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Using degradation modes for large-scale capacity and power fade diagnostics

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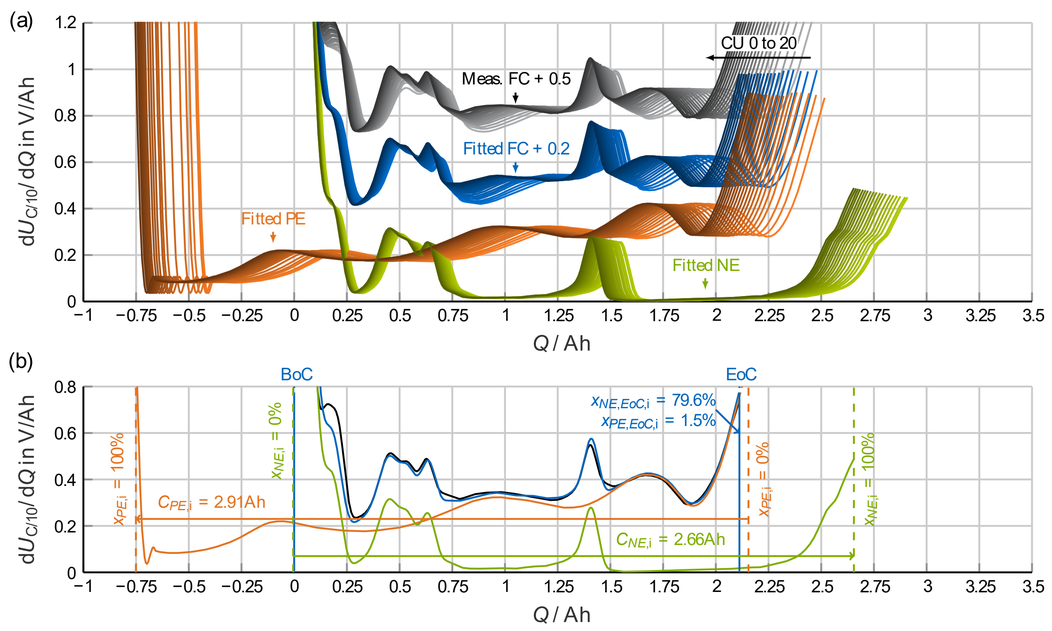
Estimating Degradation Modes

- C/10 charge curve during check-up (CU) is used to estimate degradation modes (DMs), which can be used to categorize mechanisms occurring during lithium-ion battery aging [1].
- The DMs are calculated by half-cell fitting, which is described for this cell type (US18650VTC5A by *Sony/Murata*) in a previous publication [2] and is illustrated in the following figure:



(a): Differential voltage evolution of C/10 charge between check-up (CU) 0, corresponding to a pristine state and CU 20, corresponding to an aged state after 1200 EFC, of a cell cycled around 35% mean SOC at 50°C ambient temperature, with a depth of discharge of 30% at 1.5C constant current charge and discharge (light to dark grey curves). The measured curve is shifted by +0.5V/Ah for better visibility. The corresponding fitted curves are plotted in light to dark blue. The fitted curves are shifted by +0.2V/Ah for better visibility. The fitted curves are calculated from the difference of fitted PE, plotted in light to dark orange, and fitted NE, plotted in light to dark green. (b): All described curves exemplarily at CU 20 only, together with all measures calculated at every CU. These measures can be used to calculate the DMs according to the equations to the right.

- The three DMs are loss of active material at the positive and negative electrodes(LAM_{PE} and LAM_{NE}) and loss of lithium-inventory (LLI).
- The equations to calculate the DMs from the half-cell fitting procedure at every CU i are (adapted from [3]):

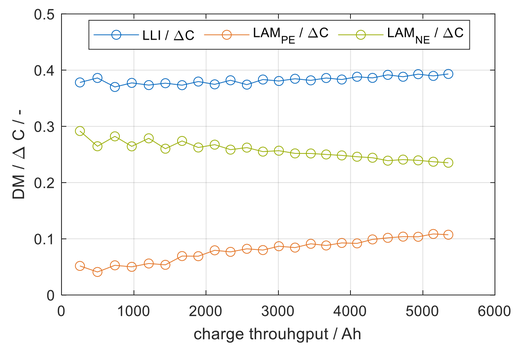
$$\mathrm{LAM_{PE}} = 1 - \frac{C_{\mathrm{PE},i}}{C_{\mathrm{PE},0}}$$, which can be interpreted as the scaling of the cathode potential curve.

$$\mathrm{LAM_{NE}} = 1 - \frac{C_{\mathrm{NE},i}}{C_{\mathrm{NE},0}}$$, which can be interpreted as the scaling of the anode potential curve.

$$\mathrm{LLI} = 1 - \frac{(x_{\mathrm{NE},i,0\%} - x_{\mathrm{FC},i,0\%})C_{\mathrm{NE},i} + (x_{\mathrm{PE},i,0\%} - x_{\mathrm{FC},i,0\%})C_{\mathrm{PE},i}}{(x_{\mathrm{NE},0,0\%} - x_{\mathrm{FC},0,0\%})C_{\mathrm{NE},0} + (x_{\mathrm{PE},0,0\%} - x_{\mathrm{FC},0,0\%})C_{\mathrm{PE},0}}$$, which can be interpreted as the shift between potential curves.

Outlook

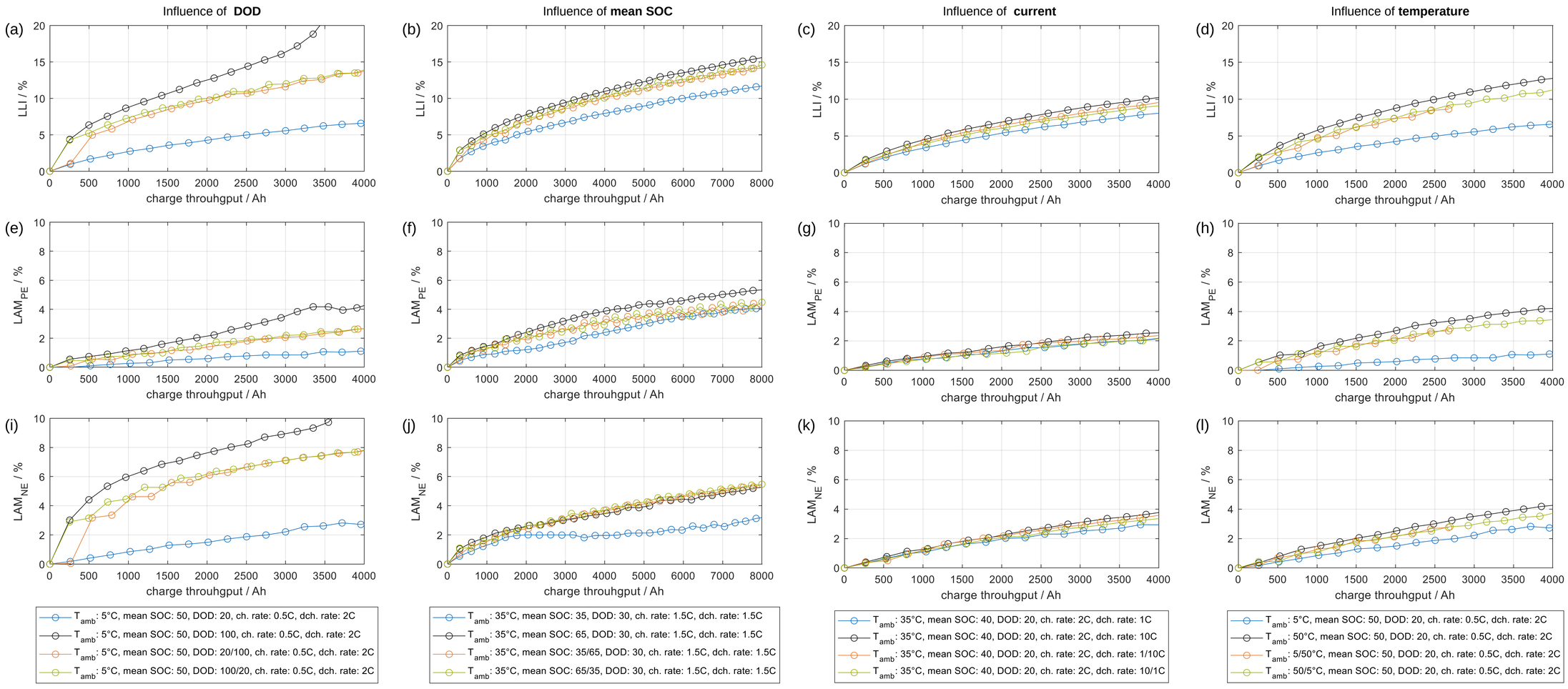
- Dividing the DM values with capacity fade, uncovers the individual contribution of DMs to capacity fade.
- Share of DM with capacity fade changes with aging. Share of LLI dominating for the tested cell type.
- Potential to predict the onset of non-linear capacity fade.
- Open-source dataset will be published.



Division of DMs by capacity fade ΔC to highlight the contribution of the individual DMs to capacity fade for the cell cycled cell cycled around 50% mean SOC at 5°C ambient temperature, with a depth of discharge of 20% at 0.5C charge and 2C discharge. The circular markers indicate a CU. This plot highlights the correlation of LLI and ΔC for this test case.

Results

- Estimated DMs during changing DOD, mean SOC, discharge current rate and ambient temperature.
- LLI is dominating DM for the tested cell type during all conditions, compared to LAM_{PE} and LAM_{NE}.
- Depth-of-discharge (DOD) has the largest influence on DMs and switching DOD conditions is detrimental to anode, even if total charge-throughput for both conditions is identical.
- LAM_{NE} during switching mean SOC similar to LAM_{NE} during high SOC instead of low SOC condition.



Estimated DMs during switching DOD, mean SOC, discharge current and ambient temperature (left to right). The circular markers indicate a CU. LLI is the dominant DM for all tests. LAM_{PE} is the DM with the lowest values, which we attribute to the cycling stability of NCA. We notice that, for the cells subjected to switching aging conditions plotted in orange and green, LAM_{NE} follows rather the curve of the cell subjected to the harsher aging condition plotted in black, instead of lying between the black and blue curve. *The capacity fade of these tests was also evaluated and published and is currently under review.

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