Technical Note *Cycle Life of LiPo Packs* N°: **TN07004**

Device under test	**Kokam 4000 4S1P H5 series** Weight 478g incl. cable & connectors Dimension 165x42x37mm 
Test method ***Test conditions***	**a) Evaluation of dc discharge properties**: Idc = 5C/12C/20C/25C/30C **b) Life test** according to PA06002-v4 with the following settings: (I) 0 -320 cycles: Icharge = 8A, Vcharge =4.2V/cell, Vcutoff = 3V/cell (II) 321 - 360 cycles: Icharge = 8A, Vcharge =4.25V/cell, Vcutoff = 2.7V/cell Discharge: Ip = 120A (30C), Iaverage = 36A (9C), see appendix A for details **c) Intermediate capacity measurements** @ Idc = 48A, Icharge = 4A, Vcutoff = 3V/cell

Results

DC discharge properties (Fig. 1)

discharge current	capacity [Ah]		discharge voltage Vm/cell		ΔT [K]
20A	3.83	100%	3.60	100%	27
48A	3.81	99%	3.51	98%	41
80A	3.81	99%	3.40	94%	54
120A	3.60	94%	3.23	90%	67+)

+) forced air cooling

Life test, 360 cycles (Fig. 2-10)

	discharged capacity [Ah]	Vm [V/cell]	supplied energy [Wh]	Ri *) [mΩ/cell]	temperature rise ΔT [K]
new	3.83	3.48	53.4	3.0	42
150 cycles	3.63	3.47	50.3	3.3	43
320 cycles	3.50	3.46	48.4	3.5	44

*) measured in the middle of the discharge period
Energy density under the life test conditions: 112Wh/kg (initial value)

Intermediate testing with **48A dc** (Fig. 4)

	12C capacity [Ah]		12C discharge voltage Vm/cell		ΔT [K]
before life test	3.79	100%	3.50	100%	41.8
after 100 cycles	3.70	98%	3.49	100%	43.3
after 200 cycles	3.61	95%	3.48	99%	44.1
after 360 cycles	3.50	92%	3.46	99%	45.4

Cell symmetry (Fig. 6a/b, 7-9)
The cell symmetry was perfect at the beginning. After life test some drift was observed but the maximum deviation of the individual cell capacities remained below 3%.

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Conclusions & Comments

- The new Kokam 4000mAh cells have impressive discharge properties. They can handle DC currents up to 100A without forced cooling. Temperature rise and internal resistance are low.
- The cells are very rugged and a cycle life far beyond 300 cycles can be expected even under harsh discharge conditions.
- The battery came with perfectly matched cells (Fig. 6).
- The battery is qualified for high current burst discharges. The life test was performed with 120A but the limit is certainly higher. However, for very high currents, >120A …150A, the voltage drop due to Ri would get relative high resulting in a suboptimal energy efficiency. For such cases a paralleling of cells should be considered.
- The energy density is slightly higher than for former Kokam series which is the result of the higher discharge voltage Vm. The discharge voltage curve has a characteristic decline after 2/3 of a full discharge but Vm is still somewhat higher than it was for previous Kokam types.
- The cells can be recharged with 8A (2C) without putting the cycle life at risk.

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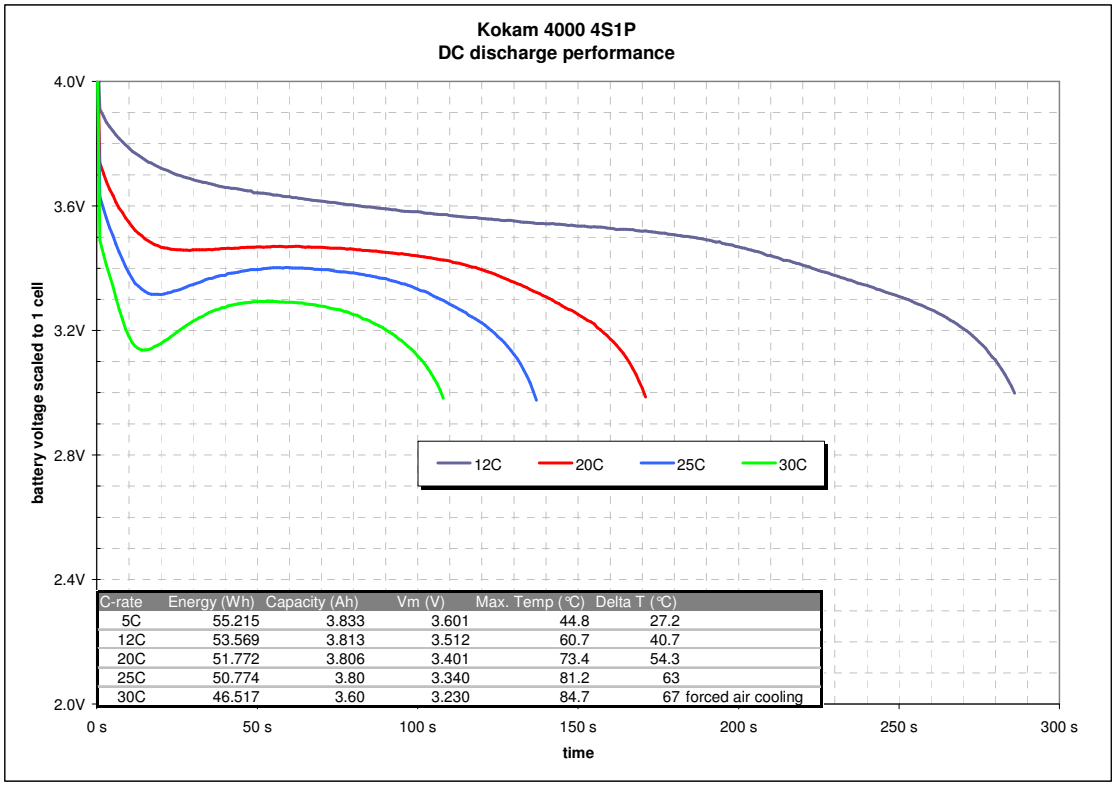
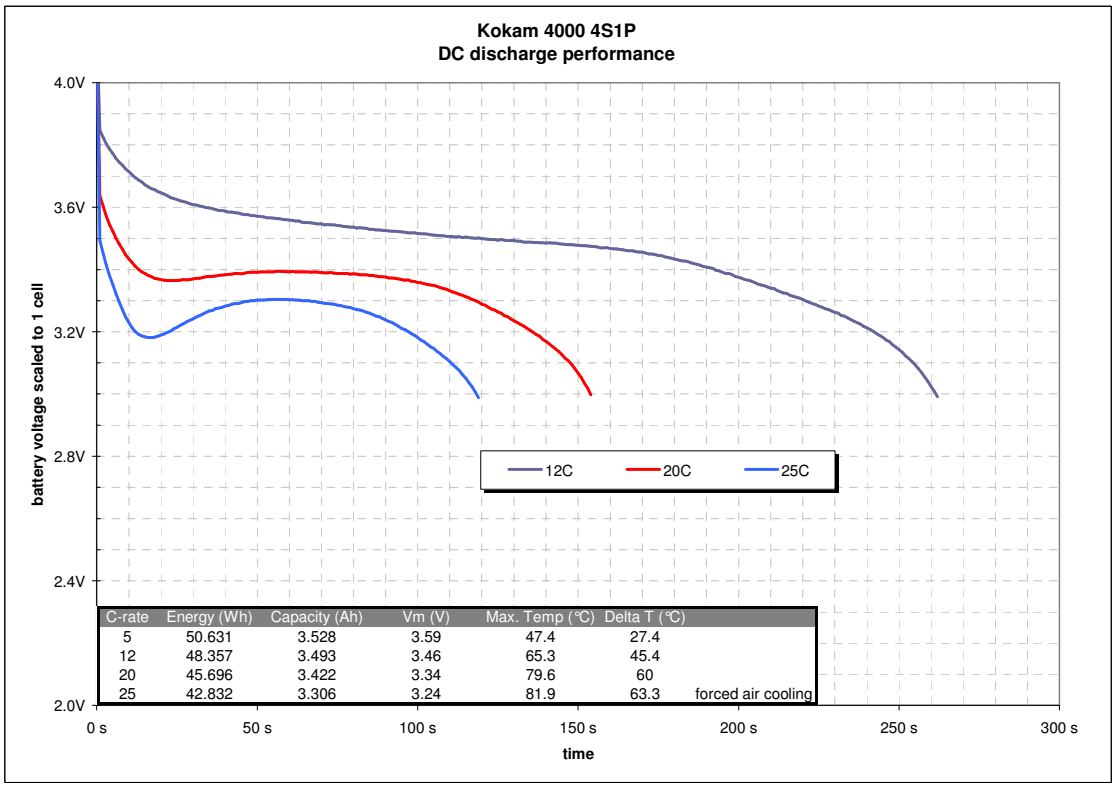
DC discharge performance



C-rate	Energy (Wh)	Capacity (Ah)	Vm (V)	Max. Temp (°C)	Delta T (°C)	
5C	55.215	3.833	3.601	44.8	27.2	
12C	53.569	3.813	3.512	60.7	40.7	
20C	51.772	3.806	3.401	73.4	54.3	
25C	50.774	3.80	3.340	81.2	63	
30C	46.517	3.60	3.230	84.7	67	forced air cooling

Fig. 1a, discharge performance before life test
In order to prevent an overheating, the 30C discharge was done with forced air cooling (3m/s). Up to 100A (25C) the measured capacity is almost constant.



C-rate	Energy (Wh)	Capacity (Ah)	Vm (V)	Max. Temp (°C)	Delta T (°C)	
5	50.631	3.528	3.59	47.4	27.4	
12	48.357	3.493	3.46	65.3	45.4	
20	45.696	3.422	3.34	79.6	60	
25	42.832	3.306	3.24	81.9	63.3	forced air cooling

Fig. 1b, discharge performance after life test (360 cycles)
The loss of capacity after the life test was about 8% while the temperature rise increased by 10% for discharge currents of 48A and up. The 120A discharge was not repeated after life test (temperature rise!).

Life test

For the life test a current pulse pattern with Ip = 121A and Iav = 36 A was used (refer to ppendix A). For the second part (after 320 cycles) the conditions were made harsher by increasing Vcharge to 4.25V/cell and decreasing Vcutoff to 2.7V/cell. But even under these conditions no significant change in the rate of degradation was observed.

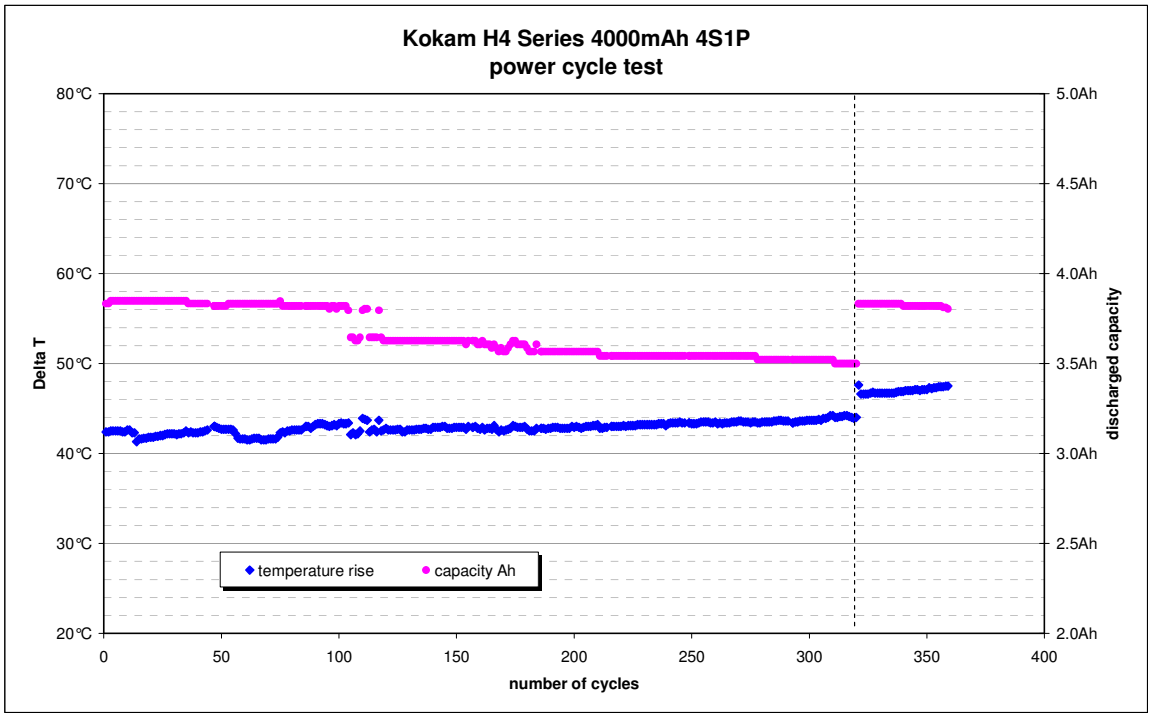


Fig. 2, discharged capacity and measured temperature rise cycle by cycle.

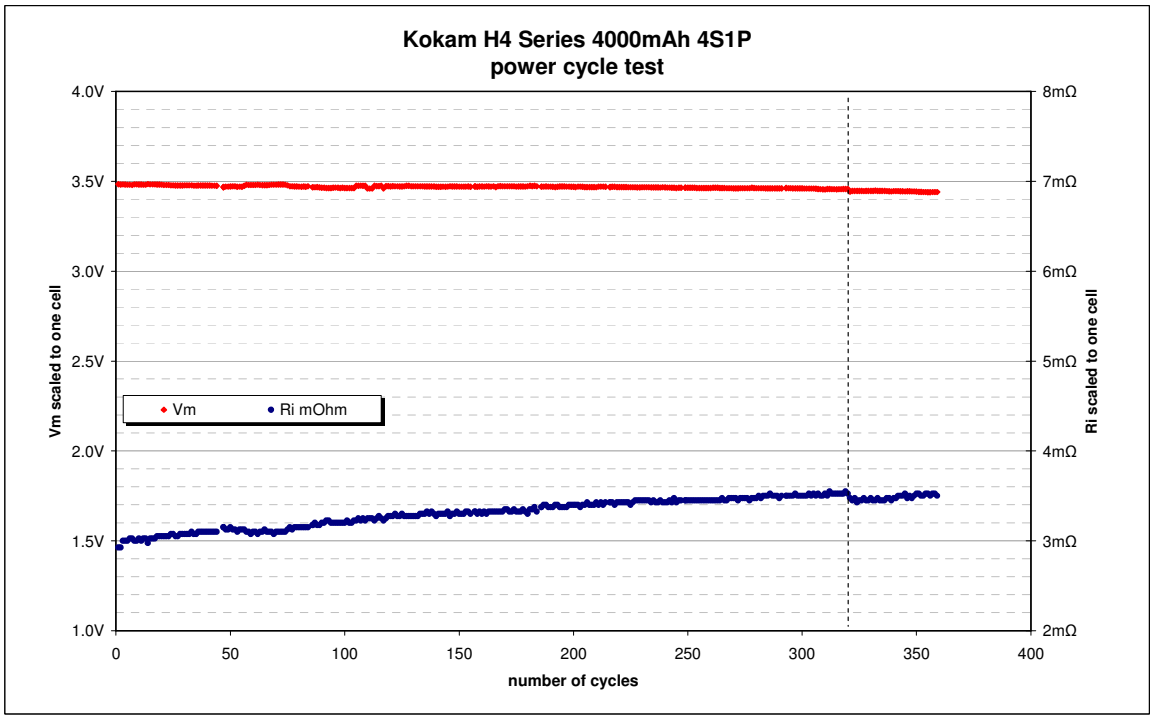


Fig. 3, discharge voltage Vm and internal resistance Ri vs number of cycles

The displayed Ri values are mean averages from the time period of 200s to 240s after beginning of discharge. This is precisely the time where the Ri reached its minimum (refer to Fig.6).

An increase of Ri from 3mΩ to 3.5mΩ was observed after 320 cycles in life test.

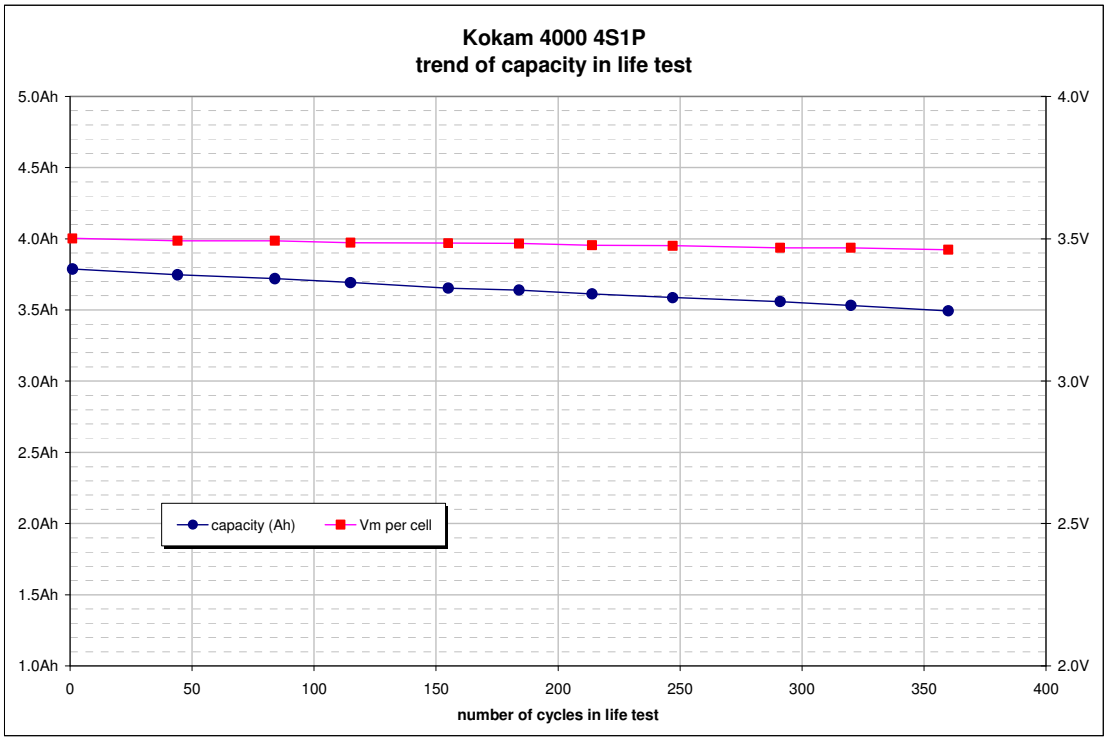


Fig. 4, trend of capacity vs. number of cycles. The capacity was measured @48Adc and Vcutoff = 3V/cell

An 8% capacity drop from 3.8Ah to 3.5Ah was observed after 360cycles.

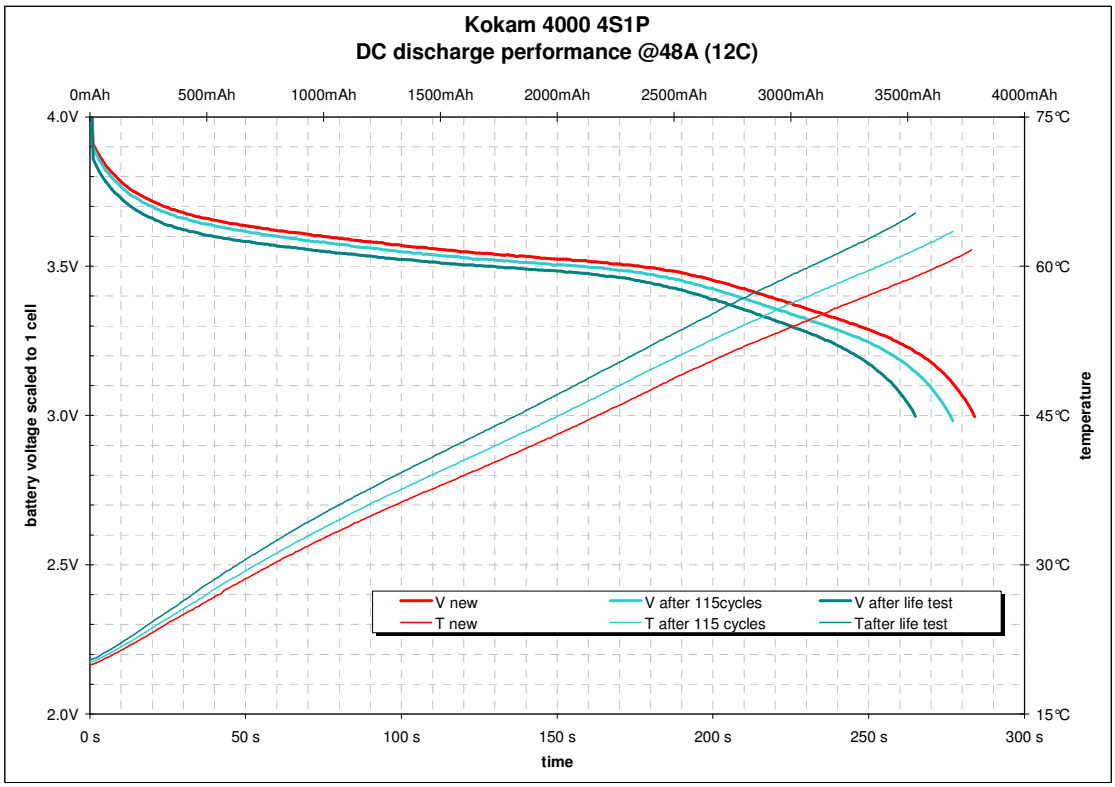


Fig. 5, comparison of the discharge voltage curves and temperatures @ 48A (12C)

Cell symmetry

Part (I) of life test

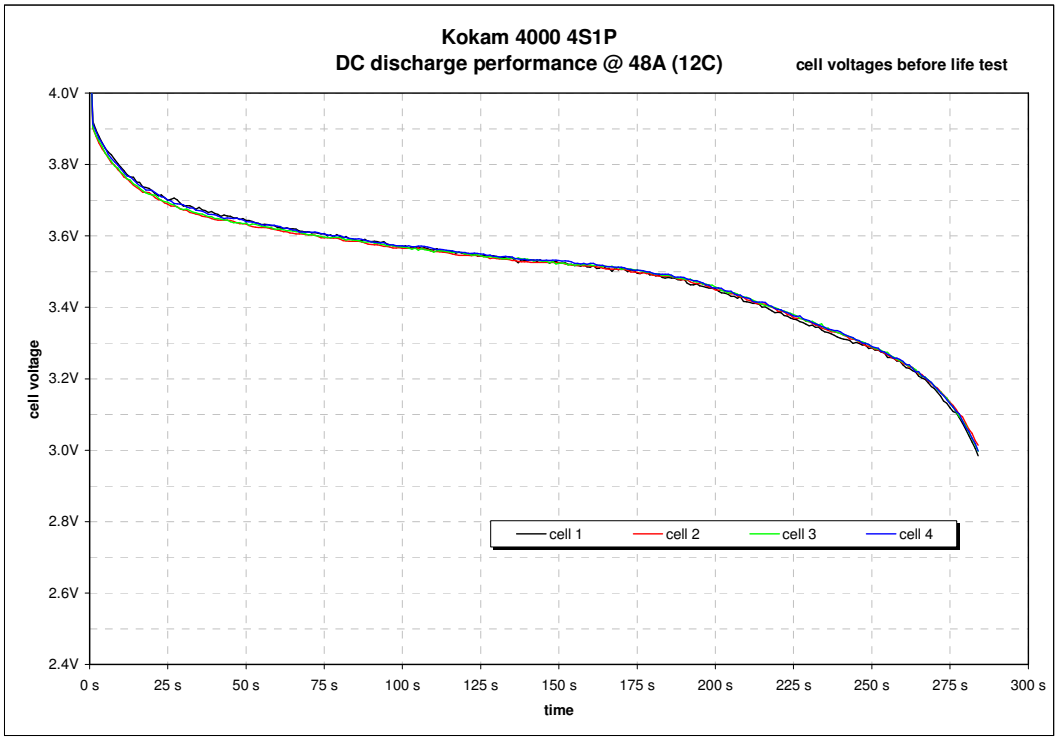


Fig. 6a, cell voltages before life test during 48Adc discharge

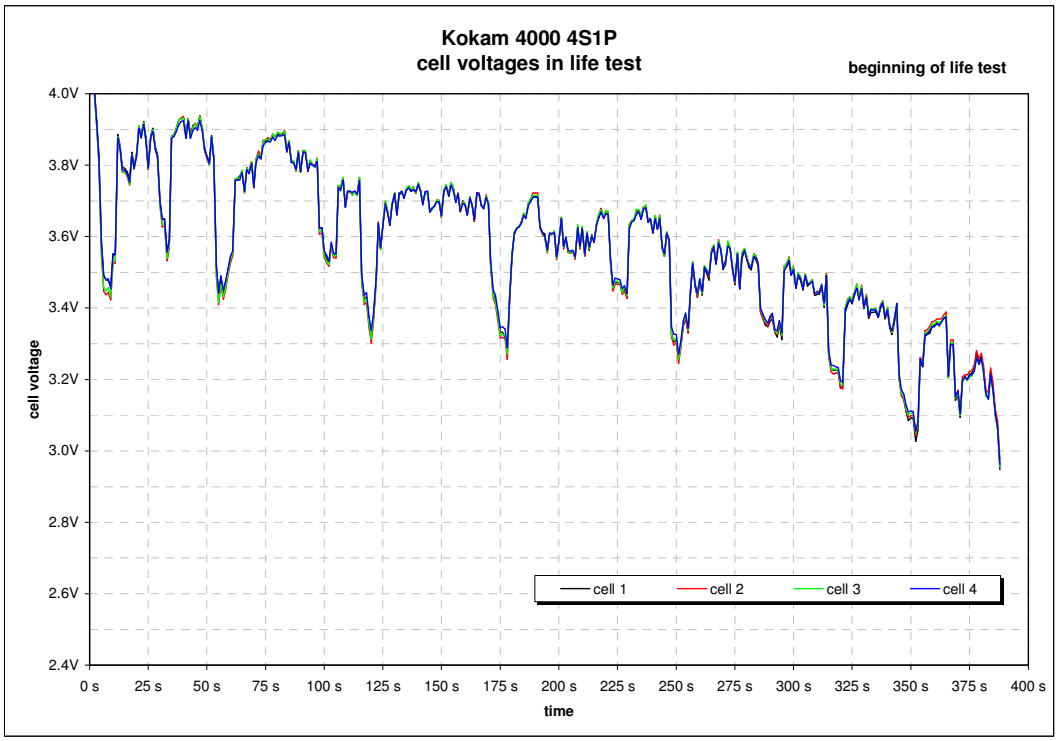


Fig. 6b, cell voltages during the first cycle of life test

The 4 cells were perfectly matched for capacity and discharge voltage.

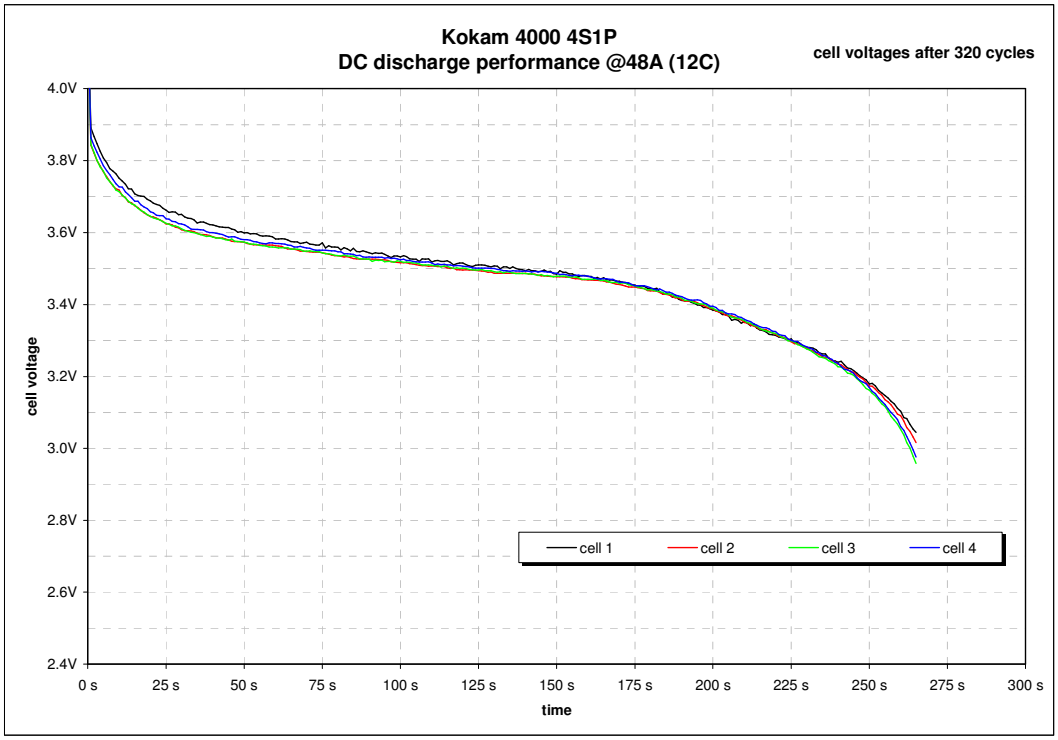


Fig. 7, cell voltages after the first part of life test (320 cycles)

After the first part of life test (320 cycles) some differences between the cells became visible. The maximum capacity deviation was around 2%.

Part (II) of life test

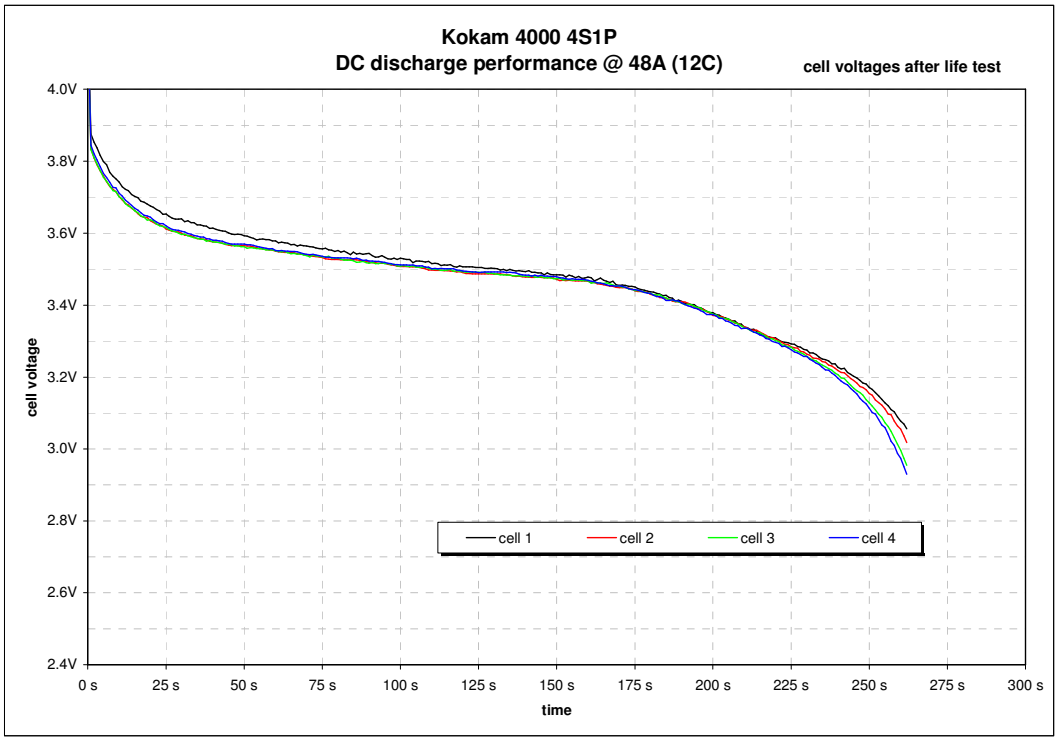


Fig.8, cell voltages after life test

After the second part of life test (total of 360 cycles) the differences between the individual cells became more noticeable but the maximum capacity deviation is still below 3%.

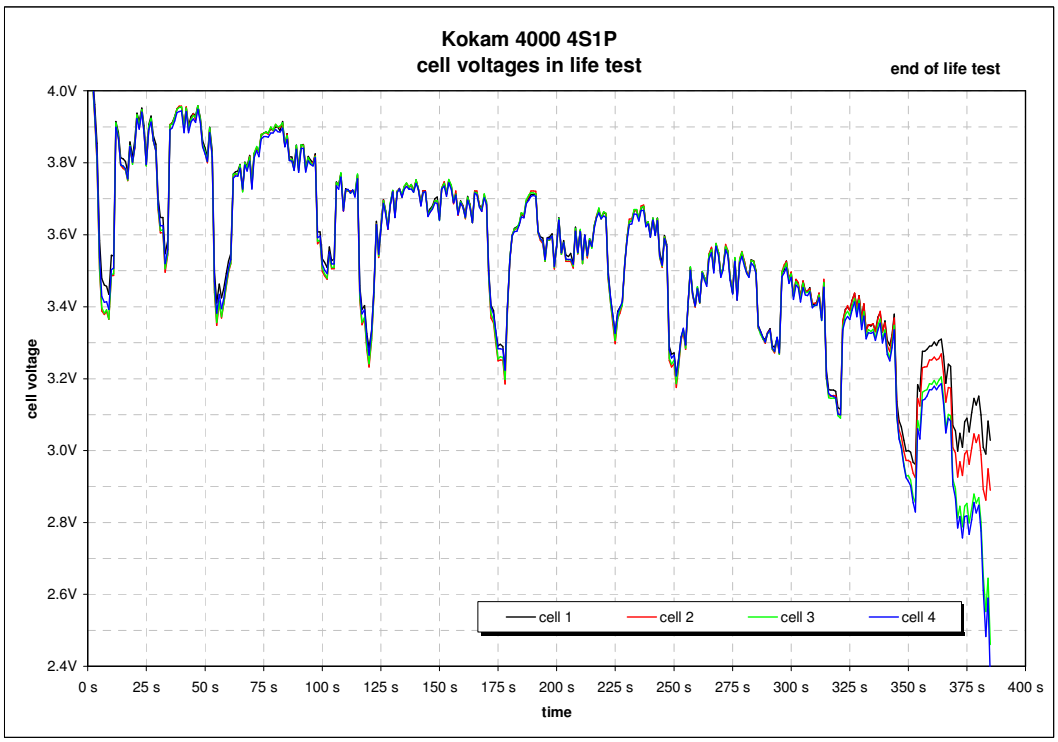


Fig. 9, cell voltages in the last cycle of life test (cycle #360)

At the very end of the discharge period the cell voltages drifted heavily apart and cell 3 and 4 were driven into a deep discharge. This was the result of the low Vcutoff setting (2.7V/cell) in combination with the observed capacity differences (2-3%).
Even under these conditions no significant change of the rate of deterioration was found compared to the first part of life test (-> Fig. 2/3).

Internal resistance

Internal resistance within one discharge cycle.

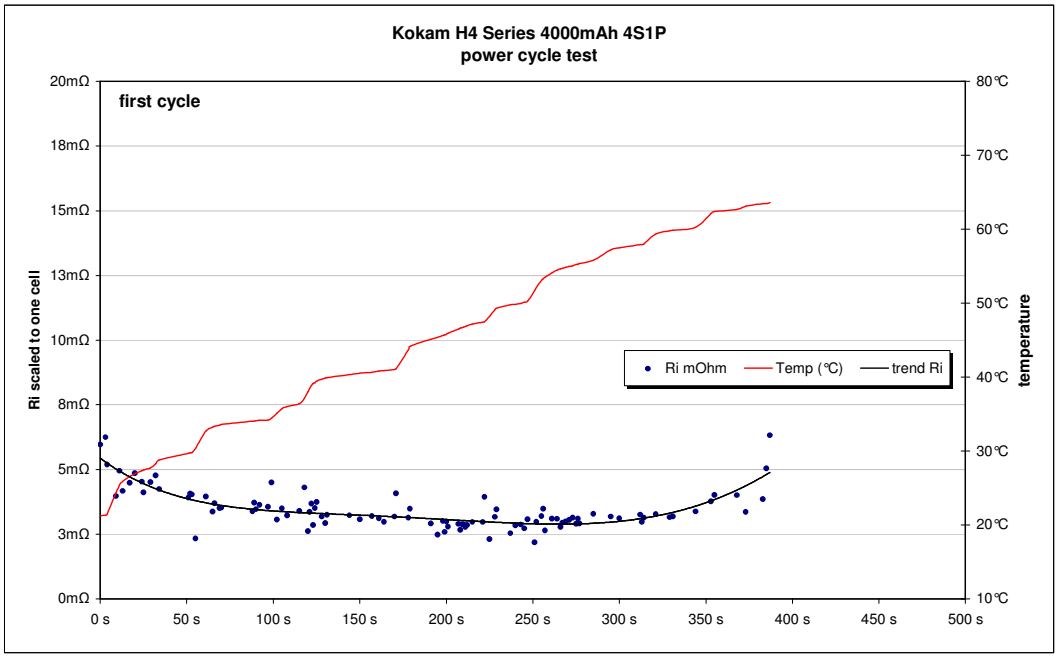


Fig. 10a Ri as a function of temperature and discharge time during the **first cycle** of life test

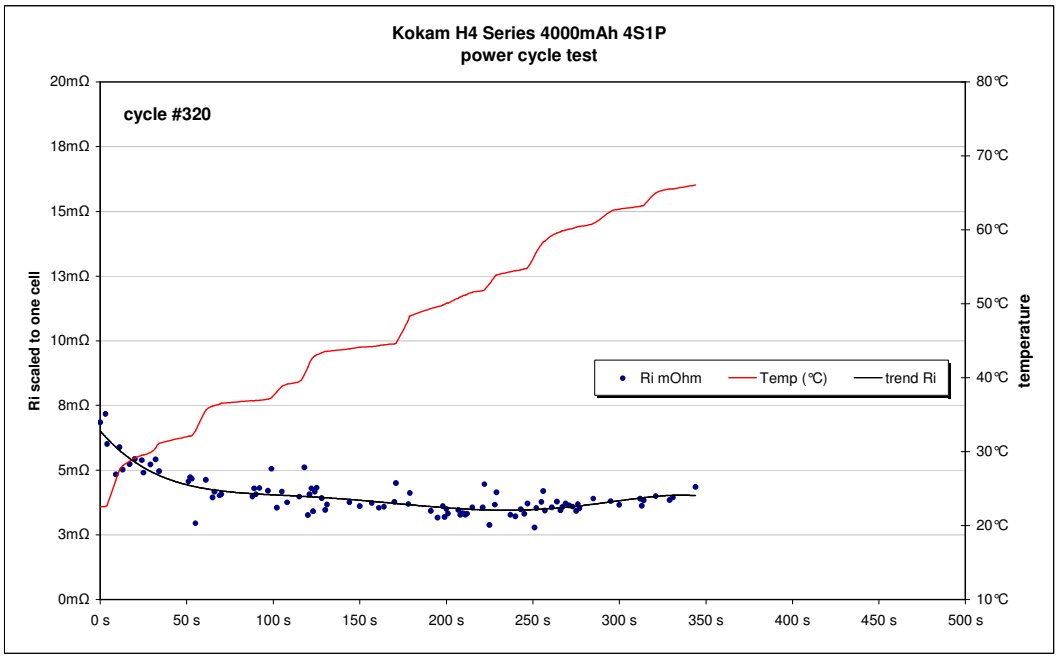


Fig. 10b the same as Fig.6a but **after 320 cycles** in life test

The temperature coefficient of Ri is moderate and a low Ri is already reached at temperatures of 30°C and higher.

Appendix A life test settings

The life test was performed in two parts. The first part with standard settings for Vcharge and Vcutoff, the second part with more aggressive settings to explore the robustness of the battery.

Charge	**0-320 cycles**	**321-360 cycles**
Recharge current	8A (2C)	8A (2C)
Recharge time	50 minutes	50 minutes
Charge voltage	4.2 V/cell	**4.25V/cell**
Discharge (-> Fig. A2/3)		
Peak current	121A (30C)	121A (30C)
Average current	36A	36A
RMS current	~ 47A	~ 47A
Cut-off voltage	3V/cell	**2.7V/cell**
Resulting DoD	> 95%	100%
Ambient conditions	Ta = 18°C, cooling method: natural convection	
	No voltage balancing equipment was used	

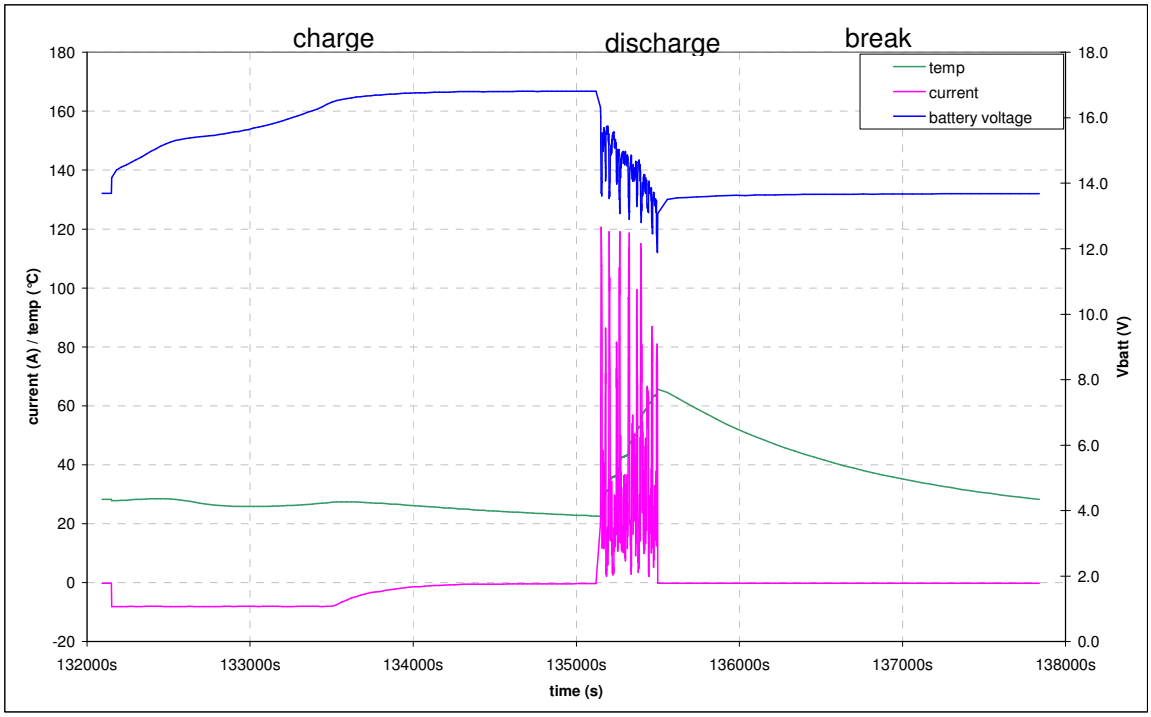


Fig. A1, a typical cycle of the life test

During the break time the battery temperature dropped below 30°C.
The 8A charge current didn't cause any considerable temperature rise.

Discharge current profile

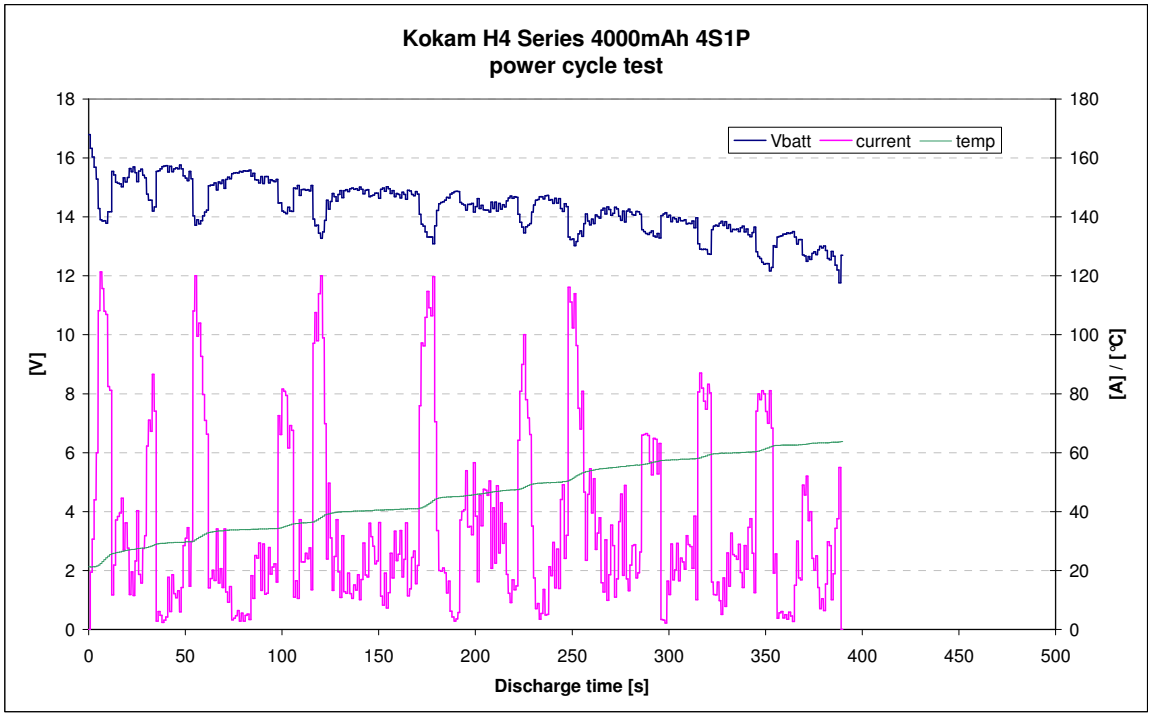


Fig. A2, discharge phase at the beginning of life test

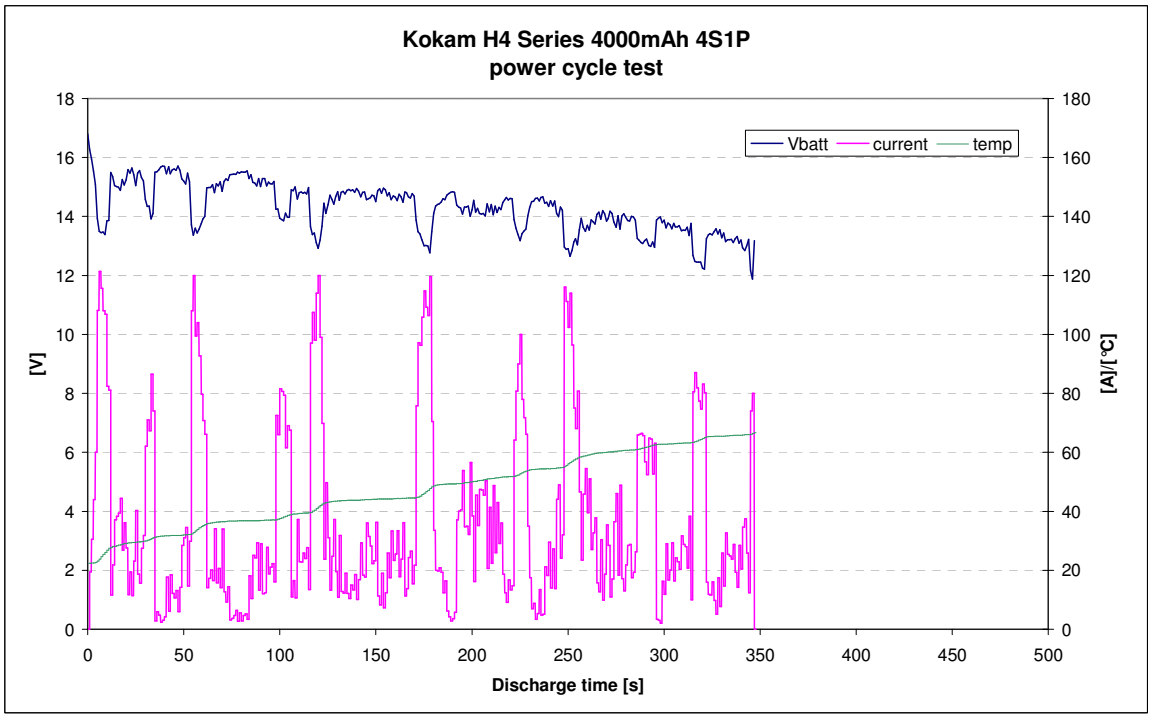


Fig. A3, discharge cycle towards the end of life test.

For the whole life test the current profile remained unchanged. The resulting discharge time was between 350s to 385s.