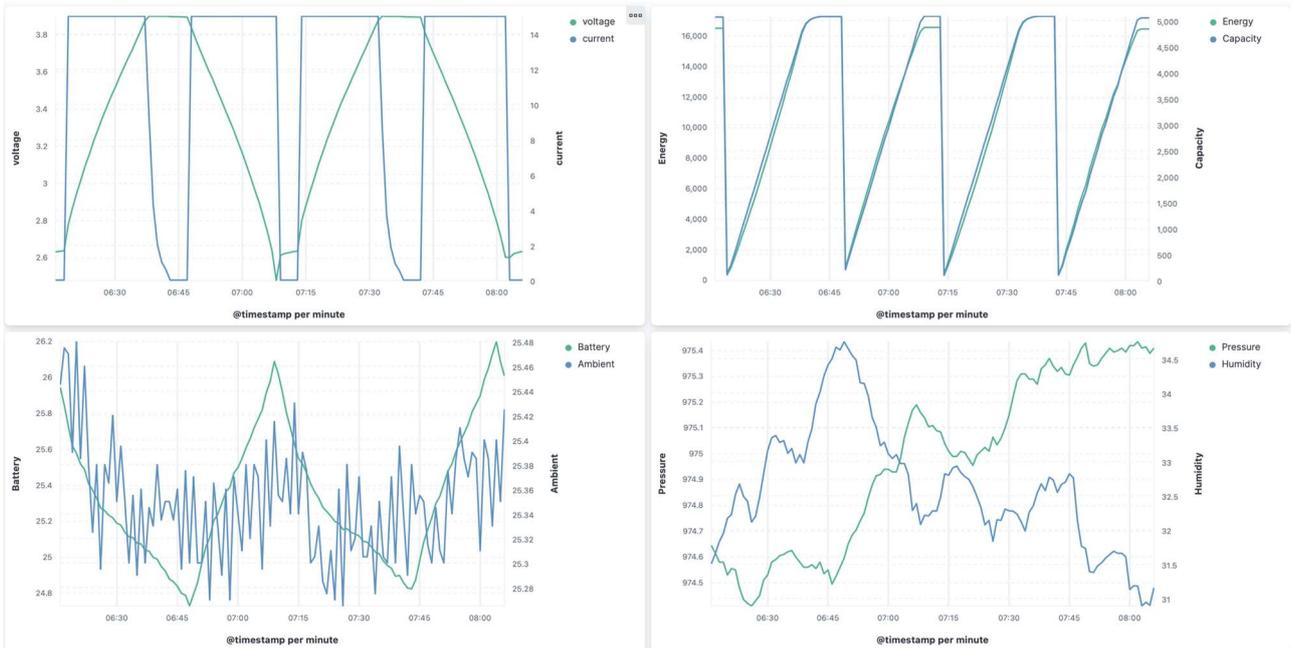
Picture 1. Two example cycles at beginning of the test:

The average Charged capacity in these 2 cycles was: 4,99 Ah

The average Charged energy in these 2 cycles was: 17,06 Wh

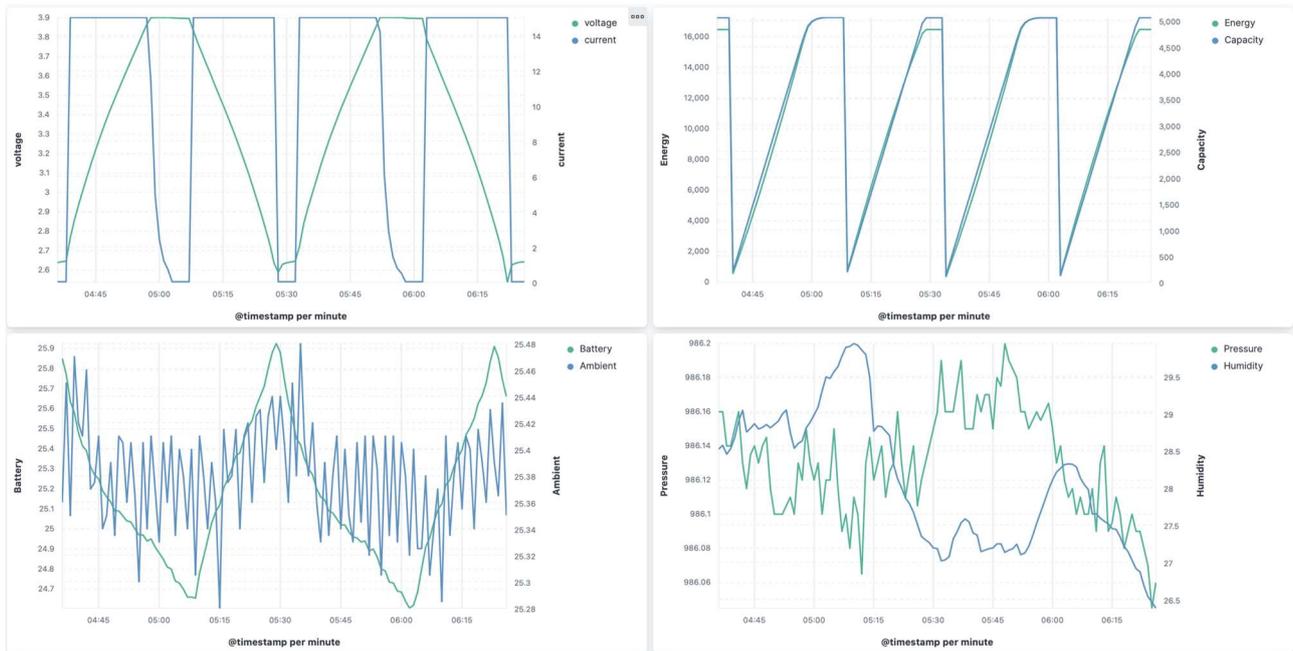
The average Discharged capacity in these 2 cycles was: 5,00 Ah

The average Discharged energy in these 2 cycles was: 16,31 Wh



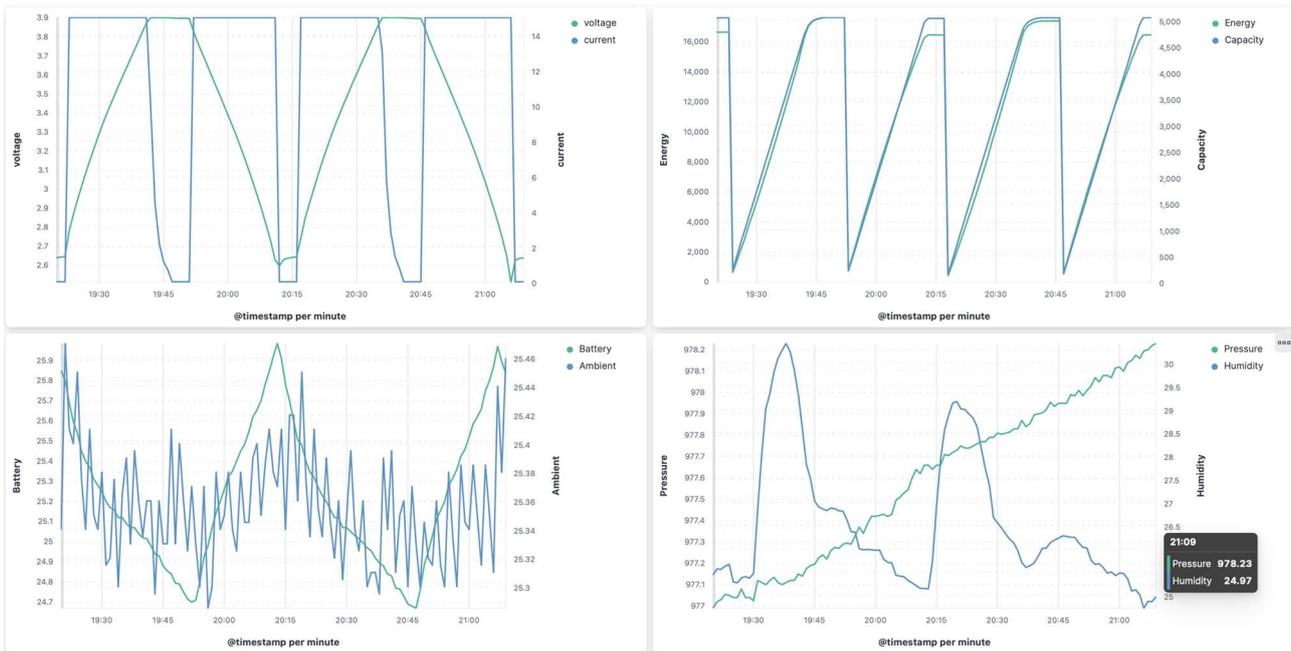
Picture 2. Two example cycles at aprox. 20% of the test:

The average Charged capacity in these 2 cycles was: 5,08 Ah
 The average Charged energy in these 2 cycles was: 17,29 Wh
 The average Discharged capacity in these 2 cycles was: 5,06 Ah
 The average Discharged energy in these 2 cycles was: 16,51 Wh



Picture 3. Two example cycles at aprox. 70% of the test:

The average Charged capacity in these 2 cycles was: 5,05 Ah
 The average Charged energy in these 2 cycles was: 17,24 Wh
 The average Discharged capacity in these 2 cycles was: 5,05 Ah
 The average Discharged energy in these 2 cycles was: 16,47 Wh



Picture 4. Two example cycles at the end of the test:

The average Charged capacity in these 2 cycles was: 5,05 Ah

The average Charged energy in these 2 cycles was: 17,50 Wh

The average Discharged capacity in these 2 cycles was: 5,05 Ah

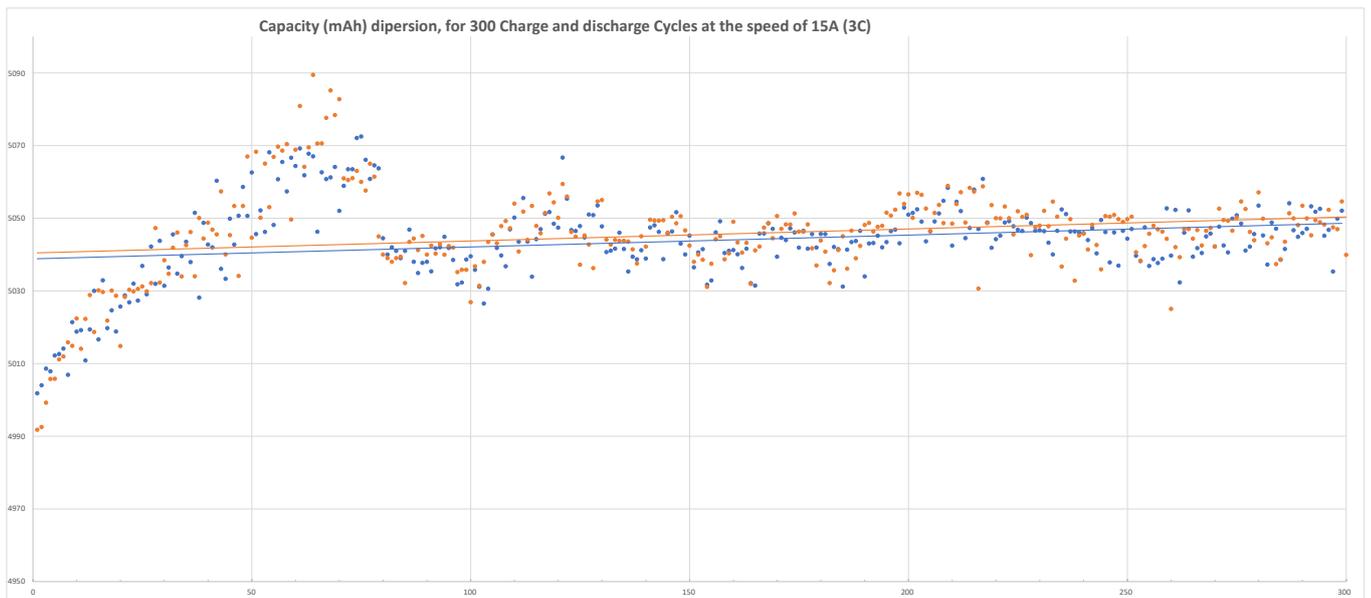
The average Discharged energy in these 2 cycles was: 16,46 Wh

This data acquired with the available instruments shows a consistent and stable behavior of the tested cell during the whole period of 300 cycles.

The calculation of the Capacity (Ah) does not show any degradation, comparing end with beginning capacity. The test duration of 300 cycles, even at the given high rate of 3C, was not able to show a degradation of capacity beyond the measurement fluctuations due to the noise introduced by the instruments and the available sampling rate.

To appreciate a degradation with this test setup, in order to use this to estimate the life expectation of the cell, a much longer test is advisable.

Next picture 5. explains graphically the results of the entire tests.



Picture 5. Charged Capacity (Orange dots) Discharged Capacity (Blue dots) dispersion graph, all 300 Cycles.

Fitting Lines:

In Red the 5th grade polynomial fitting is highlighted.

In Orange the linear fit for the Charged Capacity trough the 300 Cycles

In Blue the linear fit for the Discharged Capacity trough the 300 Cycles

As already introduced in the previous pages by the numerical data, here the fitting shows a very small increase of capacity, if comparing first and last cycles of the test: due to this fact it's impossible, without executing many more cycles, to identify the magnitude and moment of initial degradation of the capacity, related with the natural and inevitable aging of the cell.

For the same reason it's not possible to use this data to extrapolate the life expectation of the cell, since it's not known after how many cycles the capacity of the cell will trend downwards and with what rate. This behavior, under the harsh 3C conditions, is not typical for other storage devices (electrochemical cells) and induces to suppose that the expected life is probably much higher than that of usual storage cells.

MOU Test no. 4 – 100 Fast cycles at aprox. 6C

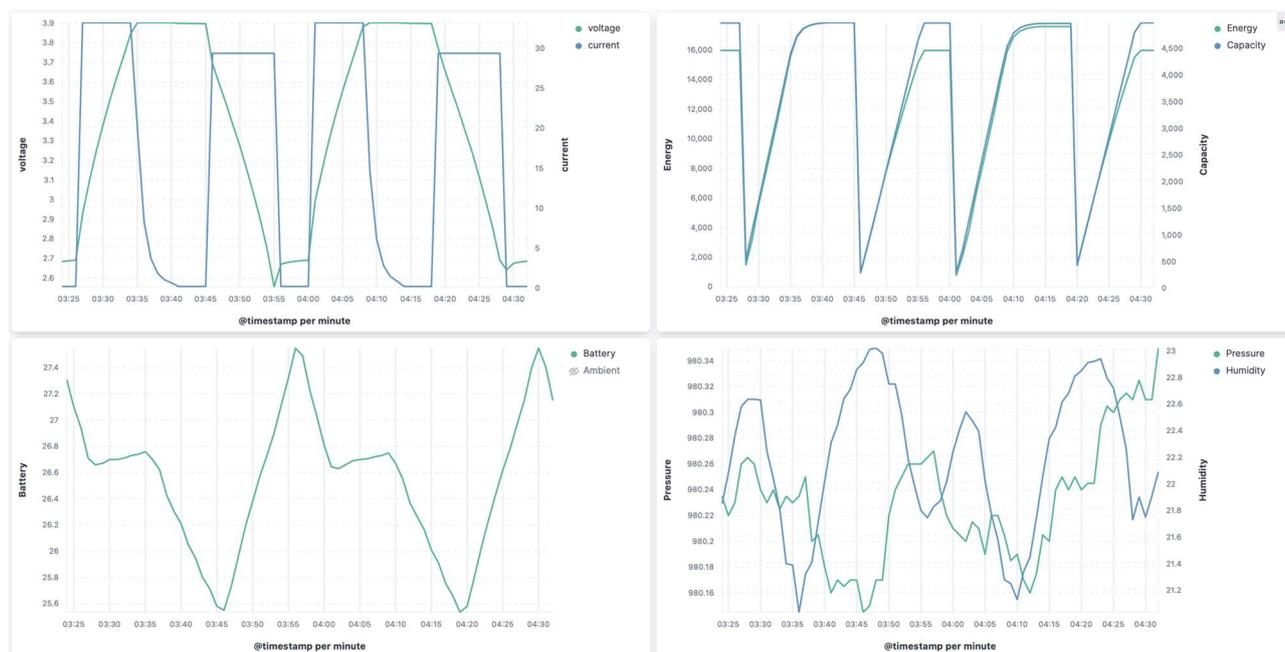
Following Test Process was repeated 100 times :

- Cell start status: empty (2,5V).
- Charge with 33A constant current (approx. 6C)
- Charge constant voltage at 3,9V (end when C/10 reached = approx. 500mA)
- Pause: 5min
- Discharge with 29,2A constant current to 2,5V (6C)
- Pause: 5min

Climatic Chamber ON at 25 °C.

The following 3 Pictures show two complete cycles taken:

- at the beginning of the test (13th October between 3.20 and 4.20)
- at approx. mid of the test (14th October between 5.05 and 6.20)
- at end of the test (15th October between 8.00 and 9.10)



Picture 1. Two example cycles at beginning of the test:

The average Charged capacity in these 2 cycles was: 4,94 Ah

The average Charged energy in these 2 cycles was: 17,71 Wh

The average Discharged capacity in these 2 cycles was: 4,95 Ah

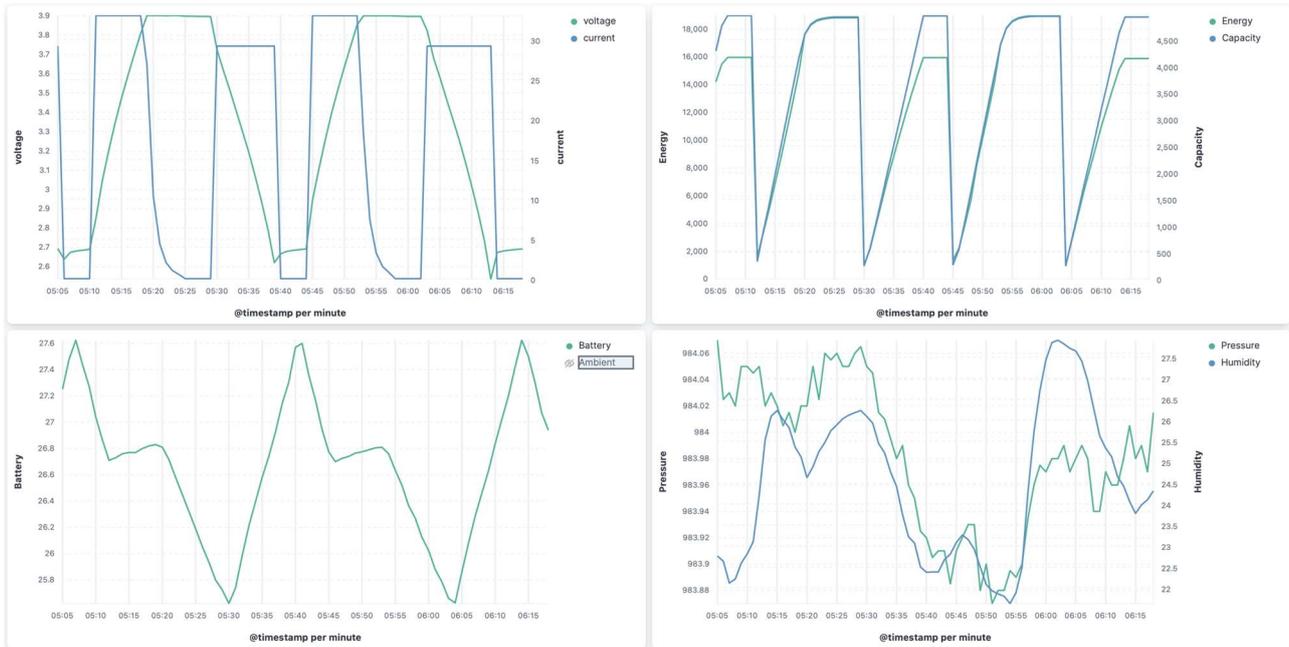
The average Discharged energy in these 2 cycles was: 15,97 Wh

Note about the temperature behavior: the rate is sustained (at least if compared with industry standard

electrochemical battery cells) and in relation to this rate, the oscillation for a full cycle of the temperature is 2°C.

The peculiar aspect is that the temperature is almost not increasing during the CC charge, and is decreasing at exactly the same rate during CV charge and during the pause (current = 0A).

Almost all heat emission is during the discharge phase.



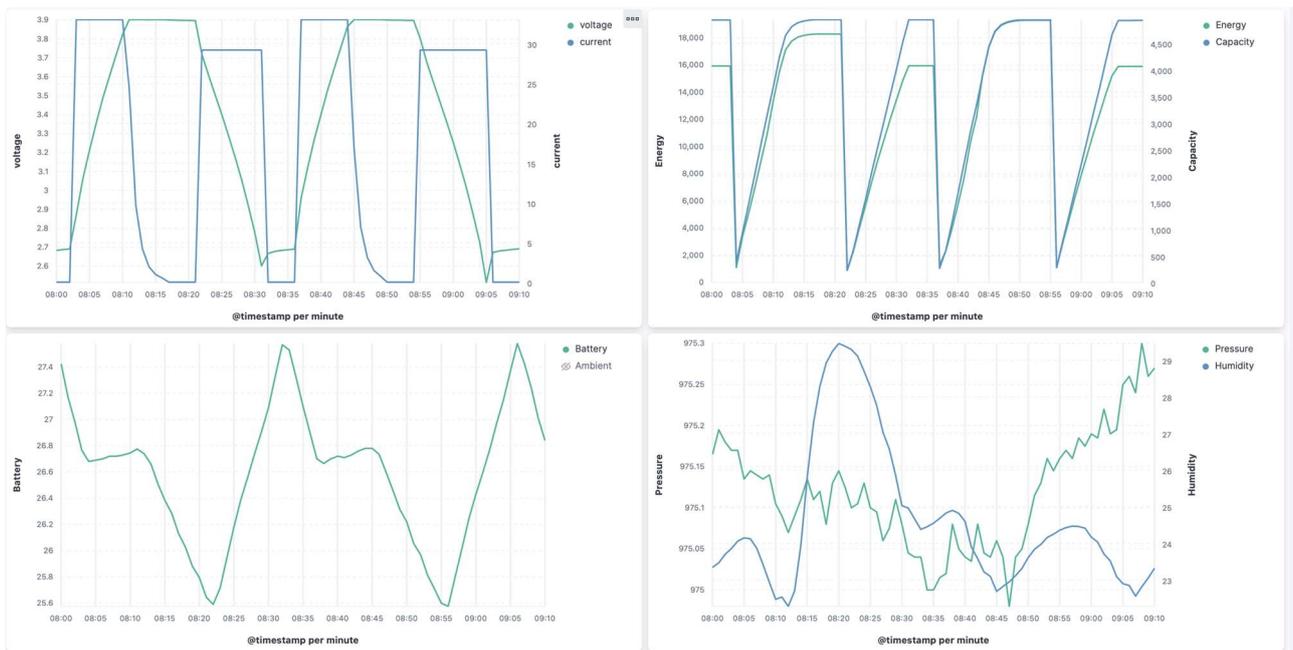
Picture 2. Two example cycles at mid of the test:

The average Charged capacity in these 2 cycles was: 4,92 Ah

The average Charged energy in these 2 cycles was: 18,93 Wh

The average Discharged capacity in these 2 cycles was: 4,93 Ah

The average Discharged energy in these 2 cycles was: 15,91 Wh

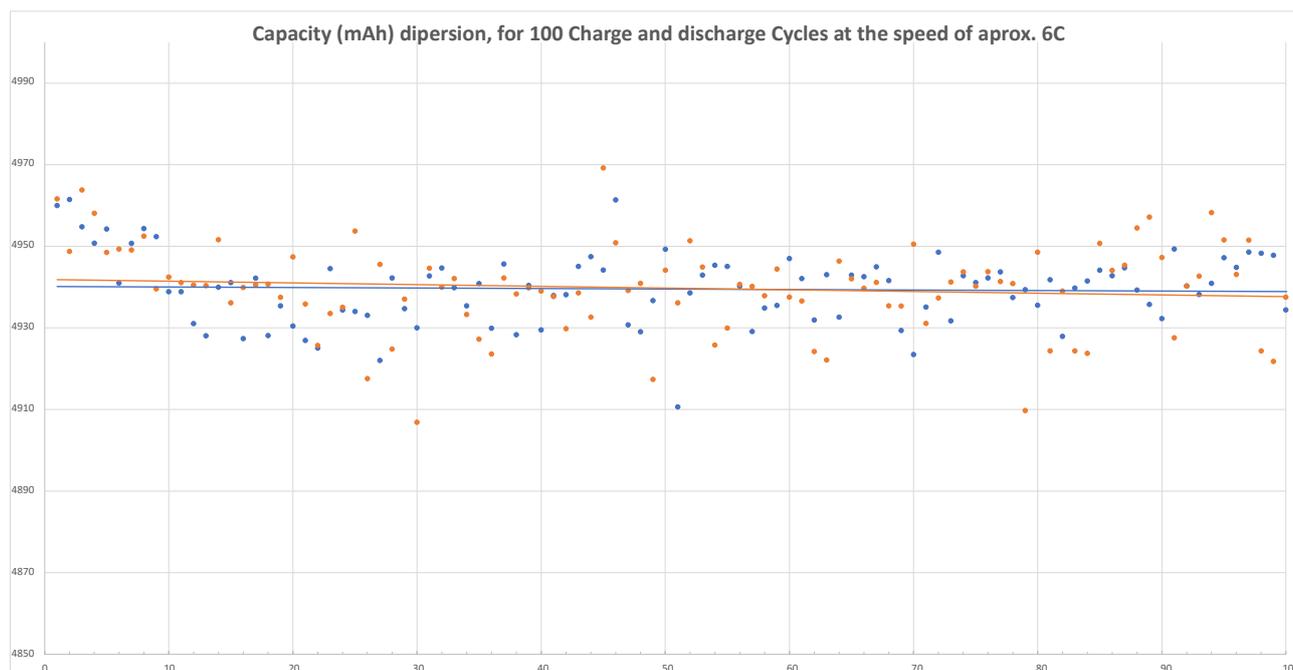


Picture 3. Two example cycles at the end of the test:

The average Charged capacity in these 2 cycles was: 4,95 Ah
 The average Charged energy in these 2 cycles was: 18,80 Wh
 The average Discharged capacity in these 2 cycles was: 4,94 Ah
 The average Discharged energy in these 2 cycles was: 15,92 Wh

The data acquired during this test, with the available instruments, shows a consistent and stable behavior of the tested cell during the whole period.

The calculation of the Capacity (Ah) does not show relevant degradation, comparing end with beginning capacity: the test duration of 100 cycles was not able to show a degradation of capacity beyond the measurement fluctuations due to the noise introduced by the instruments and the available sampling rate.



Picture 4. Charged Capacity (Orange dots) Discharged Capacity (Blue dots) dispersion graph, all 100 Cycles.

Fitting Lines:

In Red the 5th grade polynomial fitting is highlighted.

In Orange the linear fit for the Charged Capacity trough the 100 Cycles

In Blue the linear fit for the Discharged Capacity trough the 100 Cycles

With the gathered data the fitting lines show an almost constant capacity during the test: due to this fact it's impossible, without executing more cycles, to identify the magnitude and moment of initial degradation of the capacity.

It's not simple to explain the initial small but fast reduction of capacity (left of the graphic): since the magnitude of this reduction is small (< than 0,5%) it could be due to the initial condition of the cell prior of beginning or due to initial heating, or due to other Ambiental conditions, or due to other noises introduced by the sampling process.

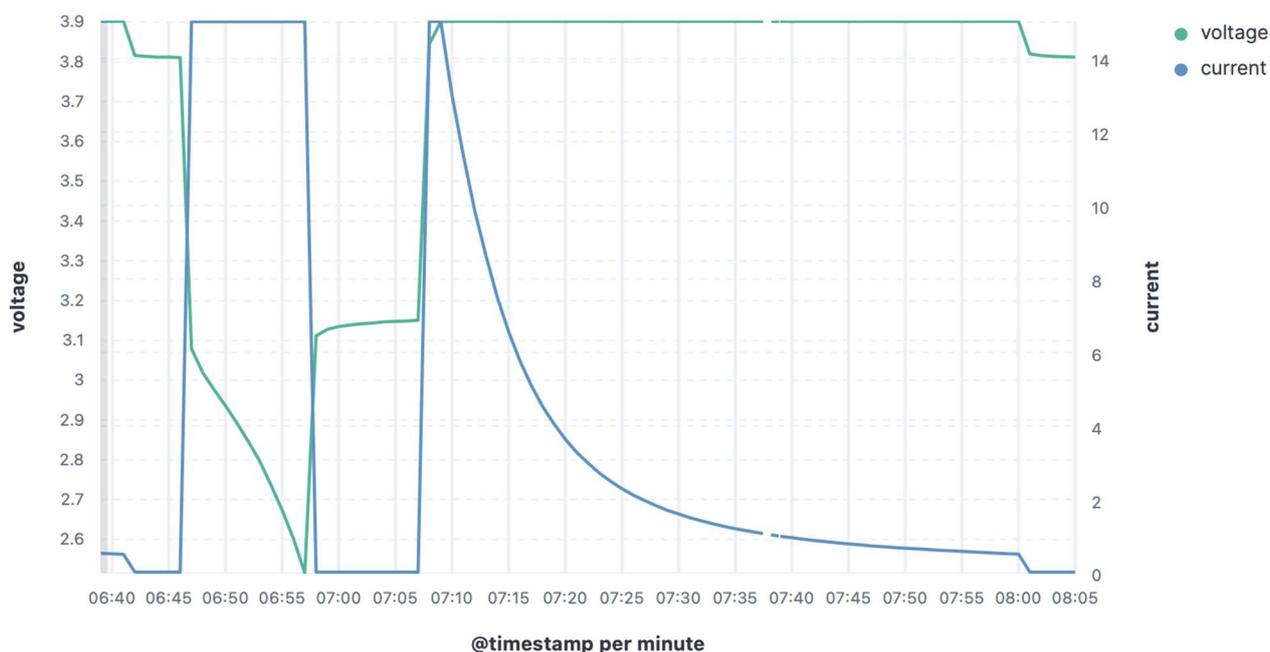
After that small initial decrease the capacity remains almost constant. A much higher count of cycles would help to identify a trend, that with only 100 cycles remains buried in the inevitable noise and fluctuation, that anyway is less than 1% on all these 2x100 measure points.

MOU Test no. 5 – Cold test: 10 cycles at 3C at a temperature of -20°C

Following Test Process was repeated 10 times at the extremely cold temperature of -20°C:

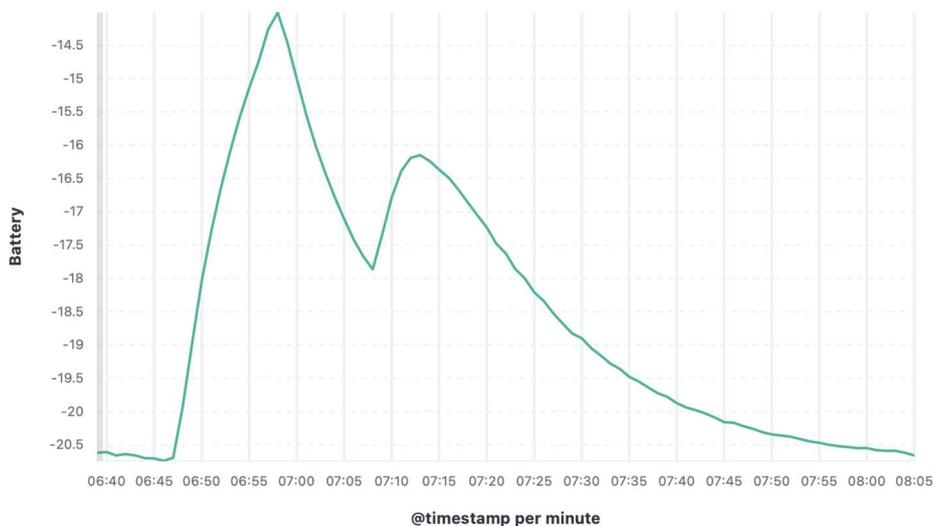
- Cell start status: empty (2,5V).
- Charge with 15A constant current (nominal 3C)
- Charge constant voltage at 3,9V (end when C/10 reached = approx. 500mA)
- Pause: 5min
- Discharge with 15A constant current to 2,5V (nominal 3C)
- Pause: 10min

Climatic Chamber ON at -20 °C.

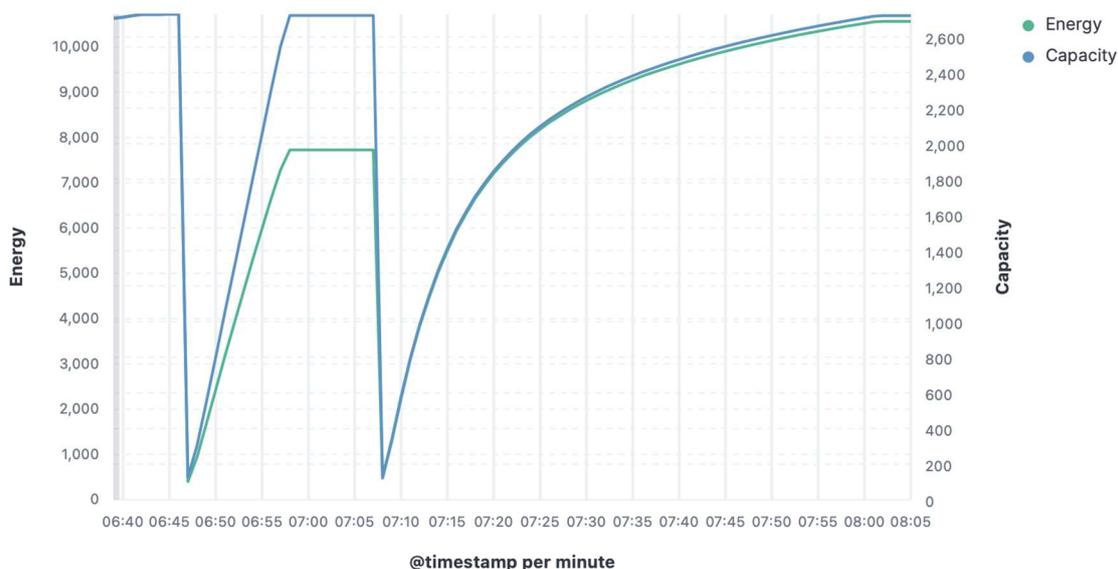


Picture 1. Shows the entire cycle at the end of the 10 executed: here in this graph starting from a fully charged status, left the discharge phase, then 10min pause (with 0,65V of voltage bounce when load is detached) followed by a rather long charging phase where the CC is maintained little time and all following process is in CV going to right margin.

This overall picture shows a voltage and current behavior that is substantially different than at standard temperature. Immediately evident is that the discharge phase is rather short (total discharge capacity was 2720mAh (from 6:47:17 to 6:58:08)). The voltage bounce during the following pause is 650mV. The Charging CC phase at 15A begins at 7:08:10 and transitions to CV at 07:10:02. Thereafter follows a relatively long CV phase that shows that the cell is not able to maintain a so rapid charge phase at this extremely temperature. The CV phase ends at 8:01:54. The total charged energy was again 2719mAh.



Picture 2. Shows the exact temperature profile during the examined cycle. This picture shows a rapid heating during discharge. Followed by a drop during the pause, a sharp increase during the short CC charge phase, ending with a long and smooth drop during the CV charge phase.

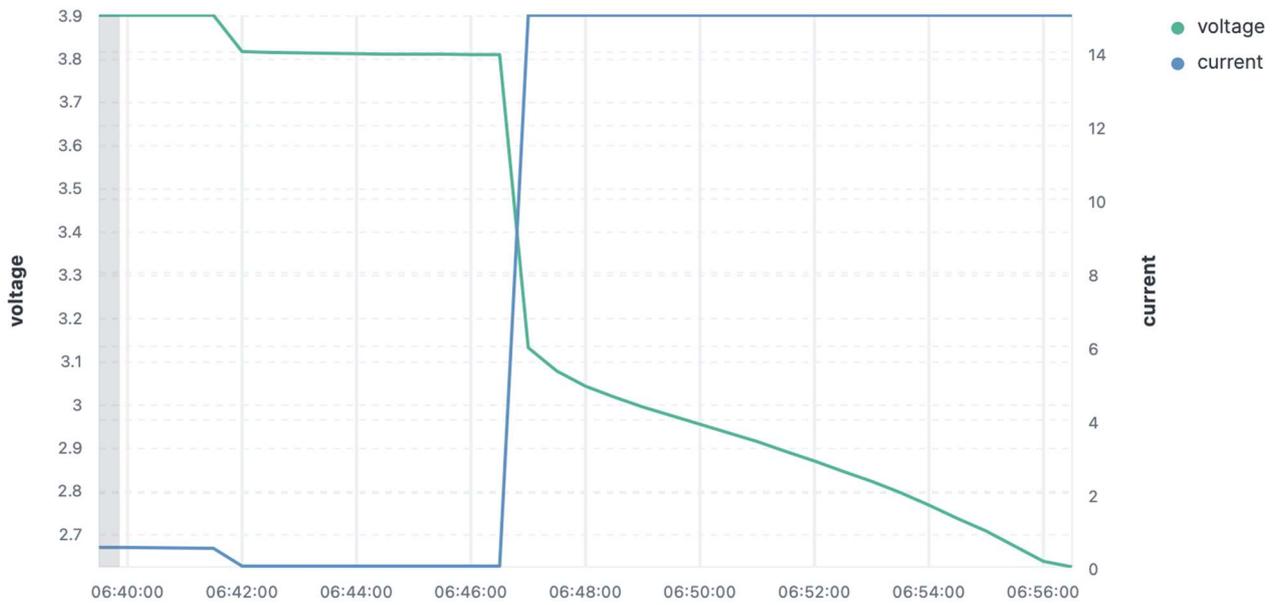


Picture 3. Shows the energy and capacity integrals through the test.

Capacity (blue line) shows an equal end of charge and end of discharge value.

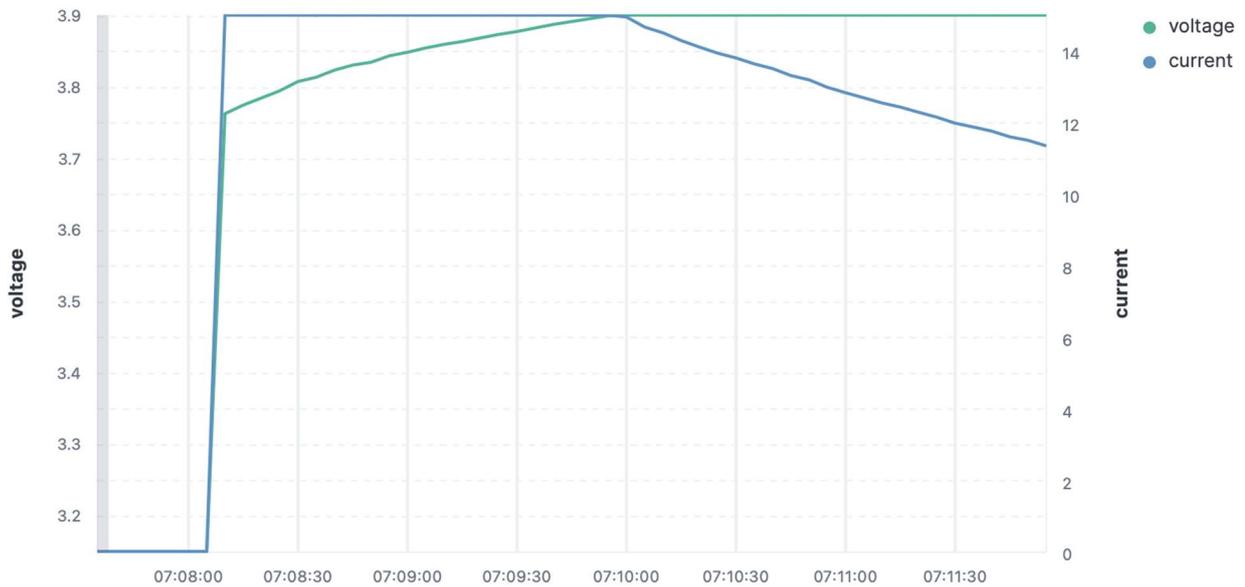
Discharged energy was: 7727 mWh

Charged energy was: 10566 mWh



@timestamp per 30 seconds

Picture 4. Shows the CC discharge phase and the sharp voltage drop attaching the 15A load.



@timestamp per 5 seconds

Picture 5. Shows the short CC 15A charge phase lasted only a couple of minutes.

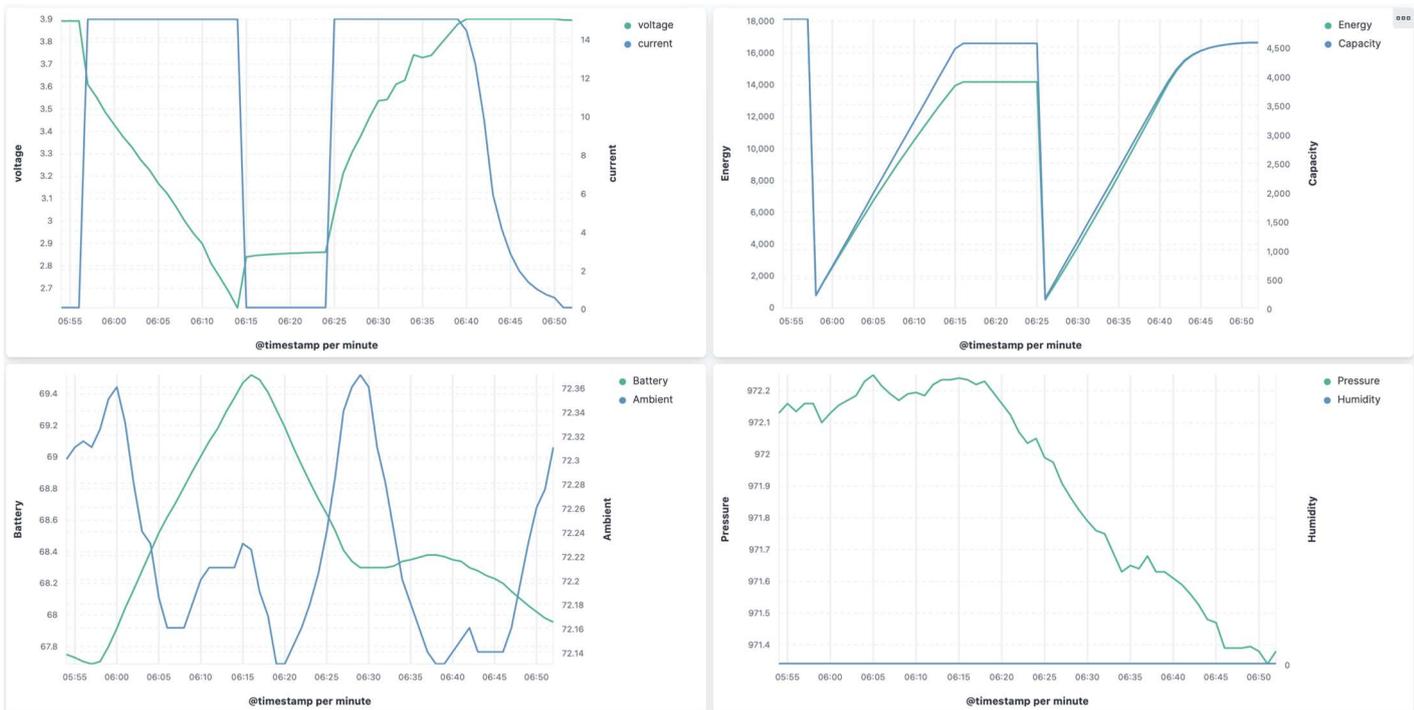


MOU Test no. 6 – High temperature test: 10 cycles at 3C at a temperature of aprox. +72°C

Following Test Process was repeated 10 times at the extremely high temperature of +72°C:

- Cell start status: empty (2,5V).
- Charge with 15A constant current (nominal 3C)
- Charge constant voltage at 3,9V (end when C/10 reached = approx. 500mA)
- Pause: 5min
- Discharge with 15A constant current to 2,5V (nominal 3C)
- Pause: 10min

Climatic Chamber ON at +72°C.



Picture 1. In the top left quadrant, shows one entire cycle at the end of the 10 executed: in this graph, starting from a fully charged status, left the discharge phase, then 10min pause (with aprox 0,35V of voltage bounce when load is detached) followed by a rather long charging phase divided in CC and CV in similar proportions. The top right quadrant shows the exchanged energy (green line) and calculated capacity. The bottom left quadrant shows the temperature increasing during discharge, decreasing during the 10 min pause, stable during the 15A CC charge and decreasing again during the CV charging.

The Discharge starts at 05:57:38 with a CC discharge at 15A rate ending at 06:15:52

Then 10 minutes of pause ending at 06:25:52.

Followed by CC charge at 15A rate ending at 06:40:28 and finally a CV phase ending at 06:51:11.

This picture shows some differences compared with same speed (3C) at standard temperature of 25°C (see MOU Test 3 starting at page 13). The main difference can be found in the proportions of the curves during the charging phase: In this test the CC charge duration is around 58% of the total timing charge (and 42% the CV), where at standard temperature the CC phase was around 80% of the total charge time (20% circa for the CV).

In this test:

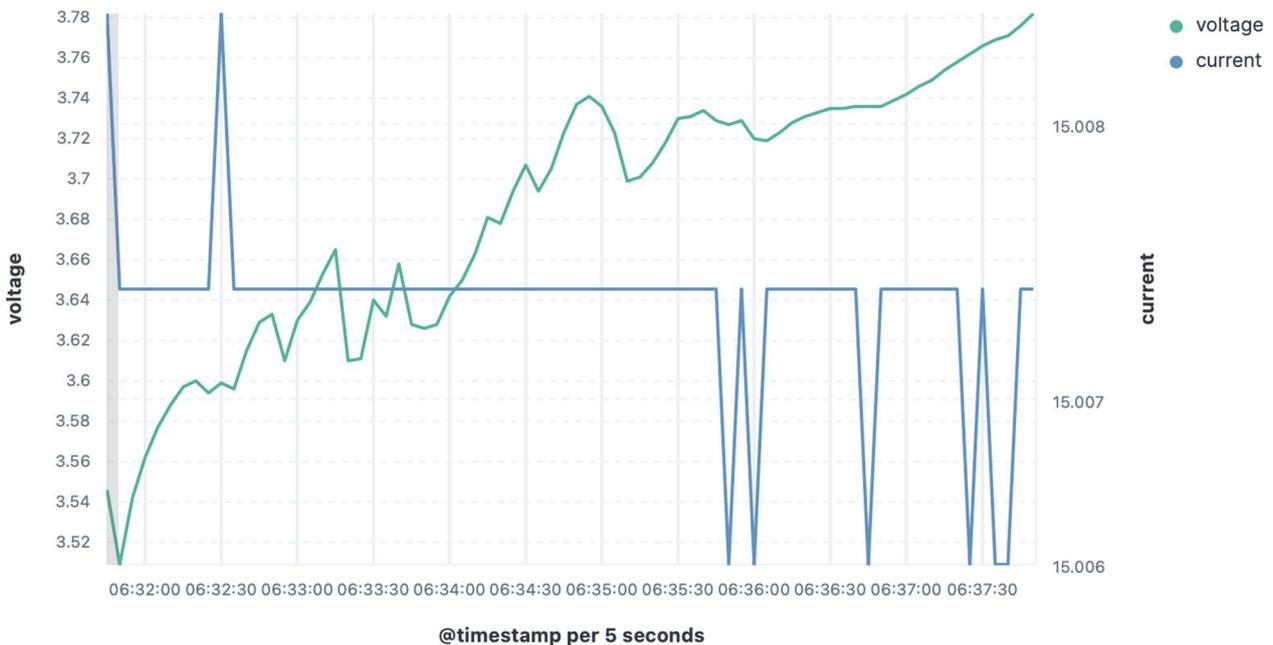
Total charged capacity was: 4572mAh and charged energy: 16665mWh

Total discharged capacity was: 4561mAh and discharged energy: 14190mWh

During an example 25°C cycle, with same rate (MOU test 3):

Total charged capacity was: 5040mAh and charged energy: 17980mWh

Total discharged capacity was: 5035mAh and discharged energy: 16600mWh



Picture 2. It's interesting to note that zooming-in at the end of CC charge phase of this test, it's possible to see some voltage fluctuations (green line) that were not present at any other test. It's not possible to tell without further investigations the origins of these fluctuations: it's possible these are related to the internal physics of the cell or that external factors caused these.

MOU Tests Conclusions

The executive summary of the reported tests shows that the cell under test has:

- a behavior characteristic (voltage curve) that resembles that of a Capacitor (for example that of a hybrid LIC cell)
- at slow speeds has a very high energy round trip efficiency
- a very high tolerance to very high speeds, maintaining a comparably good energy efficiency, that does not drop even at the fastest executed test (34A = aprox 7-8C)
- At extremely low temperatures the cell limits strongly the speed effectively available. With the limited executed tests at very low temperature a speed of 1C seems max given. It's not known if the cell can suffer damages working at these low temperatures. Further cycling at low temperature is needed to find out.
- At extremely high temperatures the cell shows a remarkable speed, without diverging due to excess additional heat, added internally by the charge and discharge processes. It's not known if the cell can suffer damages working at these high temperatures and at what speeds. Further cycling at High temperature is needed to find out.
- The low internal generated heat (even at high speeds) in all conditions, and mainly concentrated at discharge, let assume that the heat handling and battery management system of a battery pack based on this cells could be rather simple.
- During several weeks of cycling it's not possible to measure an aging effect. This tends to let assume that the expected life of this cell is longer of that of other storage cells. Further cycling would be needed to set an estimation of the aging and so of the expected life span (on a set of cells, that are new and never stressed with other extreme tests, like the ones executed during this testing session).

Additional Tests

Some other cycling tests were executed in addition to the MOU Tests discussed in all previous pages of this document.

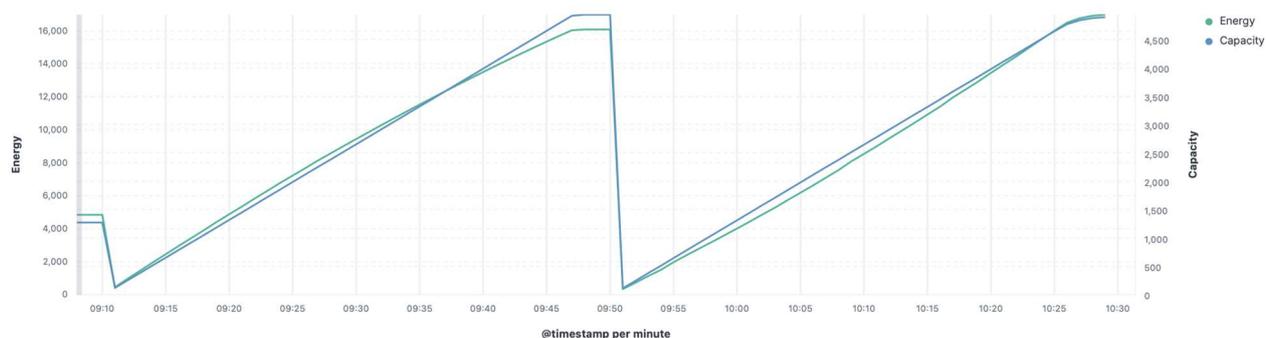
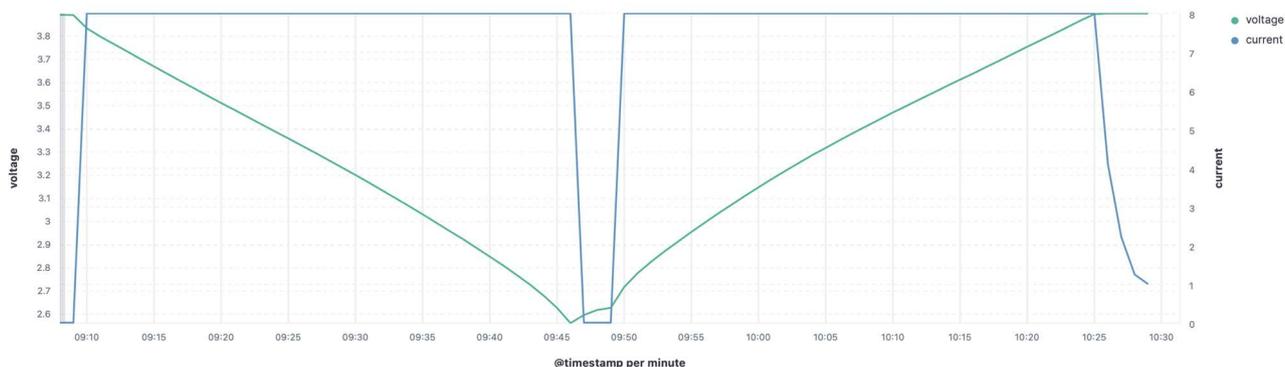
Following fast summary of all additional tests:

Additional test 1 – executed the 29/09/21 - before MOU test 1

Consisting of one full discharge and charge cycle at 8A (aprox = 1,6C)

Discharged: Energy = 16088mWh Capacity = 4939mAh

Charged: Energy = 16983mWh Capacity = 4896mAh



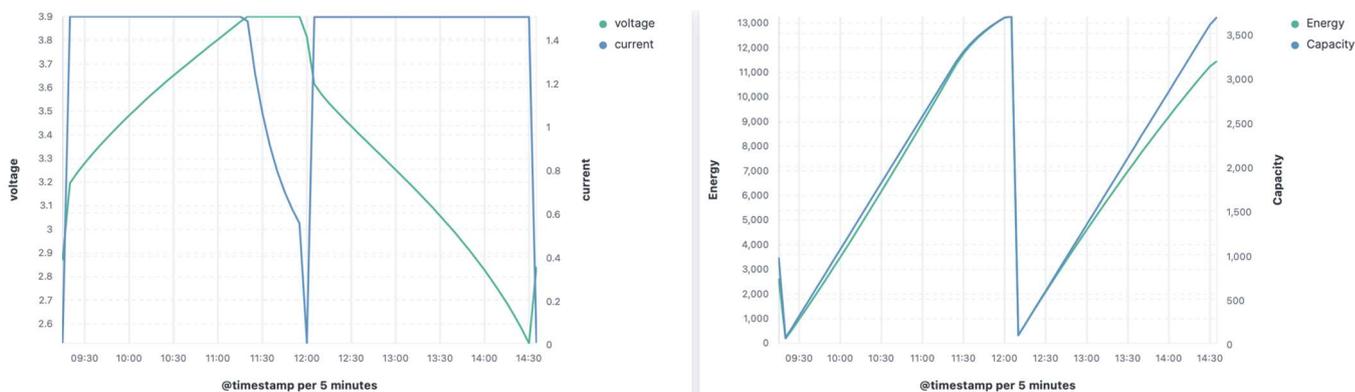
Additional test 2 – executed the 29/09/21 - before MOU test 1

Consisting of one full discharge and charge cycle at 34A (same parameters of TÜV test)



Additional test 3 – executed the 19/10/21 - before MOU test 6

Consisting of one full charge and discharge cycle at 1.5A at -20 °C (relatively slow rate of approx. 0,3C at an extreme cold temperature)



This test showed a consistent behavior even at this extreme cold temperature: The voltage curve (green) is regular and the CC charge phase is not too short, showing that the cell is well accepting the charge for large part of the charging phase at this rate. The total capacity is reduced towards nominal capacity but the energy efficiency remains good.

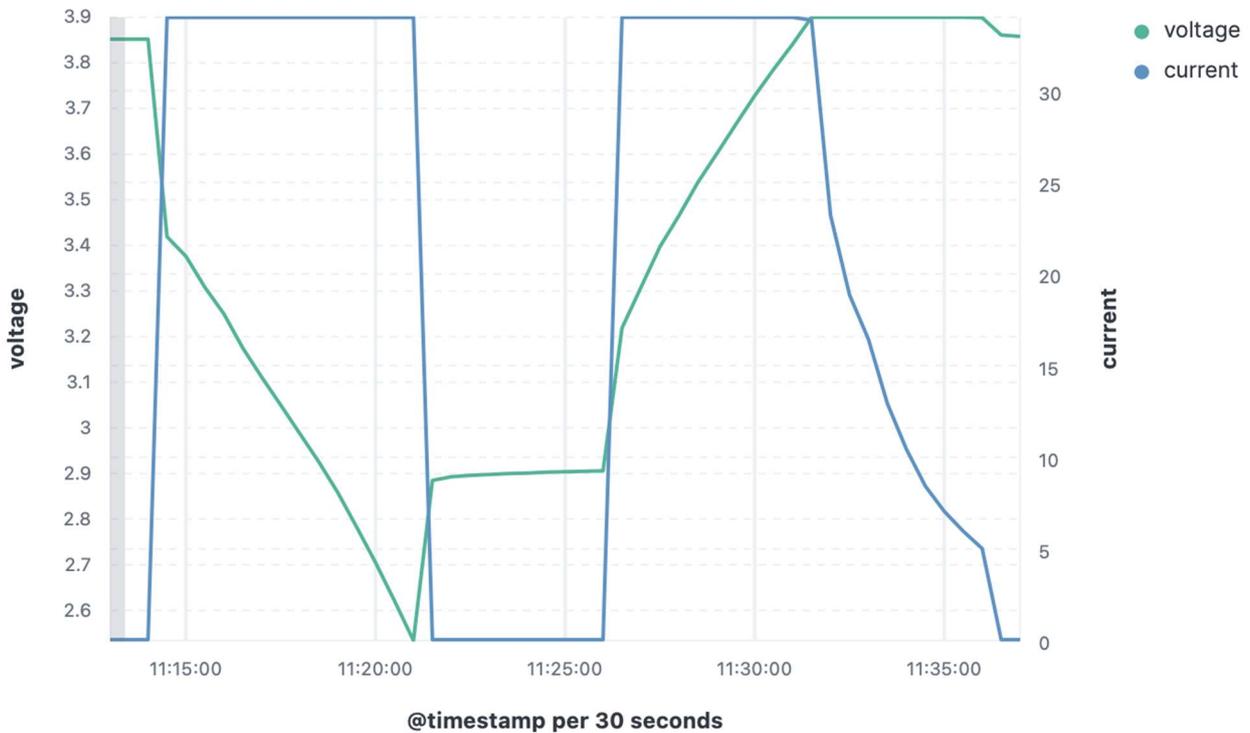
Discharged: Energy = 11480mWh Capacity = 3690mAh
 Charged: Energy = 13265mWh Capacity = 3681mAh



This picture shows the Temperature profile during the cycle: it shows cooling during the pause at the center and a light temp increase during discharge.

Additional test 4 – executed the 20/10/21 - after MOU test 6

Consisting of a full “TÜV test”: 11 cycles, 34A charge, stop at 3.4A, 5 min pause, 34A discharge stop at 2.5V, 5 min pause, at standard temperature (25 °C)



The picture shows one of the 10 cycles.

Towards “additional test 1” (that has same parameters) it’s evident that the voltage is dropping more on load (left), growing more on charge (immediately after the pause) and has a higher “bounce” during the pause. The reason of this difference compared with “additional test 1” can not be verified and interpreted here and would be very interesting to investigate further.